KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI

COLLEGE OF SCIENCE

DEPARTMENT OF ENVIRONMENTAL SCIENCE

IMPACT OF MINING ON AIR QUALITY WITHIN THE HWINI-BUTRE AND BENSO AREA IN THE WESTERN REGION OF GHANA

BY

ALFRED HENYO

JULY, 2011

DECLARATION

It is hereby declared that this thesis is the outcome of research work undertaken by the author, any assistance obtained has been duly acknowledged. It has neither in part nor whole been presented for another degree elsewhere.

Signature…………………………………......................DATE………………..................

NAME: **Alfred Henyo** (**STUDENT**)

Signature………………………………….........................DATE………………..................

NAME: Prof. Kwasi Obiri-Danso (**SUPERVISOR**)

Signature……………………………………………........DATE………………....…………

NAME: Dr. P. K. Baidoo (**HEAD OF DEPARTMENT**)

DEDICATION

This study is dedicated to all missionaries of the gospel, and to another great man Mr. Francis Henyo (my late father) whose love, dedication and inspiration carried me through this course but could not wait to see the end of it. To these great and loving people do I honour by dedicating this MSc theses.

ACKNOWLEDGEMENT

I acknowledge the abundant grace of the Lord God almighty that has brought me this far. My sincerest thanks go to my supervisor Prof. Kwasi Obiri-Danso whose commitment to ensuring a quality research, imbibed in me an invaluable skill words cannot thank him for. Prof. you guided me with intelligence and expertise. With diligence and patience, you challenged me to carry out a good study. Your directions and responses were incontrovertibly good and prompt. You have left an indelible positive impact on my research methodology. God bless you.

I have been blessed enough to be surrounded by a wife and children who continually give me the best of home environment to finish whatever good course I begin. No phrase is enough to express my heartfelt thanks to you Reggie, and my boys Gilbert and Elorm. You have always been wonderfully supportive. Special thanks to my friends Mrs. Lydia Opoku, Asiedu Michael, Ankamah Emmanuel and Ayisah Divine for the numerous supports.

I am also very thankful to Ms. Charlotte, the environmental manageress of Golden Star (Wassa) Resources Limited and the staff of the EHS department for the immense support they gave me during this research. Special mention of Mr. Sefa and Oscar is laudable for the irreplaceable roles they played during the sampling at Huni-Butre and Benso communities. I am also grateful to Elder Akwa and Elder Nkrumah for the help.

I would also like to thank the following individuals; Mr. Berko-Asamoah Boateng (laboratory manager) and Peter of SGS laboratory, Tema for the help. You were wonderful.

Finally I acknowledge the numerous physical and spiritual supports from Rev. and Mrs Cobbina of Temple of Praise (TOP) ministries, and the brethren at TADISCO especially Rev. Mrs. E. Akuoko, Mr. Moses Ansah and Mr. P.K Dametey. God bless you all.

ABSTRACT

Mining is one of the main sources of particulate matter contamination to the environment. A six-month study on the impact of mining on ambient air quality within the Huni-Butre and Benso mining concession area was carried out in the Mpohor Wassa East District of the Western Region, Ghana. Air quality samples were collected at six sampling sites between August 2010 and January 2011 using deposit gauge bottles (AS/NZS 3580) to sample dust fallout from the ambient air, and dusttrak Aerosol Monitor (8535) to determine real-time suspended dust concentrations. Dust fallouts were also analysed for total solids, insoluble solids, combustible solids and ash contents while the dusttrak aerosol monitor measured ambient PM_{10} concentrations. The levels of nuisance dust and mass concentrations of suspended particulate matter at Yayaho, Subriso, Ningo, Anlokrom, Mpohor Pentecost area and Mpohor Police station were determined. Results revealed that the levels of particulate matter, mainly suspended dust were above WHO threshold limit in some of the communities. Insoluble dust fallout values ranged between 3.6 mg/m^2/month and 109.2 mg/m^2/month, while suspended dust recorded values within 5.1$\mu g/m^3$ and 74.0$\mu g/m^3$. The highest PM_{10} was recorded at Yayaho and the minimum at Mpohor Police Station. Both short term and long term exposures to such particulate matter have serious health effects on the inhabitants of the area. The study brings to the fore the need for annual and daily fine particle monitoring and development of ambient air quality standards and targets for mining companies to help protect the health of populations of communities in these mining environments. Studies to assess the relationship between air pollution levels and health problems in mining communities have been recommended.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES **PAGE**

LIST OF ACRONYMS

COPD: Chronic Obstructive Pulmonary Disease

EIA: Environmental Impact Assessment

EPA: Environmental Protection Agency

GSRL: Golden Star Resources Limited

HBB: Huni-Butre and Benso

IMF: International Monetary Fund

ISSER: Institute of Statistical, Social and Economic Research

KNUST: Kwame Nkrumah University of Science and Technology

NO: Nitric Oxide

NO_2: Nitrogen Dioxide

NO_3: Nitrate

NO_x: Oxides of Nitrogen

PAH: Polycyclic aromatic hydrocarbons

PM: Particulate matter

PM_{10}: All particles smaller than 10 μm in diameter. It includes all particles within the size range of 2.5 μm to 10 μm in diameter. They are referred to as coarse particles

$PM_{2.5}$: All particles less than 2.5μm in diameter. They are referred to as fine particles.

SPM: Suspended particulate matter

TSP: Total Suspended Particles

UNEP: United Nations Environment Programme

US EPA: United States Environmental Protection Agency

USA: United States of America

VOC: Volatile Organic Carbons

WHO: World Health Organisation

DEFINITION OF TERMS

Adverse health effect - Abnormal or harmful effect to an organism caused by exposure to a chemical. It includes results such as death, other illnesses, altered body and organ weights, altered enzyme levels, etc.

Aerodynamic diameter - Is the diameter of a spherical particle that has a density of $1g/cm^3$ and which has the same terminal settling velocity as the particle of interest.

Aerosol - A suspension in a gaseous medium of solid particles, liquid particles or solid and liquid particles having a negligible falling velocity.

Air pollutant - Any substance in air that could, in high enough concentration, harm humans, animals, vegetation or material.

Air Pollution - The presence of contaminants or pollutant substances in the air that interfere with human health or welfare, or produce other harmful environmental effects.

Air shed - A body of air bounded by topography and meteorology in which a contaminant, once emitted, is contained.

Air quality standards - The level of pollutants prescribed by regulations that are not to be exceeded during a given time in a defined area.

Airborne particles - Total suspended particulate matter found in the atmosphere as solid particles or liquid droplets.

Ambient air - The external air environment, which excludes the air environment inside buildings or structures.

Anthropogenic - Produced by human beings or human activities.

Asthma - A respiratory disease caused by spasmodic contraction of the bronchioles in the lungs. Characterised by attacks of wheezing, shortness of breath and/or coughing and resulting in difficult breathing.

Black smoke - Surrogate for suspended particles used in UK and is defined according to a special measuring procedure, indicating the density of blackness on a certain filter system.

Brownian motion – The continual random movement due to molecular agitation of fine particles suspended in a gas or a liquid.

Carbon dioxide - A colourless, odourless, non-combustible gas. It is approximately 50% heavier than air, of which it is a normal constituent.

Cardiovascular - A medical term that refers to the heart and blood vessel system around it.

Chronic exposure - A long-term exposure to a toxic substance.

Chronic health effect - Refers to an adverse health effect that develops slowly over a long period of time or from prolonged exposure to a health hazard without implying a degree of severity.

Coagulation - the process whereby aerosol particles collide with each other due to a relative motion between them, and adhere to form larger particles. Coagulation leads to a decrease in particle number concentration and to an increase in particle size, and leaves the total particle mass unaffected.

Combustion - A chemical reaction in which a material combines with oxygen with the evolution of heat:

Chronic obstructive pulmonary disease (COPD) - A disease process that decreases the ability of the lungs to perform ventilation.

Crustal elements - Elements derived from a crustal origin

Cumulative effects - Health effects that increase if exposures last several days.

Disease - A pathological condition of the body that presents a group of clinical signs, symptoms, and laboratory findings peculiar to it and setting the condition apart as an abnormal entity differing from other normal or pathological condition.

Dry deposition – The collection of precipitant dust during periods with no rainfall

Epidemiological studies - Studies pertaining to epidemiology.

Fine particles - Particles with the aerodynamic diameter smaller than 2500 nm.

Fly ash - Particles of ash entrained in flue gas produced by fossil fuel combustion.

Gravitational deposition or gravitational settling - Particle motion in gravitational field.

Health hazard - Evidence based on scientific data (human or animal) that acute or chronic effects might occur.

Heterogeneous nucleation - Formation of droplets on condensation nuclei

Homogeneous nucleation - Formation of droplets in the absence of condensation nuclei; also called self-nucleation.

Inhalation - Breathing into the lungs of a substance in the form of a gas, vapour, fume, mist, or dust.

Mass concentration - The concentration of particles in air expressed as mass per unit volume.

Meteorology - the earth science dealing with phenomena of the atmosphere (especially weather).

Mobile sources - Motor vehicles and other moving objects that release pollution. **Nanoparticles** - Particles below 50 nm in diameter.

Nitric acid - A colourless or yellowish fuming liquid. It is highly corrosive and the vapour is very hazardous. Nitric acid and nitrates (mainly ammonium nitrate) occur in the atmosphere in the form of aerosols: the acid is formed from oxides of nitrogen and then reacts with ammonia to form ammonium nitrate.

Nitrogen - A gaseous element, atomic number 7, relative atomic mass 14.0067, symbol N.

It is the principal constituent of air (78% by volume).

Nitrogen oxides - A series of seven compounds, of which only three (N_2O, NO and NO_2) are of any significance in the atmosphere. Nitrous oxide (N_2O) is a colourless gas that is believed to play an important role in the nitrogen cycle. It is the most abundant atmospheric nitrogen compound and a greenhouse gas but is of no significance as a pollutant. Nitric oxide (NO) is a colourless poisonous gas that reacts readily with oxygen (and very rapidly with O_3) to form the dioxide. It is formed in combustion processes. NO_2 is a reddish-brown poisonous gas.

Nucleation - The process of forming a central point about which matter is gathered. It is the process whereby new aerosol particles are spontaneously formed from gaseous species.

Particulate matter - All airborne pollutants, which are not gases. It can include droplets of liquids or solid matter.

Particle size distribution - The distribution of equivalent diameters of particles in a sample or the proportion of particles for which the equivalent diameter lies between defined limits.

Personal exposure - The concentration of particulate matter near the breathing zone.

PM_{10} -Mass concentration of particles collected by a sampler with with aerodynamic particle diameters of 10 micrometers or less.

$PM_{2.5}$ - Mass concentration of particles with an aerodynamic diameter of 2.5 micrometers or less.

Pollutant - Any substance introduced into the environment that adversely affects the usefulness of a resource or the methods for estimating health of humans, animals, or ecosystems.

Pollution - The presence of a substance in the environment that because of its chemical composition or quantity prevents the functioning of natural processes and is harmful to the environment and health.

Primary particles - Particles that are emitted directly into the atmosphere. Most common examples of primary particles are road and desert dust, sea salt, soot and carbonaceous particles from combustion.

Relative humidity - The ratio of the quantity of water vapour present in the atmosphere to the quantity which would saturate at the existing temperature.

Respirable particle - Particles able to penetrate and deposit in the lower bronchioles and alveolar region.

Risk - The probability that damage to life, health, and/or the environment will occur as a result of a given hazard.

Source apportionment - Method of assessment of the contributions to air pollution concentrations of individual emitting sources.

Time series study - Epidemiological or ecological study of the health state of a population exposed, example to air pollutants.

Total suspended particulates - Mass concentration of particles of all sizes collected from the atmosphere.

Ultrafine particles - Particles with diameters smaller than 100 nm

Volatile organic compounds - Hydrocarbon-based emissions released through evaporation or combustion.

Wet deposition – The collection of precipitant dust and any soluble substance in the rainwater during periods of rainfall

CHAPTER ONE

INTRODUCTION

Background

Ghana is principally a mining country with abundant deposits of gold. There are also deposits of diamond, bauxite, manganese, natural gas, petroleum, salt, and silver (United States Geological Survey, 2006). The country has produced and exported gold from pre-colonial times through colonial times to present-day. Most gold mining in Ghana before the mid-nineteenth century was alluvial. Modern gold mining that plumbs the rich ore deposits below the earth's surface began about 1860 in the western region of Ghana, when European concessionaires imported heavy machinery and began mining. Indigenous population of Ghana got more involved when the Europeans arrived in Ghana (Tsikata, 1997; Akabzaa and Darimani, 2001).

The economic recovery programme coupled with the institution of generous mining laws by governments since 1983 has made Ghana to attract investors into the mining sector. The result is the considerable investment boom and increased production, particularly in the gold mining sector (Awudi, 2002). By 1990, there were over sixty (60) mining companies engaged in mineral exploration including twenty (20) foreign companies (Armstrong, 2008). Now, there are about fifty (50) mining companies of which twenty five (25) are large mining companies operating in the country. Presently there is a considerable growth in the number of mines and exploration companies, and Ghana is now Africa's second most important producer of gold after South Africa, (Armstrong, 2008).

The most predominant mining operation of most of the mining companies in Ghana is surface mining, which takes about 75% of the mining activities in the country (Tsikata, 1997). Unfortunately this gold rush has come with its associated negative environmental impact. Awudi

(2002) reported that the gains from the mining sector in the form of increased investment are being achieved at great environmental, health and social costs to the people. These have led to the promulgation of laws to protect the environment (Akabzaa and Darimani, 2001; Hilson and Nyame, 2006).

Nevertheless mining activities continue to have lots of environmental and health impacts. These include water pollution, land degradation, air pollution, loss of biodiversity and increase in health related problems. Others are noise pollution, vibrations, land subsidence and landslides. These environmental threats suggest that mining is a destructive development activity where the environment suffers at the expense of economic development.

Mining in contemporary Ghana is mainly open pit (surface) mining which is considered to be highly environmentally unfriendly due to the activities involved. Such activities include deforestation, habitat and biodiversity destruction, ore extraction, hauling and processing of ores and minerals. These activities impact negatively on air quality, which in turn has the ripple effect of taking enormous toll on the health of people and the environment. However the dilemma is that, Ghana also cannot afford to give up the gold mining which contributes to her gross domestic product.

Well researched mining activities aimed at meeting basic standards in mining operations, accompanied by respect for basic human rights as outlined in international conventions and laws must be the antidote. The researcher agrees with some other environmentalists on the statement that: "As in other problems affecting public health, it is important that, as needed research proceeds on the problem of pollution emissions from various sources, all practicable steps be taken to minimize such pollution rather than waiting until the results of all the needed research are available."

A case study of Hwini-Butre and Benso (HBB) mining concession area in Mpohor Wassa East of the Western Region of Ghana, gave some insight of the impact of mining on ambient air quality.

With the current investment incentives offered by the Government of Ghana to mining companies, more surface mining activities are expected to be carried out, since it is the least expensive compared to underground mining. Conceptually, the more these mining activities are carried out, the more negative environmental consequences on the air quality and ultimately on the people living in these mining areas. It therefore behoves on all stakeholders to carry out continual research throughout a mining company's operations to inform all stakeholders to manage any environmental impacts that such operations are likely to bring.

The basis of this study was built on the conviction that a poorly managed open pit mining has the potential to impact negatively on the ambient air quality, and thus threaten the lives of inhabitants within the area. On the contrary, a well-developed and improved surface gold mining activity has the potential to become a major export commodity, as well as have a reduced or tolerable level of impact on the environment and health.

The impact of surface mining on ambient air quality and the consequences on the people living in these mining areas and beyond is a source of worry to environmentalists. According to the USEPA (2007) mining impacts seriously on ambient air with six major criteria pollutants namely particulate matter, carbon monoxide (CO), sulphur dioxide (SO_2), ozone (O_3), nitrogen oxides (NOx), and lead (Pb), with open pit mines being the worst.

Sinha and Banerjee, (1997) posited that surface mining is the prime mining activity which generates tons of respirable and inhalable particulate matter into the environment through vehicular emissions in which lead and gaseous pollutants are the major concern (Meenalbal and Akil, 2000; Almbauer *et al*., 2000). All such pollutants pose a major risk to health and the environment (WHO, 2008). Prominent among the risks are reduction in air quality which ultimately affects people, fauna and flora in and around mining areas (Chaudhari and Gajghate, 2000; Crabbe *et al*., 2000; Wheeler *et al*., 2000; Nanda and Tiwary, 2001). Thus the gains of open pit mining are achieved at a great cost as it endangers the environment and human health (Amonoo-Neizer and Amekor, 1993).

Non-the-less when the appropriate environmental management practices are followed, the negative impact of undertakings such as open pit mining can be drastically reduced or avoided (Environment Australia, 1998). Hence Ghana needs to pay the needed attention to ambient air pollution from open pit mining activities. There is also the need to have national ambient air quality standards based on dependable data to assess the extent of gold mining on ambient air, and to compare the air pollution levels for different areas.

Problem statement

The chemical and microbiological quality of air in mining areas is considered to be a serious health risk to life (Atkinson *et al*., 2001; Lee and Ferguson, 2009). This is a concern to environmentalists, regulators and public health authorities. Ghana's case received a serious academic discourse on the 2nd of August, 2006, by the Centre for Biodiversity Utilization and Development (CBUD), Kwame Nkrumah University of Science and Technology (KNUST) when it organized a conference on the theme "The mines corporate social responsibility towards sustainable alternative livelihood to affected communities in the Ghana mining sector". This was in response to the health problems that were arising from mining activities in the country.

Many studies have linked particulate matter levels in the air environment to increased hospital admissions and emergency room visits and even to death from heart and lung diseases (Atkinson *et al*., 2001; Lee and Ferguson 2009). It is estimated that the mining industry in Africa may be implicated in as many as 760,000 new cases of tuberculosis each year, due to silica dust in mines (Stuckler *et al.*, 2011), while globally about 1.9 million people die annually in developing countries, due to exposure to high concentrations of suspended particulate matter (WHO, 2000). In the US particulate matter causes about 65,000 excess deaths per year and large associated morbidity (USEPA, 2004). The number of diseases associated to particulate matter that have been reported throughout the world, including the mining centres of Ghana, demonstrates that air quality is a serious indicator of good health for people living in gold mining areas. Unfortunately there have been cases where the levels of dust emissions in some mining communities in Ghana have been a serious concern to the inhabitants, inferring that acceptable and tolerable standard levels of the WHO have been exceeded (Akabzaa and Darimani, 2001).

Apart from its impact on health, mine dust also impacts on amenities, example dust deposition on fabrics, or on house roofs which are transported into water tanks during rainfalls (WHO, 2005).

Justification for the study

Emissions and dust from surface mining of gold impact negatively on the environment and health. In particular fine and coarse particles when inhaled into the lungs have serious health risks such as heart failure, lung cancer, infant mortality, and other cardiovascular diseases. Moreover inhaling particulate matter may make existing health conditions worse, or may contribute to the development of other diseases.

The following therefore summarise why the research was justified in a mining community.

- Air quality is a serious indicator of good health for people living in mining areas. Hence the components of local air at every mining community must be well documented for public health.

- Particulate matter levels are linked to increased negative health impacts resulting in hospital admissions and emergency room visits, and even to death from heart or lung diseases (Atkinson *et al*., 2001; Medina *et al*., 2006; Lee and Ferguson, 2009).
- Serious health problems can result from exposure to high levels of mine dust and emissions. However, there seem to be little air quality monitoring programs in most areas in Ghana.
- There is the need to undertake a thorough and broader outlook into the negative environmental and health effects of mining on the study area, and recommend policy directives to improve the already instituted ones.

From the above, there is the need for a scientific assessment of the impact of surface mining on the air quality in the study area in order to provide the requisite data to inform stakeholders and policy makers on decisions relating to the best practices on mining.

Objective for the study

The general objective of the study was to assess the air quality within the Hwine-Butre and Benso (HBB) community due to the surface mining activities of Golden Star (Wassa) mines, and to ascertain the levels of ambient air particulate matter in the study area.

Specific Objectives

The specific objectives of the study were to:

1. Measure ambient mass concentrations of dust particles smaller than 10 μm in diameter (PM_{10}) over a period of six months at six locations within the HBB project area.
2. Measure the total dust fallout in the ambient air due to mining activities, and their levels at different locations at the Huni-Butre and Benso concession area.
3. Determine the levels of the inorganic particulate matter present in the ambient air around the Huni-Butre and Benso mining concession area as a result of mining activities.

Limitation of the study

The study was designed to cover the entire mining operations in the Western Region gold mining industry, however due to financial and time constraints, coupled with the specificity that the researcher wanted to be achieved, the study was restricted to only Golden Star Resources Limited HBB concession area.

CHAPTER TWO

LITERATURE REVIEW

Overview

The literature review examines the identified problem in order to determine its causal factors, as established by both theoretical and empirical research. The wealth of research which exists on mining operations, the impact of mining on ambient air quality and the effects on health testifies both to the presence and significance of the problem. All of the impacts of mining on ambient air quality are incontrovertibly critical problems whose damages and long-term consequences are not limited to local mining communities but extend to impinge upon the health of entire communities, and stand as a threat to national ambient air quality and public health. Consequently, not only is the identification of the causal factors imperative but the design of strategies for the correction and eventual elimination of the air quality problem are equally important.

A Brief History of Mining in Ghana

Ghana is principally a gold mining country with abundant deposits of Gold. History about gold mining in Ghana dates back to at least the 15th century. From 1493 to 1600, the Gold Coast (now Ghana) produced over 8 million ounces of gold, accounting for 36% of total global output, and was estimated to have annually exported gold to European ports worth some 200,000 pounds sterling through the 1600s (Akabzaa and Darimani, 2001; Wolf, 1982).

However Ghanaians were completely eliminated from the ownership structure of the mining industry (Akabzaa and Darimani, 2001; Donkor, 1997).

The situation changed after independence. From 1957 to 1986, the government controlled all mines either through outright ownership or holding the majority of shares, at least 55% (Donkor, 1997; Hilson & Nyame, 2006). However there was a sluggish production of gold after independence, and according to Akabzaa and Darimani (2001) this could be attributed to market conditions, investor uncertainty about the safety of their investment under Ghanaian self-rule, and the effects of state intervention in the industry.

The system changed after the implementation of the mining sector policy reforms in 1986. The ownership structure of the industry radically changed with foreign investors now controlling an average of 70% of shares in all mining operations in the country (Akabzaa and Darimani, 2001). The incentive provided by the mining sector reform policy, coupled with the extraordinary rise in the price of gold on the international market since 2001, have resulted in an unprecedented boom in mining activity in Ghana.

Approximately over one hundred local and foreign companies are currently prospecting for gold in the country, with more than 20 companies being granted leases to mine gold, of which 16 large-scale surface gold mines are in operation (Aryee, 2001; Awudi, 2002; Hilson and Nyame, 2006).

Mining operations are categorised as either large-scale or small-scale depending on the area (size) of operation. Concessions less than 10 hectares are considered as small scale mining; otherwise they are considered as large scale mining. Small scale mining activities are not allowed to use explosives, and are solely owned by Ghanaians (Babut, *et al.*, 2003).

Either of the operations may be carried out as open-pit (surface) mining or underground mining. In this study, the definition of mining is limited to the large scale open pit mining of gold.

The Huni-Butre and Benso mining project

The Huni Butre and Benso mining property is owned by Golden Star Resources Ltd (GSRL), an international gold mining and exploration Company. Golden Star Resources acquired the Hwini-Butre and Benso (HBB) properties in 2005, which covers a mining lease of 12 km^2 (12 000 000 m^2). The HBB has not gotten its own processing facilities and hence depends on Wassa mines (property owned by GSRL) for ore processing. As a result ore from the HBB project sites are hauled to the Wassa processing facility.

The Hwini-Butre (HB) deposits occur in the southern part of the HB concession, which includes the mineral resources named Adoikrom, Father Brown, and Dabokrom (figure 3.1). In the Benso concession, the main mineral resources include Subriso East, Subriso West, C-Zone and G-Zone (Figure 3.1).

Mining activities at Benso started at Subriso in 2008, while mining activities at Hwini-Butre commenced in Adoikrom in April 2009. The Hwini Butre access road to Benso was substantially completed in April 2009, and the first ore was hauled to Wassa from HB in the same month, (Bourke, *et al.* 2007).

Project Description of HBB mines

Several components of the Hwini-Butre and Benso mines are linked to the main processing plant at the Wassa mine site. Generally the Wassa mine and processing operations include the following: Open pit with associated waste dumps, haul roads and run of mine (ROM) pads, infrastructure for support including fuel station, workshops, warehouse, power station, administration buildings and offices; processing plant including crushing and grinding, leaching, assay laboratory, reagent storage, and process water ponds; tailings disposal facility with water recovery system; accommodation camp and support infrastructure.

The Benso Mine includes the following: Open pit with associated waste dumps; haul roads and ROM pad; infrastructure for support including fuel station, workshop, small warehouse, administration buildings and offices; and access road to Wassa operations camp.

The Hwini Butre Mine includes: Open pit with associated waste dumps, haul roads and ROM pad, Fuel station and local support facilities, and access road to Wassa operations.

BASIC OPERATIONS IN SURFACE MINING

All surface gold mining projects are characterized with different stages of operations, with each stage having its associated environmental impacts (Chakradhar, 2008). The main activities carried out in surface mines that lead to dust emissions can be discussed under the exploratory phase, development phase, active surface mining, disposal of overburden and waste rock, ore extraction, beneficiation and tailings disposal (Hudson, *et al*, 1999).

The exploratory phase

It involves clearing of wide areas of vegetation to allow the entry of heavy vehicles mounted with drilling rigs. The impacts of this phase can be profound; however it may not ensure that sufficient quantities of high-grade mineral ore deposits are present (Bridge, 2004).

The development phase

This phase of the mining project has two distinct components:

- The construction of access roads, either to provide heavy equipment and supplies to the mine site or to ship out processed metals and ores;
- Site preparation and clearing for the construction of staging areas that would house project personnel and equipment.

Active surface mining

It involves the extraction and concentration (or beneficiation) of the gold from the earth. Heavy machinery, usually bulldozers and dump trucks, are used to remove the overburden. The mining of the ore may go a substantial depth underground, usually creating a pit that may extend below the groundwater table (Bridge, 2004).

Disposal of overburden and waste rock

According to Tillery, *et al* (2001), metallic ores are usually buried under a layer of ordinary soil or rock that must be moved or excavated to allow access to the metallic ore deposit. These create high-volume wastes, sometimes containing significant levels of toxic substances, deposited on-site, either in piles on the surface or as backfill in open pits.

Ore extraction

After the removal of overburden, extraction of the mineral ore begins using specialized heavy equipment and machinery, such as loaders, haulers, and dump trucks which transport the ore to processing facilities using haul roads. This activity creates a unique set of environmental impacts, such as emissions of fugitive dust from haul roads (Bridge, 2004).

Beneficiation

This is the grinding (or milling) of the ore to separate the relatively small quantities of gold from the non-metallic material of the ore. Milling results in very fine particles that allow better extraction of the gold. It also allows a more complete release of other contaminants.

Beneficiation includes physical and/or chemical separation techniques such as gravity concentration, magnetic separation, electrostatic separation, flotation, solvent extraction, electrowinning, leaching and precipitation. Wastes from these processes include waste rock dumps, tailings and heap leach materials.

Leaching involves the use of cyanide, in which finely ground ore is deposited in a large pile (leach pile) on top of an impermeable pad, and a solution containing cyanide is sprayed on top of the pile. The cyanide solution dissolves the desired metals and the ‘pregnant’ solution containing the metal is collected from the bottom of the pile using a system of pipes (Hudson, *et al*, 1999).

Tailings disposal

Tailings are the residue of an ore that remains after it has been milled and the gold extracted with the cyanide. The waste ores consist almost entirely of non-metallic materials and often contain undesired toxic metals such as cadmium, lead, and arsenic. Tailings disposal options include:

- The use of a wet tailings impoundment facility or ‘tailings pond’;
- Dewatering and disposal of dry tailings as backfill; and
- Sub-marine tailings disposal.

How a mining company disposes of its tailings is one of the central questions that will determine whether a mining project is environmentally acceptable.

ENVIRONMENTAL IMPACT OF SURFACE MINING OPERATIONS

Mining operations in general have adverse environmental impacts (Ghose, 1989; Bridge, 2004). It impacts on land, ecology (fauna and flora) and atmosphere, with each of the different phases of a mining project having its associated sets of environmental impacts (Bridge, 2004). According to Ogola, *et al*. (2002), surface mining is an inherently dangerous activity, in that the extraction processes of surface mining pollute the environment. Several problems are created by open pit mining (Ogola, *et al*., 2002), and Ghana is currently bearing the impact of this activity (Akabzaa and Darimani, 2001). Accroding to Akabzaa and Darimani (2001) surface mining of gold activities in Ghana have also caused widespread ecological degradation and health problems. These are manifested as water pollution, land degradation, loss of biodiversity, air pollution, increase in health related problems, occupational noise pollution, vibrations, land subsidence and landslides. The Blacksmith Institute (2007) agrees to the impacts of surface mining and further points out that it is among the most environmentally contaminating activities in the world due to the following reasons:

- Mountains are deforested, as such destroying the ecosystem and causing water depletion.
- Fertile soil is removed to discover the rocks containing the minerals of low quality.
- Explosions of the rocks and grinding of the waste rock cause dust which contains heavy metals which cause acid rain runoff.
- Open pit mining requires a dumping location for the waste (waste rock and tailings).
- Extraction requires an enormous amount of water, causing drought.
- Leaching of heavy metals.
- Acid rock drainage.

From the foregone it can be concluded that surface mining operations have the potential to impact negatively on land, ecology and the atmosphere.

Impact on land

The impacts of surface mining activities on land are outlined hereunder.

- Topography and land scenario change due to digging of open pits and dumping of overburden rock mass in the form of the heaps.
- The land-use pattern undergoes a change due to the use of the land for mining, dumping, and other mining and associated activities.

- The land-use in the surrounding areas may get affected due to the impacts of mining on water regime.
- Leachate from overburden dumps and other rock masses and polluted water from the pits affect the characteristics of the top-soil affecting the land-use.
- Mineral concentration/preparation required to make tailing dams to store the tailings from the concentration/preparation plants need land, and this may cause pollution of nearby underground and surface water sources.
- The drainage pattern on the surface undergoes a change due to the alterations in the surface topography due to mining and associated activities.

Impact on ecology

Basically the deposited particulate matter may block the plant leaf stomata hence inhibiting gas exchange, or smother the plant leaf surfaces reducing photosynthesis levels (Environment Australia, 1998). Other impacts of surface mining on ecology include the following:

- Removal of all fauna and flora from the area required for mining and other purposes.
- Dust in atmosphere, when deposited on the leaves of the plants in the surrounding areas may retard their growth.
- Water scarcity resulting from mining activities affects the growth of vegetation in and around the mining community.
- Discharge of effluents from the units and leaching from overburden dumps into water bodies impact on aquatic ecology
- Noise and vibrations due to blasting and operation of the machines drive away the wild animals and birds from the nearby forests.

Impact on the atmosphere

Atmospheric impacts include both air and noise pollution. It results from the following processes:

- Removal of vegetation from mine sites, handling, transportation and storage of ore produce dust which become air-borne and cause an increase in the concentration of particulate matter in the surrounding air.
- The use of diesel equipment in mining activities causes an increase in the level of oxides of nitrogen (NO_x).
- Drilling and blasting of overburden and the mineral contribute PM and explosive fumes into the atmosphere.
- In-pit crushing, loading and transportation of the mineral and the overburden rock mass and making of dumps contribute PM and NO_x into the atmosphere.
- Minerals and rock mass having sulphur and its compounds may contribute SO_2.
- Making of the overburden dumps and the use of diesel equipment contribute PM and NO_x into the atmosphere.
- Some sedimentary rocks may have methane (CH_4) and when mined they may contribute this gas to the surrounding air.
- Fires in opencast mines contribute heat, PM, SO_2, CO_2 and CO.
- Use of petrol vehicles in the mines contributes hydrocarbons and lead.
- Use of heavy equipment and blasting produce noise which undergo series of reflection and refraction which ultimately result as ambient noise.

AMBIENT AIR QUALITY, PARTICULATE MATTER AND SURFACE MINING

Dry air contains roughly (by volume) 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.039% carbon dioxide, and small amounts of other gases. Air also contains a variable amount of water vapour, on average around 1% (Brimblecombe, 1996).

However three broad types of anthropogenic activities introduce harmful foreign substances into air to affect its quality (WHO, 2000), and these are grouped as stationary sources, mobile sources and indoor sources. Stationary sources include mining and quarrying while mobile sources comprise any form of combustion-engine vehicles, example light duty gasoline-powered cars, light and heavy-duty diesel-powered vehicles and motorcycles. Examples of indoor sources are combustion emissions from homes.

According to the USEPA (2007) there are six major criteria pollutants that can be introduced into the ambient air due to mining activities: Particulate matter, carbon monoxide, sulphur dioxide, ozone, nitrogen oxides (NOx) and lead, with particulate matter being the most abundant pollutant.

Based on WHO (2000) air quality guidelines, ambient air pollutants are usually put into three groups, namely suspended particulate matter (SPM), gaseous pollutants and odours. SPM includes dusts, fumes, mists and smokes. Examples of gaseous pollutants are sulphur dioxide and sulphur trioxide, carbon monoxide, nitrogen compounds (example nitric oxide, nitrogen dioxide, and ammonia) and organic compounds (example hydrocarbons-HC, volatile organic compounds-VOC, polycyclic aromatic hydrocarbons-PAH and halogen compounds-HF and HCl). Odours include hydrogen sulphide (H_2S) and carbon disulphide (CS_2).

For the purpose of this study, the pollutant of interest was particulate matter.

Particulate matter

Particulate matter (PM) consists of tiny particles in the atmosphere that can be solid or liquid (except for water or ice) and is produced by a wide variety of natural and manmade sources (Cuclis and Fraser, 2004). Generally they are solid particles of various sizes suspended in the ambient air and can be classified in several ways (Vallius, 2005).

One way of classifying PM is by grouping it into *primary* and *secondary* particles depending on the mechanism of their formation (Vallius, 2005). Primary particles are emitted directly as particles, whereas secondary particles are formed from precursor gases in the atmosphere via gas-to-particle conversion. Both types of particles are subject to growth and transformations since there can be formation of secondary material on the surface of existing particles.

According to the World Health Organization (2003), it is convenient to classify particulate matter by their aerodynamic properties because these properties: Govern the transport and removal of particles from the air; govern their deposition within the respiratory system and; are associated with the chemical composition and sources of particles.

Particle size is normally given as the aerodynamic diameter, which refers to the diameter of a unit density sphere of the same settling velocity as the particle in question. Studies conducted by Baron and Willeke (2001), suggest that particulate matter present in ambient air is made up of subdivisions of suspended particles ranging in sizes from about 0.001 μm to about 100 μm.

Morawska, *et al.* (2000) indicate that the terms most commonly used to define PM are 'fine' and 'coarse' particulate matter, where fine particulate matter refers to particles smaller than 2.5 μm, and coarse particles standing for particles larger than 2.5 μm. Morawska, *et al.* (2000) further classify PM into 'ultrafine' particles - those smaller than 0.1 μm, and 'super-micrometre' particles - particles larger than 1 μm.

According to WHO (2006) suspended particulate matter can be categorised as total suspended particulates, and this refers to the group of all particles suspended in the air usually with aerodynamic diameters less than 50 µm in diameter (Seinfeld and Pandis, 1998).

Based on the above, particulate matter has been grouped under the following descriptions in this research.

Table 2.1: Classification of particulate matter

Particle size	**Description**
TSP	Total suspended particulate matter refers to the total of all particles suspended in the air.
PM_{10}	It is all particles smaller than 10 μm in diameter. It includes particles in the size range of 2.5 μm to 10 μm in diameter. They are referred to as coarse particles
$PM_{2.5}$	It refers to all particles less than 2.5μm in diameter. They are referred to as fine particles.
Ultrafine PM (UPM)	They are particulate less than or equal to 0.1 µm

Composition of Particulate Matter

Air samples may show considerable different proportions according to the sampling location (Harrison and Yin, 2000). Both solid particles and liquid droplets may be involved, which could be a mixture of organic and inorganic materials of various sizes and shapes. A single particle may be made up of sulphate, nitrate, ammonia, chloride, elemental or organic carbon, crustal biological materials, which may have bound to it other substances that cause toxicity (Vallius, 2005).

The chemical composition of any particulate matter determines its source; either it originated from a primary or a secondary source (Xiong and Friedlander, 2001), and it is determined by the area and daily activities, as well as local and distant sources.

Combustion processes, mining activities or other anthropogenic activities form a significant portion of the PM pollution (Guttikunda, 2009). Secondary PM formed in the atmosphere mostly come from chemical interactions among primary PM and normal atmospheric constituents.

The most abundant primary PM generated through mining activities is silica (silicon dioxide - SiO_2) dust which exists both in crystalline and amorphous forms (Heaney and Banfield, 1993). The most common of the crystalline forms are quartz, cristobalite and tridymite, with quartz being the most abundant (Heaney and Banfield, 1993). Generally about 30% free silica is found in dust generated though gold mining (Hnizdo, 1992), and activities that introduce respirable crystalline silica dust into the ambient air include grinding, mixing, hammering and cutting of any material with silica content. Other fugitive dust sources include crushers or screens, haul and mine roads, transfer points on the ore conveyors, drilling and blasting in the mine pit and materials handling.

PM_{10} is primarily oxides or salts of elements found in dirt (example Fe, Ca, Si, Al) while $PM_{2.5}$ is composed of sulphates, nitrates, ammonium, organic and elemental carbon and acid aerosols (Abramson, 2004).

In summary all the following components are identified with particulate matter.

- Sulphate: Derived predominantly from sulphur dioxide oxidation in the atmosphere;
- Nitrate: Formed mainly from oxidation of nitrogen oxides (NO and NO_2) to nitrate; NO_2 oxidises much more rapidly than SO_2.

- Ammonium: Atmospheric ammonia forms ammonium salts in neutralisation reactions with sulphuric and nitric acids.
- Chloride: Main sources are sea spray and de-icing salt during winter; also from ammonia neutralisation of HCl gas from incineration and power stations
- Elemental carbon and organic carbon - combustion processes emit primary carbonaceous particles and semi-volatile precursors
- Crustal materials: They are soil dusts and wind-blown crustal material; they are quite diverse in composition reflecting local geology and surface conditions. Their concentrations are dependent on climate as the processes which suspend them into the atmosphere tend to be favoured by dry surfaces and high winds; these particles reside mainly in the coarse particle fraction (Harrison *et al.*, 1997)
- Biological materials: Bacteria, spores, pollens, debris and plant fragments; generally coarse in size are considered as part of the organic carbon component in most studies rather than as a separate biological component.

Interestingly there is no clear cut boundary between fine and coarse particles; hence categorising of particulate matter is only an approximation (Wilson and Suh, 1997).

Formation of Secondary PM from emissions

Primary particulates emitted into the atmosphere undergo various types of changes and transformations to form secondary particulate matter. Nitrates and sulphates form on dust through the uptake of acidic gases like HNO_3, SO_2, and H_2SO_4 (Usher *et al*, 2003).

Sulphur dioxide is oxidized in the atmosphere to form sulphuric acid, which can be neutralized by ammonia to form ammonium sulphate. Nitrogen dioxide is oxidized to nitric acid (HNO_3), which in turn can react with ammonia to form ammonium nitrate. The particles produced by the intermediate reactions of gases in the atmosphere constitute the secondary particles and these particles can be coated with sulphates, nitrates, organic and black carbon as they age in the atmosphere (Sasakawa, *et al.*, 2003).

Generally air-borne secondary sulphate and nitrate particles are usually the dominant components of fine particles (Bauer and Koch, 2005; Hodzic *et al*., 2006), with a substantial portion of nitrate particles found in the coarse class size of air-borne particulate matter (Campbell *et al*., 2002).

Surface mining and dust

Mining operations and aggregate extraction sites are significant sources of fugitive dust emissions (Chakradhar, 2004). The amount of dust that is generated as well as their impact depend on: The type of mineral and working method; climate, local meteorology and topography; the types of processing activities undertaken on a site and the character and land use of the area surrounding the site (Vallius, 2005).

The principal air emissions from mining activities consist of wind-borne dust and mine transportation on unpaved roads. The fugitive dust generation process is caused by the basic physical phenomena of pulverization and abrasion of surface materials by application of mechanical force, through implements and entrainment of dust particles by the action of turbulent air currents such as wind erosion of an exposed surface by larger wind speeds (Chakradhar, 2008).

Dust emission in mining areas occurs through saltation (or jumping) of particles across a surface and suspension of particles and their entrainment in airflow (Vallius, 2005).

The main sources of fugitive dust generation are various types of heavy equipment used for the extraction of minerals, example, reclaimers, stackers, bucket wheel excavators, dumpers and bulldozers (Chakradhar, 2008). Table 2.2 summarizes some mining activities and the main emissions into the ambient air.

Table 2.2: Basic mining operations that generate dust

Mining Activities	Pollution
Drilling	Dust pollution is the main concern
Blasting	Dust and gaseous pollutants like sulphur dioxide and oxides of nitrogen
Loading operation	Dust pollution is the main concern
Haul road	Dust pollution
Transportation	Dust and gaseous pollutants like sulphur dioxide and oxides of nitrogen
Crushing of ore	Dust pollution
Storage	Dust pollution
Solid waste handling	Dust pollution
Tailing waste	Dust pollution

Source: Centre for scientific and Environment, New Delhi.

Behaviour and Residence time of particulate matter

Air particulate matter may change their sizes and composition by condensation or evaporation; coagulating with other particles; or by chemical reactions (Seinfeld and Pandis, 1998). Meteorological factors such as wind speed and direction, temperature, amount of precipitation, and the height of the atmospheric boundary layer are most important in governing the concentration variations of particulate matter (Pohjola *et al*., 2004). The highest PM concentrations are often reported during stable meteorological conditions such as inversion with low wind speeds (Pohjola *et al*., 2004). Also the physical and chemical processes affecting the particles are regulated to a great extent by meteorological factors, while PM from specific sources typically follow short-term and long-term trends (Yatin *et al*., 2000).

When dust particles build up in air they may collectively appear as black soot, dust clouds, or grey hazes (USEPA, 2007), and the sizes of the particles in air will decide their residence time. Particles greater than 50 microns tend to settle out of the air once released while PM_{10} particles can stay in the air for minutes. $PM_{2.5}$ particles can stay in the air for days or weeks.

PM_{10} particles usually travel as little as a hundred metres but can go as much as fifty (50) km (Cuclis and Fraser, 2004). On the contrary $PM_{2.5}$ particles can go many hundreds of kilometres (Cuclis and Fraser, 2004). According to Cuclis and Fraser (2004) the potential drift distance of particulate matter is governed by the initial injection height of the particle, the terminal settling velocity of the particle, and the degree of atmospheric turbulence. Alonso *et al.* (2003), point out that the diverse mixture of size, shape, and density characteristics of particulate matter allow it to remain suspended in the air for a meaningful time period.

Gravity is a driving force that ensures that dust particles settle, but does not control the rate of settling (Cuclis and Fraser, 2004). Large particles (between 10 μm and 100 μm) can be lifted up by strong winds but when the wind stops lifting the particles up into the air, they begin to settle under gravity (Noller *et al*., 1981). Unlike large particles, smaller particles (less than 10 μm) are known to have relatively long residence time in the atmosphere (Noller *et al*., 1981; WHO, 2006). They are affected by thermals, turbulence and brownian motion and will not necessarily settle all the way to ground level. Such smaller particles remain suspended in the air for hours and days. Nevertheless they are not present in the atmosphere at all altitudes, and will precipitate when their sizes and compositions, as well as climatic conditions (rainfall, humidity, wind speed) are suitable to cause settling (Cuclis and Fraser, 2004).

Measurement of particulate matter

Dust is usually measured to assess its nuisance and health effects. Dust deposition and total suspended particulate measurements are two major parameters that are usually used to assess the levels of dust within a given ambient air (Wilson and Karpukhin, 2008).

Particulates larger than 10µm are collected as dust deposition. They mostly fall after released in the air, and can be collected by collection jars or gauges (Wilson and Karpukhin, 2008). The dust collectors simply catch the dust settling over a fixed surface area over a period of time, and the collected dust is analysed to quantify it. The result is reported in terms of the mass of dust collected per unit surface area, and over a fixed period of time. Total suspended particles (TSP) are particles that are suspended in air at the time of sampling. Generally finer suspended dust will remain airborne almost indefinitely due to the dynamic nature of the air currents and thermal activities on any given day, even if there is no wind at all. TSP is measured by sucking air through a filter and determining the weight of dust collected from a measured volume of air. The equipment used for TSP measurements are designed with sampling heads that make the system selective for specific size fractions. The collection efficiency is known to vary for different size particles, and can also vary between different TSP systems.

TSP samples are typically collected over 24-hour periods, and the corresponding results are reported in concentration terms (mg/m^3).

Other monitoring methods that can also be used for assessing dust include the following: Directional dust monitoring – This can be used to identify specific dust sources. Dust samplers are linked to a wind sensor, so that the monitor only operates when the wind is from a certain direction. Alternatively, there are also directional dust gauges in which the dust is collected through vertical slots, which can be lined up with the direction of interest (Hall, 1994).

Time-lapse video – This provides a simple method for visual monitoring of dust-producing activities over extended periods of time. Its main application is in identifying which activities on a site are in need of better dust control.

Microscopic examination – This can be very useful in investigating complaints of dust fallout. Examination of dust samples under a microscope can often assist in identifying the source. For example, fly ash from a boiler is made up of multi-coloured glass spheres, while dust from a panel beating shop will contain paint fragments. It is also extremely useful in identifying natural dust sources, such as pollen.

Tracer analysis – Analysis of dust for specific tracer elements can also be useful in identifying dust sources. For example, dust from a secondary steel mill will have high levels of iron and other metals such as lead and zinc.

Dust deposition

The potential for any mining site to emit dust is greatly influenced by weather. Rainfall decreases dust emissions, due to both surface wetting and increase in the rate at which airborne dust is removed. In contrast strong, warm and dry winds increase the rate at which dust is lifted from an untreated surface and emitted into the air. It also has the effect of spreading dust over a large area. Wind speeds increase with height, hence large mounds which project well above ground level can thus be the subject of significant wind erosion (Vallius, 2005).

The topography of a site and surrounding areas have effects on localised wind patterns, and the effect is most pronounced in or near to valleys or hills, since they can direct winds (Vallius, 2005).

Monitored dust levels can vary markedly over time because of variations in weather conditions, including rainfall, wind speed and wind direction, and also because of changes in the source emissions. In summary factors that affect dust fallout agree with those posited by Standard Australia (2006), and they include:

1. Rainfall, because dust is attracted to the water vapour in the atmosphere and it then precipitates along with the rain.
2. Wind, because dust is carried by the wind and will only fall-out when there is absolutely no wind. A rapid increase in humidity together with an absence of wind will result in precipitation of less than 5 micron particulate.
3. Geographical features or any other factor that could influence the rainfall or the wind, for reasons mentioned above.
4. Pollens and small insects, because they add to the dust levels and precipitate out in the same way.
5. "Dusty activities" such as dropping material from a conveyor onto a pile without considering the fall height.

Terminal settling velocity of particles

From Stokes' law (Nelkon and Parker, 1882; Wilson and Buffa, 2000) the gravitational force (G) acting downward on a free falling particle can be computed as follows;

$$G = \frac{1}{6}\pi d^3 (W_S - W_A)\, g$$

Where;

d = the geometric diameter of the spherical dust particles (m)

W_S = the density of the dust particle (kg/m^3)

W_A = the density of the ambient air (kg/m^3)

g = acceleration due to gravity (m/s^2)

The drag forces in air acting in resistance to the fall is F = 3 π d η υ

Where; υ = the velocity of the particle (m/s) and η = viscosity of the fluid (kg /ms).

If the motion of the fluid around the particle is symmetrical, the terminal velocity of the sphere is reached if G = F.

Equating these two equations yields: $v = \frac{d^2 g}{18\eta}(W_S - W_A)$ - Stokes law.

Stokes' law applies to spheres of sizes approximately less than 250 µm; however air pressure and moisture content will affect the terminal settling velocity to some extent, because of the effect they have on the density of air.

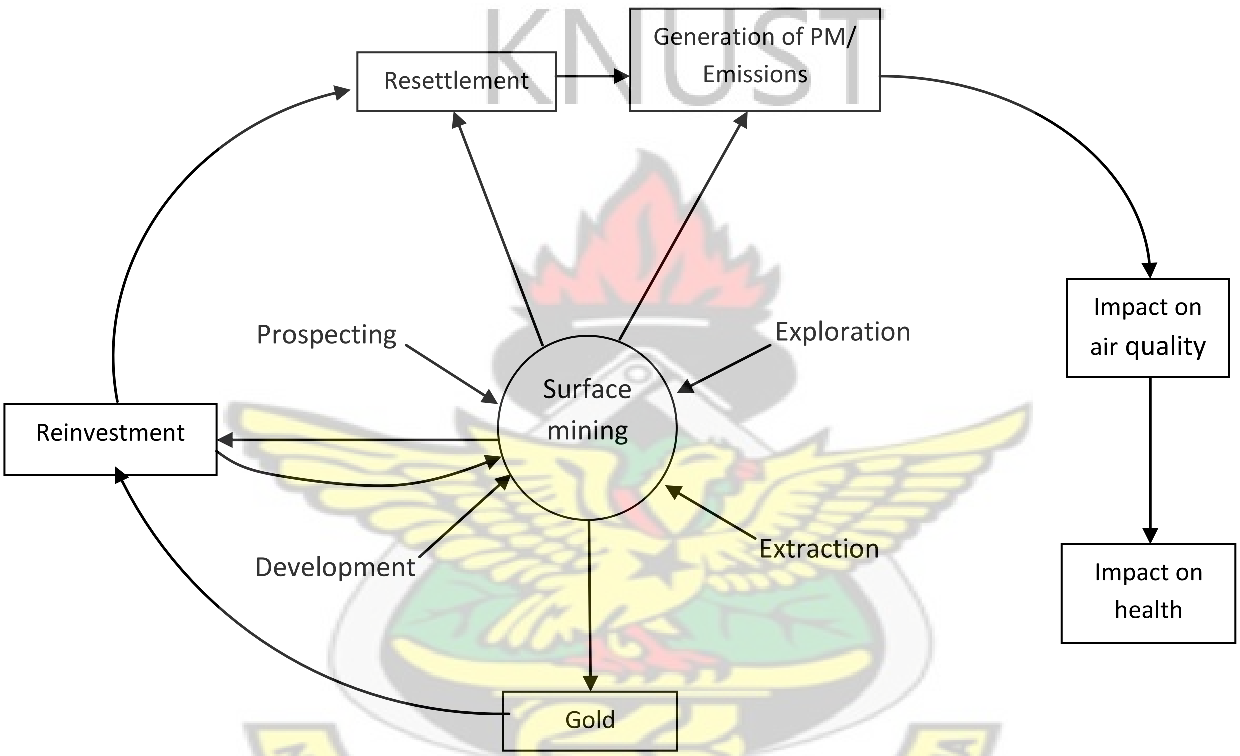
SURFACE MINING AND HEALTH

Mining activities pose serious health challenges for mining communities and people residing in close proximity to mining activities (Yelpaala, 2004). The reason being that all levels of mining activities release dust particles into the ambient air, and these particles cause many diseases (Stephens and Ahern, 2001).

Links within surface mining, air quality and health

As shown in the flow diagram (Figure 2.1), surface mining operations involve the search for mineral deposits (prospecting); assessing the size, shape, location, and economic value of the deposit (exploration); preparing access to the deposit so that the minerals can be extracted from it (development); and extracting the minerals (exploitation). The process may lead to resettlement of indigenes or new settlement of the mine staff. The activities of both the mining company and the settlers impact negatively on the environment directly or indirectly by generating particulate matter and emissions.

Figure 2.1: A flow diagram explaining the links between surface mining, ambient air quality and health impact. (Source: Henyo)



From the diagram (Figure 2.1), surface mining leads to getting gold, which brings foreign exchange to the nation and also increases the income of the mining company. Increased income of the company creates reinvestment for more gold. Subsequently the government gives more concessions which results in more surface mining activities leading to more resettlements and development projects such as roads, schools, residential places, etc within the mining area. More mining activities mean more jobs for people, resulting in increased income levels, and subsequently changed lifestyles, which together impact negatively on air quality.

Negative impacts on air quality ultimately affect the health of people, especially those within the mining environment.

Impact of dust particles on human health

Wind-borne dust is critical to health, due to its entry into the respiratory tract, or as a secondary pathway for ingestion of toxic materials (Combes and Warren, 2005). According to Dockery and Pope (1994) the impact of dust particles on human health is largely depended on: Particle characteristics particularly particle size and chemical composition; concentration of the dust particles in the air, the duration, frequency and magnitude of exposure. Moreover the factors that are involved in the development of the health effects include: Amount of exposure; duration of exposure; co-exposures and constitutional factors (age and sex) (Abramson, 2004). However epidemiological studies suggest that there is no threshold concentration below which ambient PM has no effect on health, implying that some subjects are at risk even at the lowest end of the concentration range (WHO, 2003).

The physical and chemical composition of suspended particulate matter is highly variable, resulting in a wide range of public health concerns. Many components of suspended particulate matter are respiratory irritants. Some components (such as crystalline or fibrous minerals) are primarily physical irritants. Other components are chemical irritants (such as sulphates, nitrates, and various organic chemicals). Suspended particulate matter also can contain compounds (such as heavy metals and various organic compounds) that are systemic toxins or necrotic agents. Suspended particulate matter or compounds adsorbed on the surface of particles can also be carcinogenic or mutagenic chemicals (Alonso *et al.*, 2003).

Greater portion of the dust particles in mine air are fine particles, suggesting that respirable particles are emitted into the ambient air whenever silica-bearing rocks are drilled, blasted, crushed or otherwise pulverized during gold extraction. This explains why there are dust related diseases in many mining areas (Akabzaa and Darimani, 2001).

Many evidences through studies over the past forty years also show associations between exposure to particulate matter and various types of health effects (Weichenthal, *et al.*, 2007; Franck 2006; Sioutas, *et al.*, 2005; Pope, 2000). Both long and short term particulate matter exposure can lead to these varieties of health effects, the major ones being asthma, lung cancer, cardiovascular issues and premature death (Pope and Burnett, 2002). Long-term exposure to respirable crystalline silica has been associated with inflammation, fibrosis, silicosis and cancer (Cakmak *et al*., 2004; Donaldson and Tran, 2002).

Health effects associated with PM are nonspecific, and the parameters that give potential implications for health include; size of particle, number of particles, surface area, acidity, metals, elemental and organic carbon, mass of particles, size distribution, ions, bio-aerosols, and other specific toxic constituents (Pechacek, 2003).

As indicated by Pechacek (2003), the numerous effects of exposure to particulate matter can be broadly grouped into respiratory effects and cardiac effects, and they are outlined as follows:

Respiratory effects

- Acute symptoms: irritation, coughing, wheezing, difficulty taking deep breaths
- Inflammation in the respiratory system
- Decreased lung function
- Aggravate existing respiratory diseases (example asthma and bronchitis)
- Increases airway reactivity (response to stimuli)
- Increases susceptibility to respiratory infections

– Chronic exposure to some types of PM may result in an increased risk of respiratory cancers such as lung cancer

Cardiac effects include

– Change in blood chemistry
– Can increase blood viscosity which may lead to clotting
– Inflammation disrupts cell function and activates platelets, which can rupture blood vessel plaques
– Leads to clotting of blood
– Cardiac arrhythmias – abnormal heart beats
– Change in heart rate variability, where a decrease in the heart rate variability is an early warning sign of potential heart attacks
– Aggravate existing cardiac diseases
– Can potentially stimulate heart attacks in sensitive individuals

Particle size determines the region of respiratory tract where a particle will be deposited (Abramson, 2004). Pope and Burnett (2002) indicate that $PM_{2.5}$ leads to high plaque deposits in arteries, causing vascular inflammation and atherosclerosis - a hardening of the arteries that reduces elasticity which can lead to heart attacks and other cardiovascular problems.

Based on the WHO report for Europe (2003), the following are true about the health effects of particulate matter:

– Long-term exposure to high ambient PM concentrations may lead to a marked reduction in life expectancy due to increased cardio-pulmonary and lung cancer mortality.
– The elderly and people with pre-existing heart and lung diseases are more susceptible to effects of ambient PM on mortality and morbidity.

- Life expectancy can be decreased by long-term exposure to PM.
- Fine particles are more hazardous than larger ones (coarse particles) in terms of mortality and cardiovascular and respiratory diseases however this does not imply that the coarse fraction of PM_{10} is innocuous.
- PM interacts with gases to alter its composition and hence its toxicity in the ambient air.

The diagram below shows the penetration ability of particulate matter into the respiratory system.

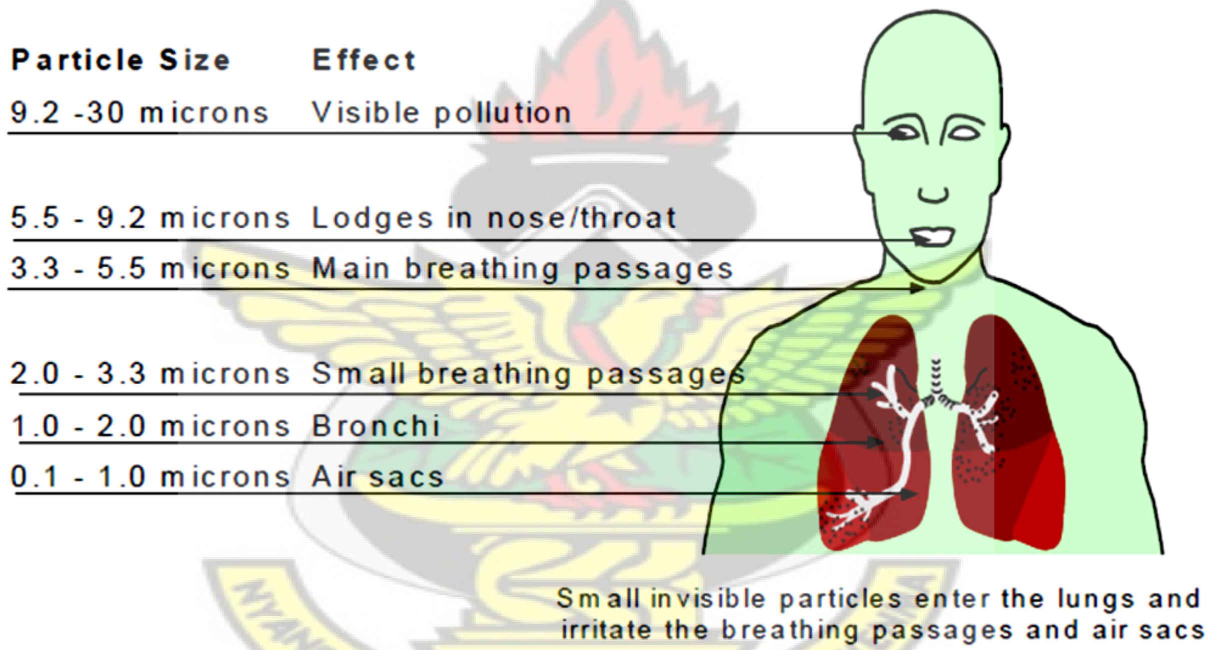


Figure 2.2: Schematic diagram of penetration of particles into the respiratory system (Source: USEPA)

Ambient air quality guidelines and standards

Air quality guidelines and standards are fundamental to effective air quality management, providing the link between the source of atmospheric emissions and the user of that air at the downstream receptor site (WHO, 2000). The guidelines and standards are normally given for specific averaging period over which the air concentration of the pollutant should be monitored at a location (WHO, 2000). Generally five averaging periods are applicable, namely an instantaneous peak, 1-hour average, 24-hour average, 1-month average and annual average. Table 2.3 gives some guidelines for particulate matter.

Table 2.3: Air quality guidelines

Dust	**Averaging Time**	**Ambient Air Quality Standards, in micrograms per cubic metre (µg/m³)**						
PM_{10}	Time	WHO	US EPA	Thailand	New Z.	Korea	UK	SA
	Annual	50	50			80		60
$PM_{2.5}$	24 hr		150	120	120		50	180
	Annual	15	15					

Generally dust fallout for a monthly average can be classified as follows:

- Slight = less than 0.25 grams per square meter per day
- Moderate = 0.25 to 0.50 grams per square meter per day
- Heavy = 0.50 - 1.20 grams per square meter per day
- Very heavy = greater than 1.20 grams per square meter per day

METHODS OF DUST CONTROL IN SURFACE MINING

Kissell, (2003) and Stanton, *et al*. (2006) indicate that dust generated through mining operations can be controlled under the various activities of mining operations. These are listed below:

Mine

Dust suppression systems (water spraying) are employed at faces or sites while loading, and the use of sharp teeth are used for shovels; Dust extraction systems are used in drill machines; Use of sharp drill bits for drilling holes and drills with water flushing systems (wet drilling) to reduce dust generation.

Stock-piles

Mist sprays are provided at appropriate places for preventing dust pollution during handling and stockpiling of mined material.

Haulage

Regular water spraying should be carried out on haulage roads during transportation of ore up to conveyor belt system by water sprinklers. Transfer points are provided with appropriate hoods/chutes to prevent dust emissions. Dumping of ore should be done from an optimum height (preferably not too high) so as to reduce the dust blow.

Crusher

Crushers are provided with “bag filters” to arrest any dust emission. Water sprinkling systems are also provided to check any fugitive emissions from the crushing operation.

Belt Conveyor

Close conduit type conveyor belts are used for transportation of crushed material to the treatment plant. The belt and idlers should be maintained in proper condition so as to avoid spillage of material and prevent any fugitive emissions.

Greenbelt

Green belts are provided in and around the mine site, crushing, loading and unloading facilities, corridor of belt conveyor route and in abandoned mine area during the reclamation process. It is expected that plants with heights 10m, 20m and 30m can reduce dust pollution by 50%, 70% and 80% respectively. A combination of these is usually planted depending on the requirements and the extent of the problem.

Controlling CO Levels

All vehicles and their exhausts should be well maintained and regularly tested for pollutant's concentration.

Controlling NOx Levels

NOx emissions in the mine mainly occur during blasting operations. Controlled blasting should be done in mining operations. The only other source of NOx is due to vehicular emissions, which should be controlled appropriately.

Occupational health and safety measures to control dust inhalation

Use of dust masks to prevent inhalation of respirable particulate matter to reduce the risk of lung diseases and other respiratory disorders is very necessary. Regular health monitoring of workers and villagers from nearby areas in the impacted zone (especially one km from the core zone) should be carried out.

Kissell (2003) further detail inevitable preventive and mitigation measures of dust control that are critical to ensuring the health and safety of mining communities (Table 2.4).

Table 2.4: Preventive and mitigation methods of dust control in open pit mining

Mining Activity	**Method of controlling/reducing**
Soil handling and storage	Restrict the duration of the activity. Seal and seed storage mound surfaces as soon as practicable. Protect surfaces from winds until disturbed areas are sealed and stable.
Overburden handling and storage	Protect exposed material from wind (by keeping material within voids or protecting them by topographical features). Spray exposed surfaces of mounds regularly to maintain surface moisture and minimise handling.
Drilling and blasting	Use dust extraction equipment such as filters, on exhaust air emissions from drill rigs. Remove the dusty material collected from the area of blast prior to detonation
Loading/Unloading activities	Reduce drop heights wherever practicable. Protect activities from wind.
Minerals processing	Varies depending on types of equipment used but generally complete enclosure is best, with use of air extraction and filter equipment as appropriate. Use water sprays.
Material storage	Dampen material. Protect from wind and store under cover. Screen material to remove dusty fractions prior to external storage.
Transport by conveyor within	Protect by use of wind and roof boards.

site	Shelter transfer points from wind. Use scrapers to clean belts, with collection of scrapings for disposal. Minimise drop heights and protect from wind. Use water sprays.
Transport by vehicle within and off-site	Restrict vehicle speed. Water unsurfaced roads. Wheel or body wash at an appropriate distance from site entrance. This should usually be inside the site entrance. Load and unload in areas protected from wind. Minimise drop heights. Sheet or cover loaded vehicles. Use water sprays/spray curtains to moisten material. Sweep paved roads

CHAPTER THREE

MATERIALS AND METHODS

STUDY AREA

The study was conducted within the gold concession area of the Golden Star Resources Limited (GSRL) located in the Mpohor Wassa East District of the Western Region of Ghana (Figure 3.0).

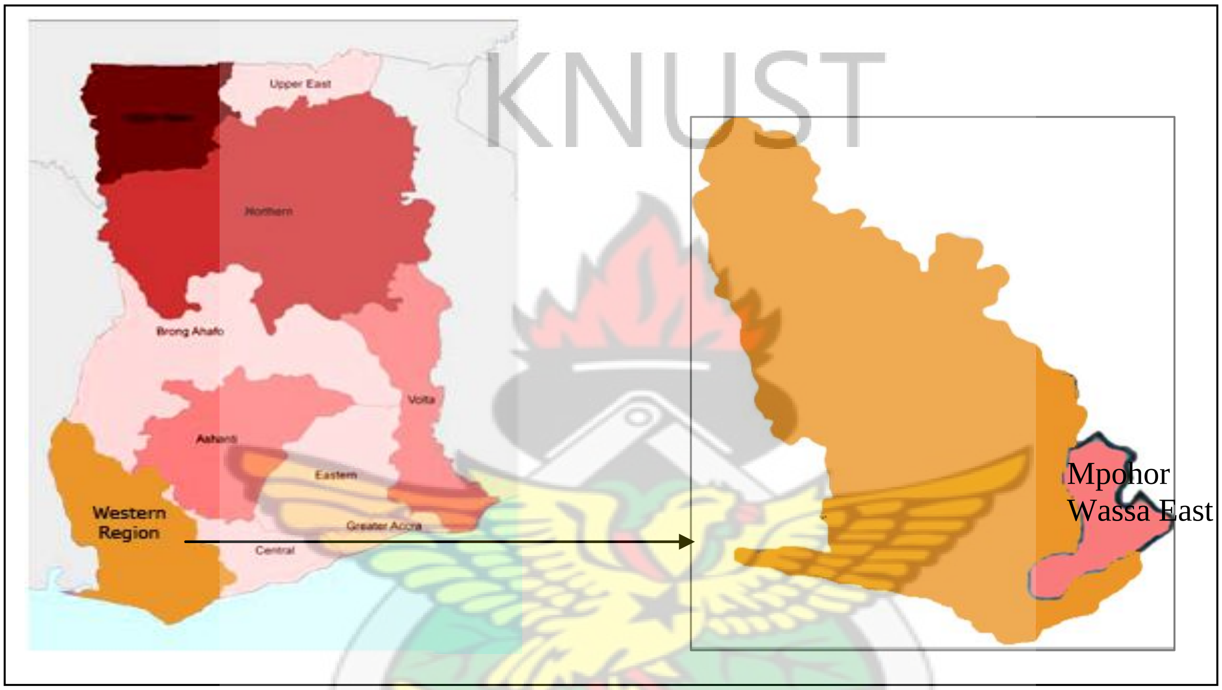


Figure 3.0: Map of Ghana showing the western region and the Mpohor Wassa East District

The district is bounded on the northeast and southeast by the Twifo Hemang Lower Denkyira (THLD) and Komenda Edina Eguafo Abrem (KEEA) districts respectively, all in the Central Region. The district is also bounded on the west by the Wassa West District, and in the south, by the Sekondi Takoradi and the Shama Ahanta East Metropolitan Area respectively. The district occupies an area of 1880 square kilometres of which 344 square km is cultivated. The district capital is Daboase, which is 6.7 km from the Cape Coast Takoradi main road (http://mpohorwassaeast.ghanadistricts.gov.gh).

The climate of the area falls within the equatorial climatic zone, primarily the tropical rain forest zone of Ghana. The District has a mean annual rainfall in the range of 1500mm and 1933mm with most of the rains occurring from April-June and October-November giving it a bimodal rainfall regime (Kwamena and Benneh, 1977)

The mines and its environs lie generally within mountain ranges covered by thick forest with a variety of fauna and flora. In some cases, the ranges are interspersed by undulating valley bottoms. These evergreen mountains which are rich in biodiversity are also rich in gold, hence they are targets for open pit mines.

The rock structure underlying the area is composed mainly of mafic and felsic volcanic rocks. Recent explorations show the following as the main composition of the rock strata underlying the area; basalt, diorite, felsic volcanic, banded magnetic unit, phyllite, graphytic mudstone and felsic porphyry (Bourke *et al*., 2007).

Topography and geology of the Wassa East area

The mines and its environs lie generally within mountain ranges covered by thick forest with a variety of fauna and flora. The ranges are interspersed by undulating valley bottoms with evergreen mountains which are rich in biodiversity and also in gold; hence they are targets for open pit mines.

The topography is quite variable and results from the erosion of extensive peneplain (old weathered) surfaces. Progressing north from Hwini-Butre towards Benso, the hills become more prominent, mostly as a result of more resistant volcanic bedrock. The sharp, narrow valley bottoms are mainly at elevations in the range 50m to 70m above mean sea level, whereas the flat, elongate ridges and hills have elevations mostly in the range 160m to 170m above mean sea level. The most prominent hill is that immediately to the west of Benso, along the west side of the Ben River; this steep-sided hill (relief of 120m to 130m) is capped by thick laterite (at 170m to 180m above mean sea level). However, most of the hills in the north are at elevations of 100m to 120m above mean sea level, with relief in the range 40m to 60m. In addition some of the valleys have even more subdued topography, especially in the vicinity of the Benso deposits (Bourke *et al.,* 2007).

Vegetation

The vegetation of the area consists of tropical rain forest characterized by rich undergrowth of climbers and shrubs of varying heights. The trees, which generally reach heights of between 15 and 45 metres, are distributed mostly at the summit of hills where mining has not yet reached. There are two large forest reserves namely; Subri River Forest Reserve which occupies 375 square kilometres and the Pra Suhyen Forest Reserve which is 204 square kilometres. There are also two small ones - Ben West Block Forest Reserve and Ben East Forest Reserve. These forests are the semblance of virgin forest in the district (Bourke *et al.,* 2007).

Nevertheless there has been a rapid reduction in the density of trees in areas affected by mining activities. Where the area has been mined out, the vegetation consists of ferns and other shrubs which grow profusely on the hilly slopes.

Drainage

The mountain ranges constitute the source of water for many of the rivers and streams in the area. Locally there are medium and small rivers and streams. Most of them originate from the Akwapim ranges and flow southwards towards the coast. The main rivers are the Pra, Subri, Butre, Brempong, Suhyen, Abetumaso, Hwini and Tipae. While most of them overflow their banks in the rainy season, some dry out in the dry season ((Bourke *et al.,* 2007). These major rivers and their tributaries facilitate mining activities in the area, particularly for illegal mining (galamsey) operators by providing the water required for the processing of gold.

Demographics

According to the 2000 population census, the population of the district was 122,595 and estimated to be 143,876 in 2005 with an inter-censal growth rate of 3.2 percent, which is the same as the regional growth rate. It is however higher than the national growth rate of 2.7 percent.

Males form 52.5 percent of the total population (64,384) as against 47.5 percent (58,211) for females. Children under fifteen years (0-14) account for 43.4 percent (53,206) of the population compared with the national figure of 41.3 percent, the economically active population (15-64 years) accounts for 50.6 percent (62,033) as against the national figure of 53.4 percent and the elderly or the aged (65 years and above) accounts for 6 percent (7,356) of the total population compared to 5.3 percent of the national figure in 2000.

The indigenous ethnic group is the Wassa people but the ethnic mix is highly varied due to mining activities. 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 *galamsey* mining are major contributory factors to the growing population (http://www.ghanadistricts.com).

Economic Activity

Apart from gold, cocoa and timber constitute the natural resource potential for varied economic activities in the area. Most people in the area engage in subsistence and commercial (mostly oil palm) farming. Currently, however, mining has overtaken farming as the single largest economic activity in the area.

Hwini-Butre Benso (HBB) Project

The Hwini-Butre and Benso mines are located in the southern portion of Golden Star Wassa mine concession area. The Benso concessions are north-northwest of Takoradi and approximately 40 kilometers (straight line distance) south-southwest of the Wassa gold mine. The three land parcels that comprise the concessions include Subriso, Amantin and Chichiwelli.

The Hwini-Butre concession is located 30 kilometres south of the Benso Subriso deposits and east of the town of Mpohor, which is 20 kilometers northwest of Takoradi. Two economic deposits have been delineated; namely Adoikrom and Father Brown. The HBB concessions lie along the south-eastern flank of the Birimian-aged (lower Proterozoic) Ashanti Belt, along the same structure as Wassa. The south-western part of the Hwini-Butre concession covers Mpohor complex, a syn-volcanic mafic intrusive that is bound to the east and north by the Butre volcanic sequence. The Mpohor Complex is a polyphase intrusion with compositions ranging from gabbroic to granophyric, with intermediate phases such as diorite and granodiorite. The Butre volcanic sequence, which also underlies the South Benso concession further north, mostly comprises volcanic flows with minor meta-sediment horizons. The main regional structural orientation trends north-easterly but extensive north to northwest trending cross-cutting fracture systems are also well developed. The latter host much of the mineralization in the district, with vein systems at Dabokrom, Father Brown, Adoikrom, the Subriso zones and Amantin located within or marginal to the Mpohor Complex (Figure 3.1) .

The mineralization on the Hwini-Butre concession is typically associated with shallow east-dipping narrow quartz veins and their associated sericitic alteration halos, with coarse free gold associated with sulphides and as specks within the quartz veins and altered host rocks. In contrast, mineralization at Subriso West and Central Subriso forms a series of relatively steep dipping, north-trending zones characterized by strong shearing and pervasive silica replacement with local silica flooding and only minor thin quartz veining (Bourke *et al.*, 2007).

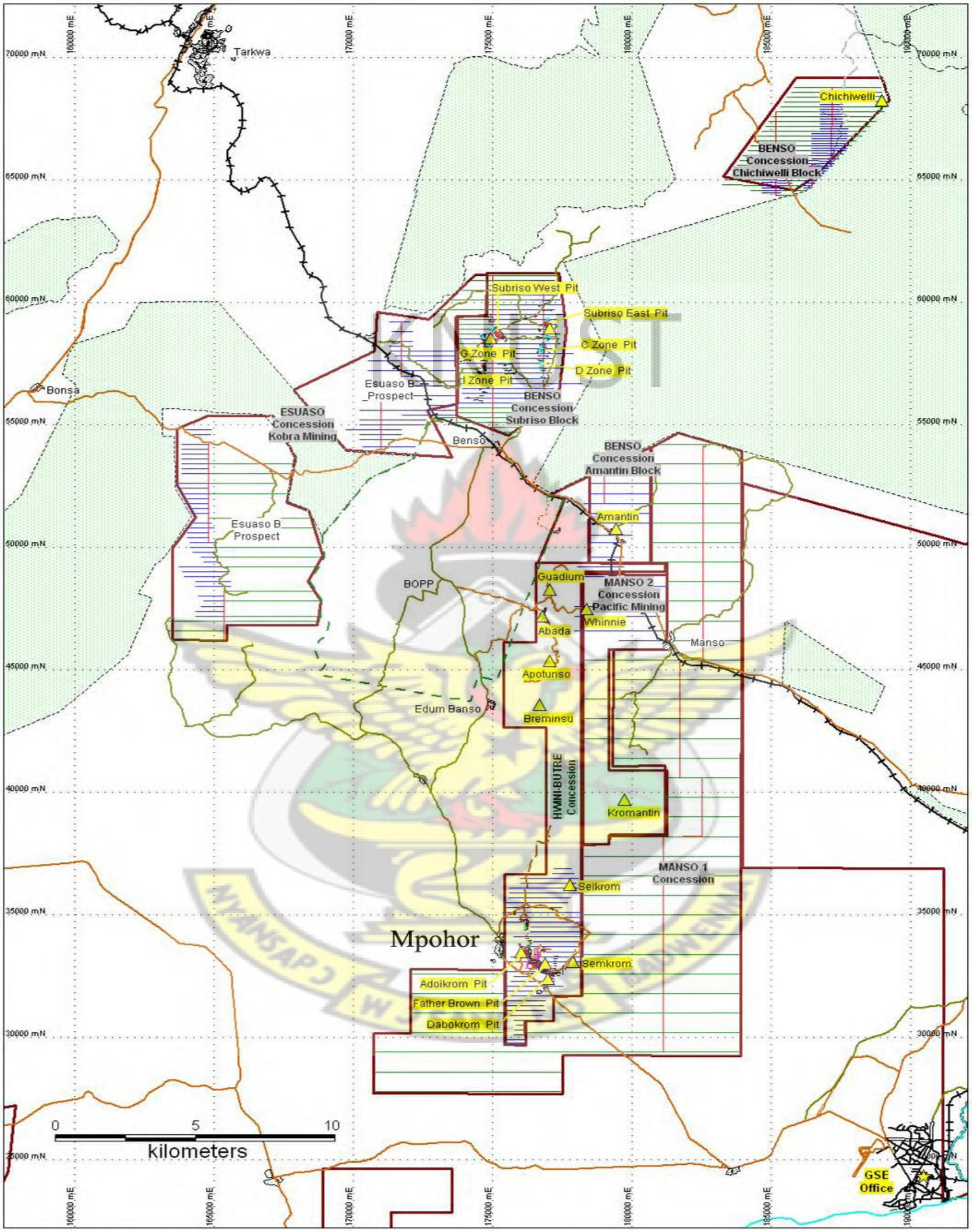


Figure 3.1: Map of Hwine-Butre and Benso showing GSRL exploration concessions. (Source: EPA, Akoben)

Sampling sites

The sampling sites were selected based on the level of impact of mining on the environment. These locations included those characterized by surface mining activity within 1km or less, as well as locations away from the Huni-Butre and Benso project site where no surface mining takes place.

Two groups of dust samples namely dust deposition and total suspended particulates were collected, measured and used as indicators. Dust fallout levels were sampled for assessing dust nuisance impacts, while suspended dust levels were sampled for assessment against international standards based on health.

Six monitoring sites in the Huni-Butre and Benso project area were chosen for the investigation based on their sensitivities to the mining operations of Golden Star Resources limited. Three sampling sites namely, Yayaho, Subriso and Ningo were chosen from Benso (Figure 3.2a), while Anlokrom was taken from Huni-Butre (Figure 3.2b). Two non-mining sites namely, Mpohor Police station and Mpohor Pentecost Area, outside the Huni-Butre and Benso concession area were also chosen for comparison. The six sampling sites are:

- Subriso
- Ningo
- Yayaho
- Anlokrom
- Mpohor Police station
- Mpohor Pentecost area

Subriso was chosen to provide an indication of the cumulative impact of dust as a result of mining activities from the Subriso west, Subriso East and G-Zone pits (Table 3.1).

Ningo was chosen to provide an indication of the cumulative impact of dust from the haul roads, Subriso west, Subriso East, G-Zone and C-Zone pits (Table 3.1).

Yayaho gave an indication of the cumulative impact of dust from mining activities due to vehicular movements on the haul roads and the Subriso pits (East and West) at Benso.

Anlokrom was chosen to provide information on the impact of the Adoikrom and Father Brown mining pits at Hwini-Butre.

Table 3.1: Distances from sampling communities to mining pits. (Source: EHS Department, GSRL).

Pit	Community	Distance from community /metres
Subriso West	Subriso	950
Subriso East	Subriso	700
Subriso East	Ningo	750
Subriso West	Ningo	1 688
G-Zone	Ningo	2 177
G-Zone	Subriso	1 512
C-Zone	Ningo	350
Dabokrom	Anlokrom	104
Father Brown	Anlokrom	387

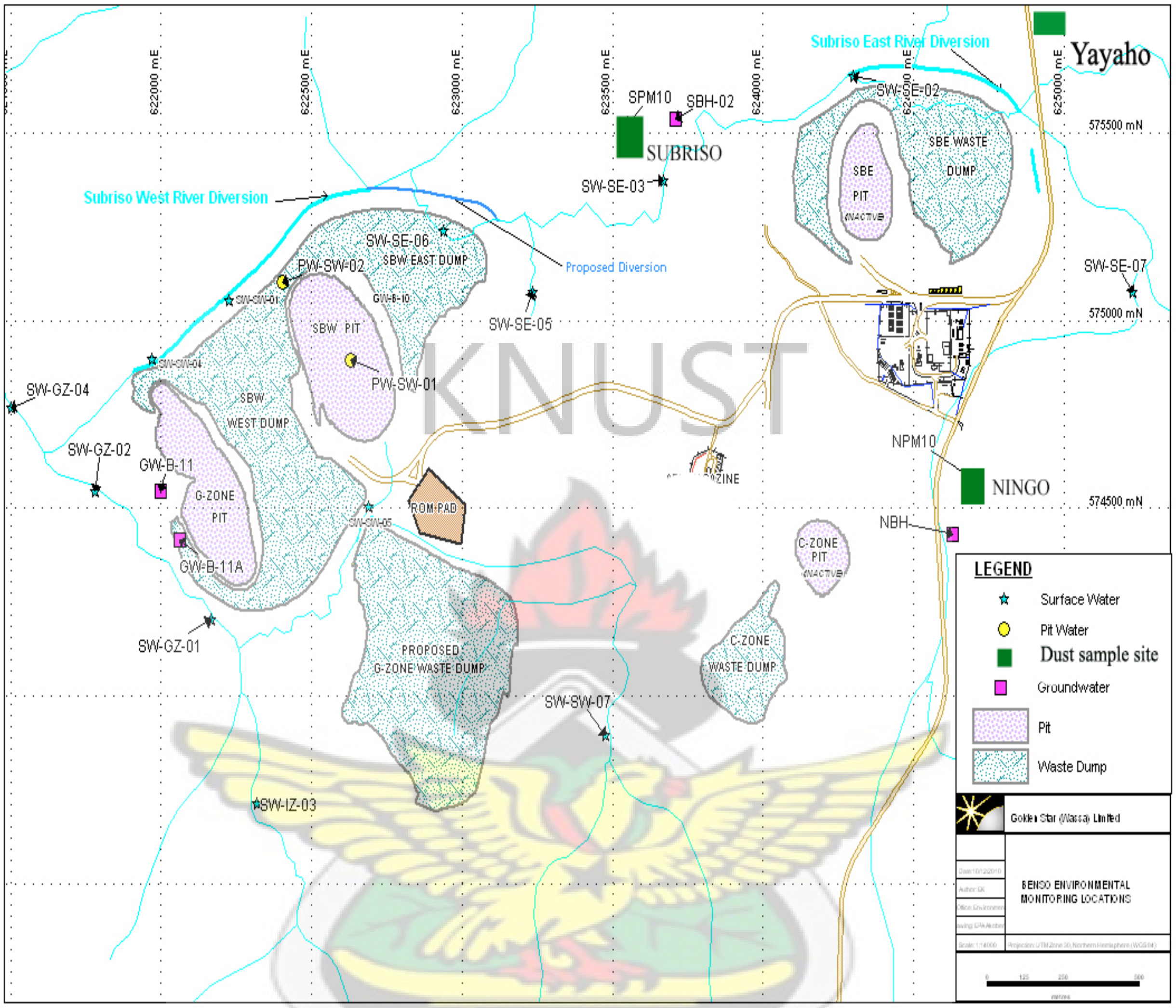


Figure 3.2a: A map of Benso showing the sampling sites. Source: EPA, Akoben

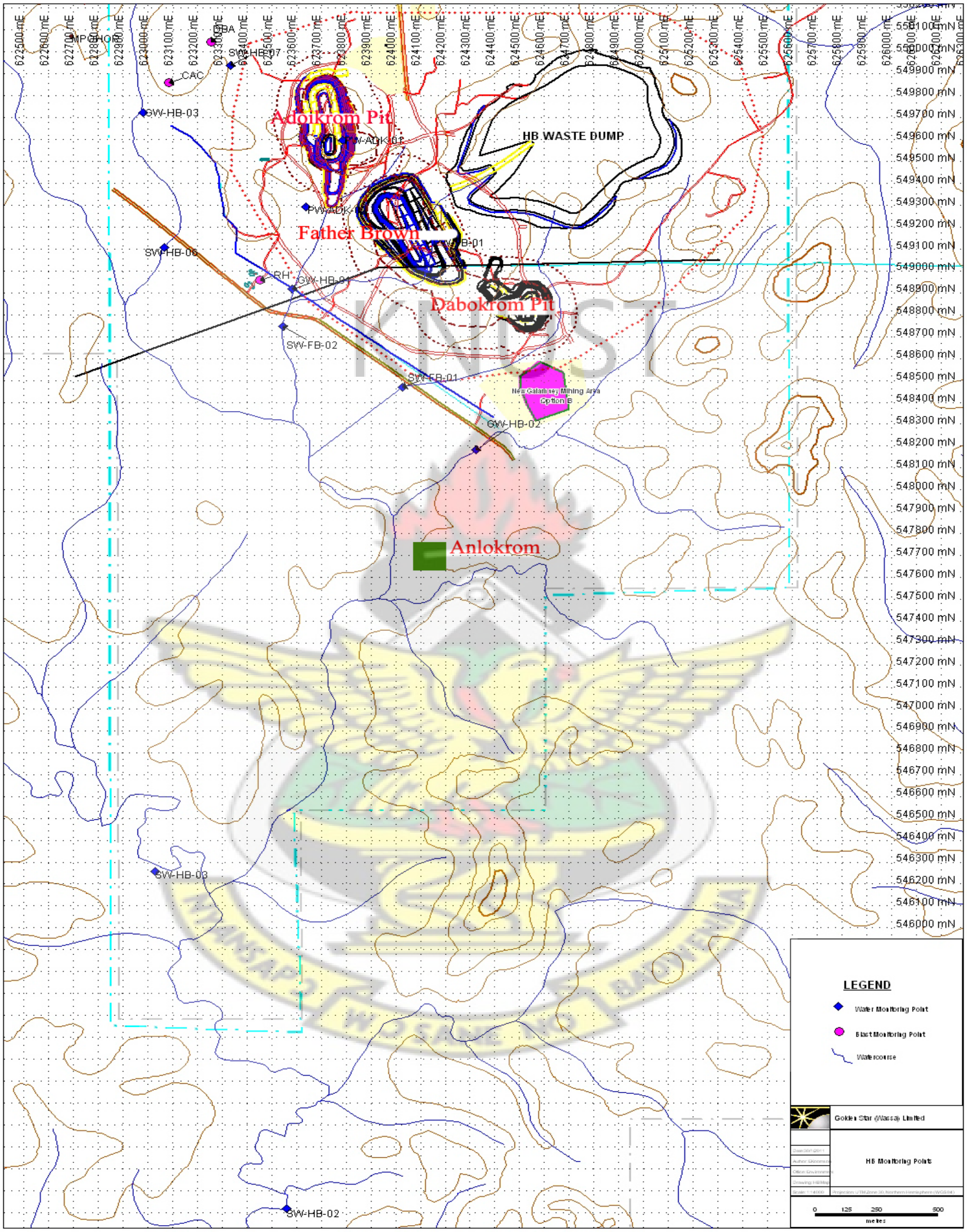


Figure 3.2b: Site map of Huni-Butre project area showing Anlokrom. Source: EPA, Akoben

Climatic factors of the sampling area

The area has a moist equatorial climate with an average rainfall in the range 1,200mm to 1,500mm per year which falls in two main rainy seasons. The longer rainfall period is usually from late March to late June, while the short period is usually from late September to early November. The driest and coolest period is quite short and corresponds to the harmattan period which usually occurs in the months of December, January and February. Except for the noticeably dry but short period of the harmattan, the area usually has high humidity.

The daytime temperatures usually peak at about 30-35°C, with the period between late October and early May recording the highest temperatures. The average daily temperatures are usually in the range 25-28°C (Bourke *et al.*, 2007).

Climatic data during the period of sampling were recorded by an automatic weather station installed at Benso. Weather elements measured include wind speed and direction, rainfall, temperature, humidity, photosynthetic active radiation and international global solar radiation. The monthly rainfall data for the sampling period is presented in table 3.2.

Table 3.2: Rainfall distribution for the HBB concession area

Date	Aug	Sep	Oct	Nov	Dec	Jan
1	0.0	10.5	0.0	2.0	3.5	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	43.5	3.2	0.0	0.0
4	0.0	5.0	32.0	0.0	0.0	0.0
5	0.0	3.5	2.0	15.0	24.5	0.0
6	0.0	3.5	0.0	8.5	0.0	0.0
7	0.0	0.0	16.5	30.0	0.0	0.0
8	5.5	0.0	6.5	0.0	0.0	0.2
9	0.0	0.0	38.5	0.0	0.0	0.0
10	0.0	0.0	12.5	0.0	0.0	0.0
Date	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**

11	36.0	41.0	0.4	0.0	2.0	0.0
12	1.5	14.5	24.5	9.6	0.0	0.0
13	2.0	28.5	4.5	0.0	0.0	0.0
14	0.50	0.0	2.5	0.0	0.0	0.0
15	0.0	8.5	4.5	0.0	0.0	0.0
16	0.5	10.5	0.0	0.0	0.0	0.0
17	0.3	2.5	0.0	46.5	0.0	0.0
18	0.3	6.0	0.0	0.0	0.0	0.0
19	0.0	0.0	36.2	0.0	0.0	0.0
20	0.4	25.5	7.5	0.3	0.0	0.0
21	5.0	23.5	0.0	6.5	0.0	0.0
22	1.5	23.5	34.5	0.0	0.0	0.0
23	6.5	39.0	43.5	0.0	0.0	0.0
24	0.0	16.5	0.0	0.0	0.0	0.0
25	0.0	4.5	0.0	0.0	0.0	0.0
26	0.0	11.5	5.0	12.0	0.0	24.0
27	0.0	25.5	0.0	2.2	0.0	0.0
28	0.0	0.0	0.0	1.8	9.5	0.0
29	8.5	0.0	5.0	0.0	0.0	0.0
30	5.5	7.5	4.5	0.0	0.0	0.0
31	7.5	N/A	6.0	N/A	0.0	0.0
Total	**81.5**	**311.0**	**330.1**	**137.6**	**39.5**	**24.2**

(Source EHS department, GSRL)

Meteorology

An automated meteorological station installed at the HBB project site recorded the rainfall, wind speed, wind direction and temperature. The meteorological data collected during August 2010 and January 2011 are shown in table 3.3.

Table 3.3: Table showing meteorological data of the project area

Date	Av. Air Temperature/^oC	Av. Relative Humidity/ %	Average Solar Radiation/ W/m^2	Average Wind Speed/ km/h	Vector Wind Direction/ Degree
August	24.82	77.34	114.55	1.83	212.52
September	24.93	78.32	118.10	1.42	215.80
October	25.42	78.15	139.19	1.16	223.94
November	25.64	76.54	150.23	0.77	220.60
December	27.19	74.53	157.13	0.73	213.87
January	27.51	75.50	158.33	0.81	214.67

The maximum and minimum air temperatures recorded at the weather station (not shown in table 3.3) during the period were 36.43°C (December) and 21.86°C (August) respectively. Relative humidity levels stayed fairly constant throughout the period ranging between 74.53% and 78.32%. The maximum and minimum solar radiation rates for the period were 158.33W/m^2 (January) and 114.55 W/m^2 (August).

SAMPLING

Air quality samples were collected at six sampling sites between August 2010 and January 2011.

Dust fallout and fine particulate matter samples were collected with dust deposit gauge bottles (AS/NZS 3580) and Dusttrak Aerosol Monitor (8535) respectively. Dust deposit gauge bottles are the most simple and cost effective method for undertaking dust monitoring (Standards Australia, 2006), while Dusttrak aerosol monitors determine real-time dust concentrations, and enable the determination of short term dust events, which give an indication of the potential health effects of the dust (TSI Incorporated, 2008).

Sampling of suspended dust (PM_{10})

The Dusttrak Aerosol monitor - model 8535 (Figure 3.3) was used to determine the mass concentration of fine particulate matter (less than 10 microns) at Yayaho, Subriso, Ningo, Anlokrom, Mpohor Pentecost area and Mpohor Police station.

Figure 3.3: Dusttrak Aerosol Monitor 8535

The dusttrak was placed at each sampling site on six different occasions between August, 2010 and January, 2011, resulting in one sampling for each month. At each location the dusttrak was set up for a period of exactly twenty four hours to sample suspended dust. The sampling process was repeated every month over the six month period. Hence each site recorded six readings for six months, with each reading representing one month. In all a total of thirty-six sample readings were taken from all the sampling sites.

To avoid errors, the following prior checks were done on the dusttrak: All components were properly installed into the enclosure; the dusttrak monitor was set at zero at the temperature at which it was to sample; the environmental enclosure was placed on a tripod away from obstructions that could affect the air flow around the enclosure; the monitor was set to the appropriate logging mode; and the enclosure was closed and locked to prevent theft or vandalism to the instrument.

Analysis to identify the mass concentration of PM_{10} was done by the dusttrak. Aerosol was drawn in to the sensing chamber (Figure 3.3) through the aerosol inlet assembly in a continuous stream using a diaphragm pump. Part of the aerosol stream was split ahead of the sensing chamber and passed through a HEPA filter and injected back into the chamber around the inlet nozzle as sheath flow. The remaining flow, called the sample flow passed through the inlet entering the sensing chamber. Here, it was illuminated by a sheet of laser light formed from a laser diode. First the light emitted from the laser diode passes through a collimating lens and then through a cylindrical lens to create a thin sheet of light. A gold coated spherical mirror captures a significant fraction of the light scattered by the particles and focuses it onto a photo detector. The voltage across the photo detector is proportional to the mass concentration of the aerosol over a wide range of concentrations. The voltage is then multiplied by a calibration constant which is determined from the ratio of a known mass concentration of the test aerosol to the voltage response of the Dusttrak Aerosol Monitor.

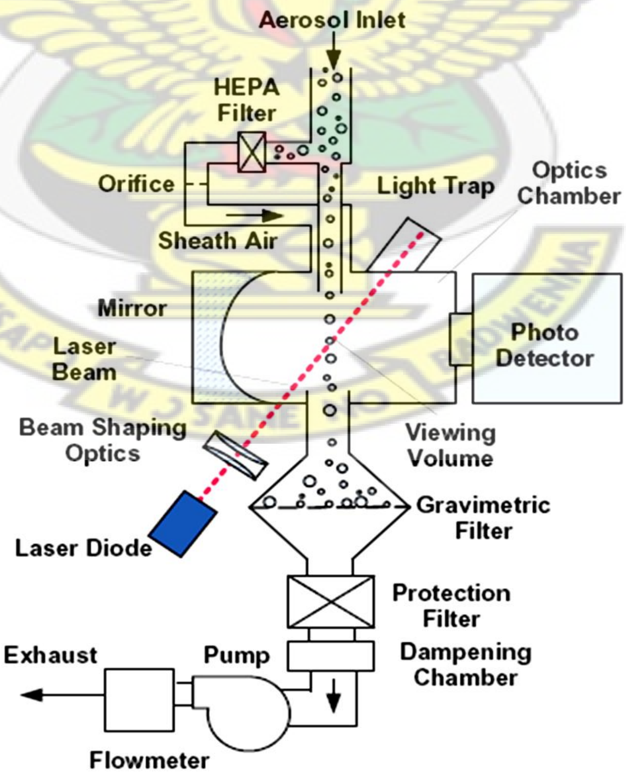


Figure 3.4: Diagram of Dusttrak aerosol monitor (Model number 8535) showing its operation. Source: TSI Incorporated

The PM_{10} concentration for each sampling was read directly through the following steps:

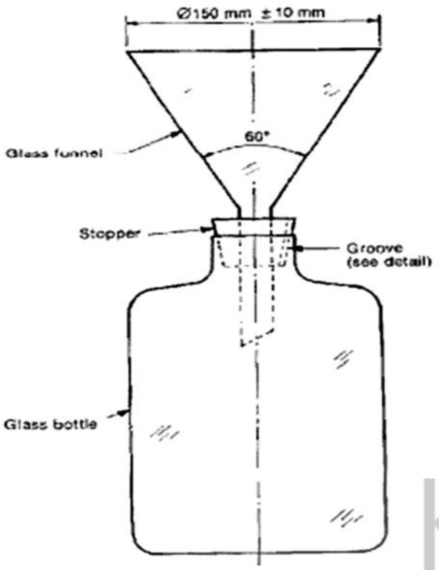
- First the sampling was discontinued and the environmental enclosure opened.
- A USB cable was then attached from the USB connector to a computer USB port, and using the appropriate commands within the TRAKPRO™ software, data was downloaded onto the computer.
- By the design of the TRAKPRO™ software, the concentration of the PM_{10} sampled dust could be read directly from the computer.

SAMPLING OF DEPOSITED DUST

The following processes were used to sample dust deposition from the ambient air.

Equipment

Dust deposit gauge bottles were used to sample dust fallout. The bottles consisted of a 150 mm diameter funnel of glass fitted firmly on a 5L wide-mouth bottle by means of a rubber stopper. The internal diameter of the stem of the funnel was designed to sufficiently permit particulate matter to pass through during washing (Figure 3.5a and Figure 3.5b).



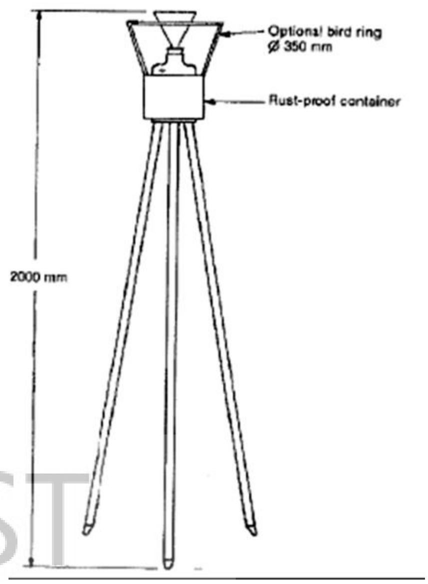


Figure 3.5a: Drawings of a dust gauge bottle   **Figure 3.5b: Dust gauge bottle on a stand**

Preparation of deposit gauges

The inside surface of the deposit gauge bottles and the lids were first washed and rinsed with distilled water. Ten (10) ml of copper sulphate solution was then pipetted into the deposit gauge bottles so as to prevent algal growth in the deposit gauge and the bottles were then tightly sealed and transported to the sampling sites.

To limit the indeterminate errors in the precipitant dust monitoring results, the following precautions were observed:

- The bottles were prepared indoors to prevent dust landing into the bottles while in the open.
- The lids remained on the bottles from when they were prepared until they were ready to be put into the canister unit.
- The bottles were changed one at a time with the system ensuring that the bottles were open for as little time as possible. Care was taken not to kick dust into the bottles or to have open bottles while setting the gauges.

Positioning of dust gauge bottles

The gauges were set up to stand in a rust proof canister which protected the glass bottle from sunlight, away from trees, buildings and other obstructions. The height was placed such that the top of the funnel was two metres above the ground level of the immediate surrounding area in an open place. Siting the gauge in an open place ensured that the dust sample collected was a true representation of the dust deposition rate of the area.

Period of exposure

Dust deposit gauges were placed at the following locations for a period of one month: Yayaho, Subriso, Ningo, Anlokrom, Mpohor Pentecost area and Mpohor Police station, to collect dust fallout. Over a sampling period of one month particles that settle from the ambient air were collected in the dust bottle. Any deposited matter adhering to the inside of the funnel was washed into the bottle with a minimum volume of distilled water from a wash bottle. The funnel and attached stopper were then removed and the glass bottle sealed firmly with a lid. The bottle was then identified with all the necessary labels and sent to the laboratory for analysis.

Gauge exchange

After a period of one month each deposit gauge was changed and replaced with a new one.
A clean funnel and a fresh dust bottle were then set up as previously explained to sample the dust for the next sampling period.

Six samples were collected for each site; one sample per month. In all a total of thirty-six sample readings were taken from all the sampling locations.

LABORATORY ANALYSIS OF DUST FALLOUT

Dust fallouts (deposited dust) were analysed for total solids, insoluble solids, combustible solids and ash content.

Total solids

- The content of each deposit gauge bottle was sieved separately into a beaker through a 1.00 mm^2 test sieve to keep insects and other debris from being added to the dust samples that have been collected. All remaining particles adhering to the internal surface of the deposit gauge bottle were transferred into the beaker with the aid of squirts of distilled water from wash bottles.
- The beaker containing the sample was then placed on a hotplate to evaporate the water to a volume of about 30mL.
- The content was then transferred into an evaporating dish already dried at 105°C for one hour, cooled in a desiccator and weighed.
- The content of the evaporating dish was placed on a hot plate and evaporated to near dryness and transferred to a drying oven (model: *Conterm Thermotec 2000*), and dried at 105°C for one hour.
- The dried sample was then cooled in a desiccator and weighed.
- The drying, cooling and weighing was repeated until the dish and its contents gave constant mass. This mass was then recorded as post weighing mass.

Expression of results for total solids was computed as follows:

Mass of total solids/g = Mass of the evaporating dish and the total solids in the sample – Mass of evaporating dish.

Mass deposition rate of total solids (S_t), in grams per square metre per month was computed as follows: $S_t = \frac{(M-0.055)\times F}{(A\times T)} = \frac{(M-0.055)\times 10^6 \times 4\times F}{\pi D^2 \times T}$

M = mass of total solid

A = Cross sectional area of the funnel in metres = $\frac{\pi D^2}{4}$; Where D = diameter of the funnel.

F = Factor to express the results to a 30-day month = 30

T = Sampling period in days

The subtraction of 0.055g is the correction for the mass of the algicide added to the gauge.

Determination of insoluble solids

– After determining the total solids, the evaporating dish with the total solids in it was placed on a hot plate, and about 50mL of water added to the dry sample and heated gently for 30 minutes to re-dissolve the soluble solids present in the total solids.

– A filter crucible (with filter pad) heated in a furnace to 850°C for 30 minutes and allowed to cool in a desiccator was initially weighed, and the heated sample passed through the prepared crucible to filter the soluble solids.

– The crucible was then dried in an oven for one hour at 105°C and cooled in a desiccator and reweighed, and the mass recorded.

Expression of results for insoluble solids was computed as follows:

Mass of insoluble solids/g = Mass of the crucible and insoluble solids in the sample – Mass of prepared crucible with filter pad.

Mass deposition rate of insoluble solids (S_i), in grams per square metre per month was computed as follows: $S_i = \frac{(M_i - 0.055)\times F}{(A\times T)} = \frac{(M - 0.055)\times 10^6 \times 4\times F}{\pi D^2 \times T}$

M_i = mass of insoluble solids; F, D and T as previously defined.

Determination of ash and combustible matter

– The crucible containing the insoluble solids was heated gradually in a furnace to 850°C to ignite the insoluble solid sample

– The crucible was then allowed to cool in a desiccator and reweighed and the mass of crucible and ash content recorded

Expression of results for ash was computed as follows:

Mass of ash/g = (Mass of the crucible + ash content) – Mass of crucible.

Expression of results for combustible matter was computed as follows:

Mass of combustible matter = Mass of insoluble solids – mass of ash

CHAPTER FOUR

RESULTS

The results of concentrations of suspended dust in the HBB mining concession area at the various sampling sites are presented in figures 4.1 – 4.7. In addition values of dust deposition (dust fallout) rates for the various sampling sites are presented in figures 4.8 – 4.14.

Descriptive statistics for both PM_{10} concentrations and deposited dust at the various sampling sites are also shown in appendices 1 to 4.

Concentrations of suspended dust in the mining environment of Huni-Butre and Benso

Results obtained from the analyses of suspended dust samples collected from the sampling sites (Yayaho, Subriso, Ningo, Anlokrom, Mpohor Pentecost Area and Mpohor Police Station Area) are shown in figures 4.1 – 4.7.

Yayaho

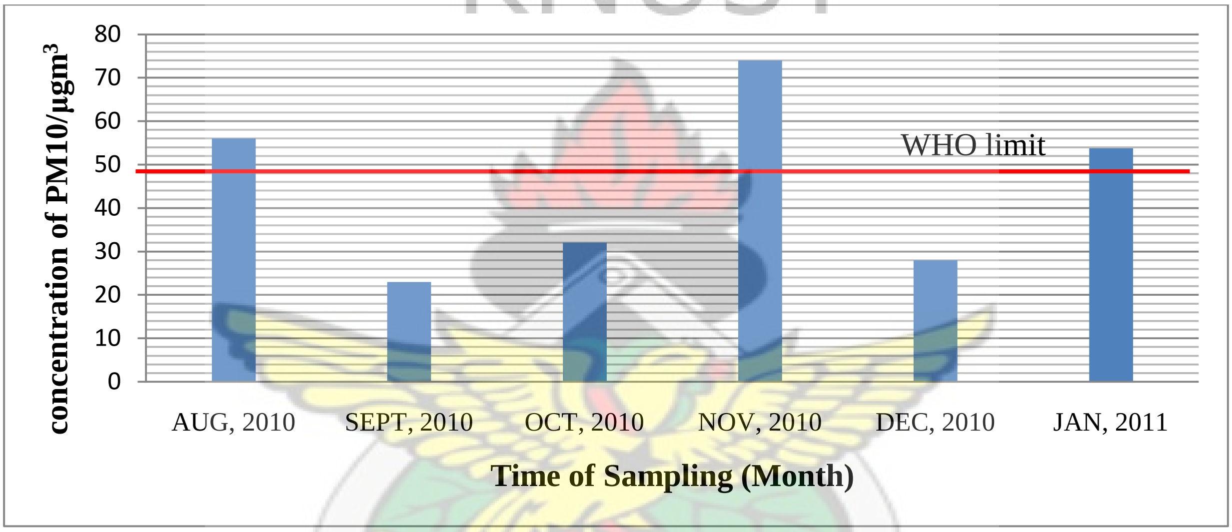


Figure 4.1: Concentration of suspended dust (PM_{10}) in the ambient air at Yayaho

The highest PM_{10} concentration (74µg/m³) for the six months period was in November, 2010 while the lowest (22 µg/m³) was in September 2010, with an overall average of 44.5µg/m³ (appendix 2). PM_{10} levels in August, November and January were well above the WHO air quality limit. Three exceedances within a period of six months suggest that the impact of mining on the ambient air quality was high since the WHO allows for four exceedances in a year.

Subriso

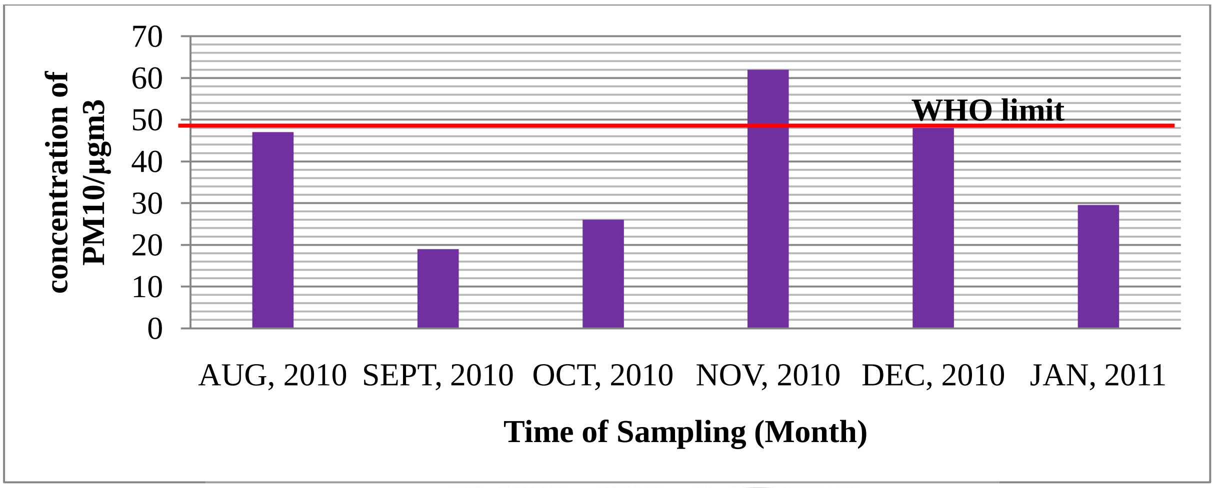


Figure 4.2: Concentration of suspended dust (PM_{10}) in the ambient air at Subriso

There was a single exceedance of PM_{10} concentration at Subriso during the month of November with a record of 62 µg/m³. All other PM_{10} concentrations were within the WHO acceptable limit of 50 µg/m³. The overall average for Subriso PM_{10} concentration was 38.6 µg/m³ (appendix 2). One exceedance (November, 2010) within a period of six months shows that though mining has impacted on the ambient air quality, the level of impact was within the tolerable limit of WHO.

Ningo

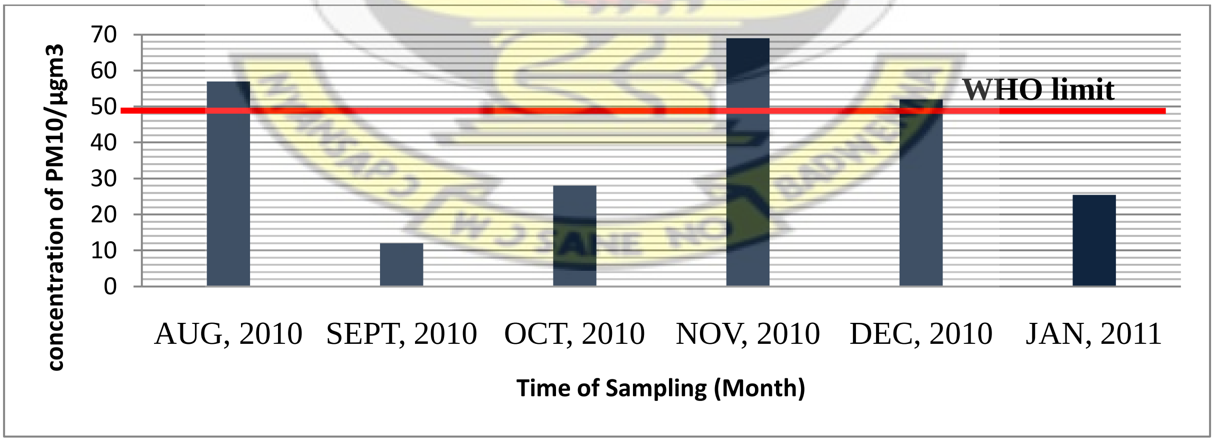


Figure 4.3: Concentration of suspended dust (PM_{10}) in the ambient air at Ningo

The highest PM_{10} concentration was 69 µg/m³ with an overall average of 40.6 µg/m³ (Appendix 2). PM_{10} levels on three sampling occasions, August, November and December were above the air quality limit of the WHO. The three exceedances in six months were not within the acceptable limit of WHO.

Anlokrom

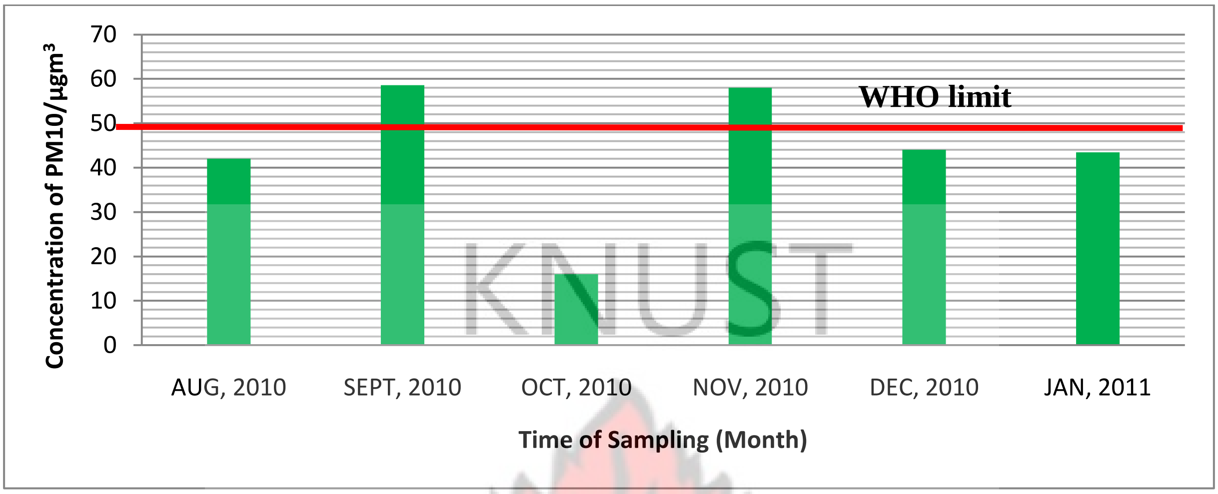


Figure 4.4: Concentration of suspended dust (PM_{10}) in the ambient air at Anlokrom

Anlokrom recorded two exceedances which occurred in the months of September and November. Analysis of the measurements taken at the Anlokrom site showed an average PM_{10} concentration of 43.7 µg /m³ for the six month period (Appendix 2). The highest concentration recorded was 58.6 µg /m³ in the month of September. The World Health Organisation's threshold limit of 50 µg /m³ was exceeded twice, inferring that surface mining activities impact negatively on ambient air quality at Anlokrom.

Mpohor Pentecost Area

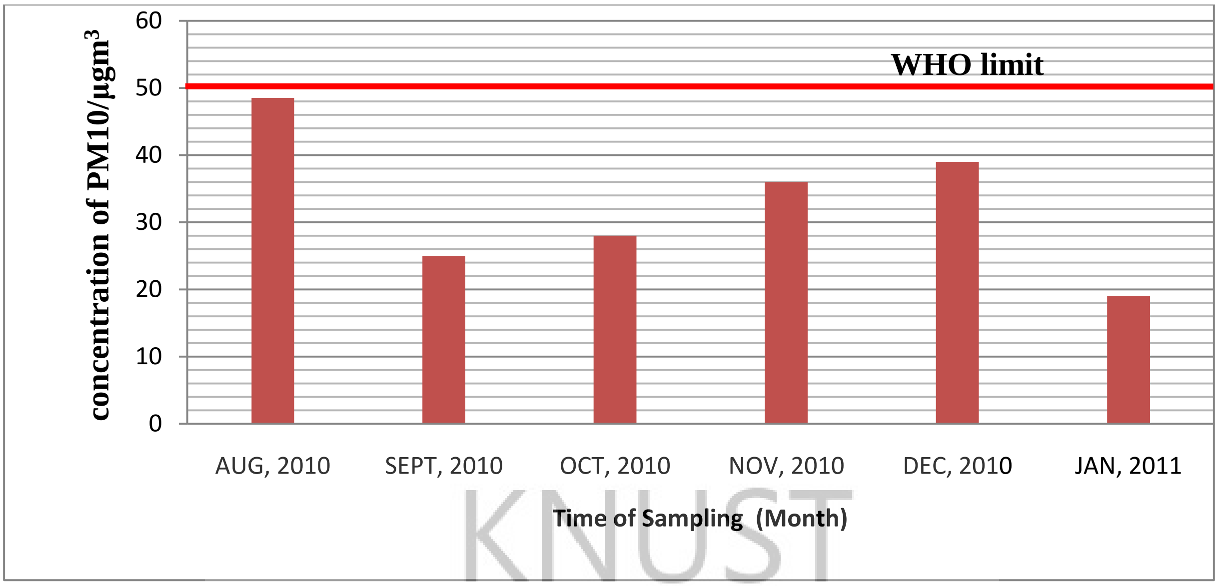


Figure 4.5: Concentration of suspended dust (PM_{10}) in the ambient air at Mpohor Pentecost Area

The ambient PM_{10} levels increased consistently from September through December after the initial maximum value of 48.5 µg /m³ in August. However there was a sharp decline in January (Figure 4.5). The overall average was 32.6 µg /m³ (appendix 2). The levels of PM_{10} concentrations in the ambient air were below the WHO threshold limit of 50 µg m^{-3}. The inference is that surface mining activities has no significant impact on the ambient air quality at Mpohor Pentecost Area.

Mpohor Police Station

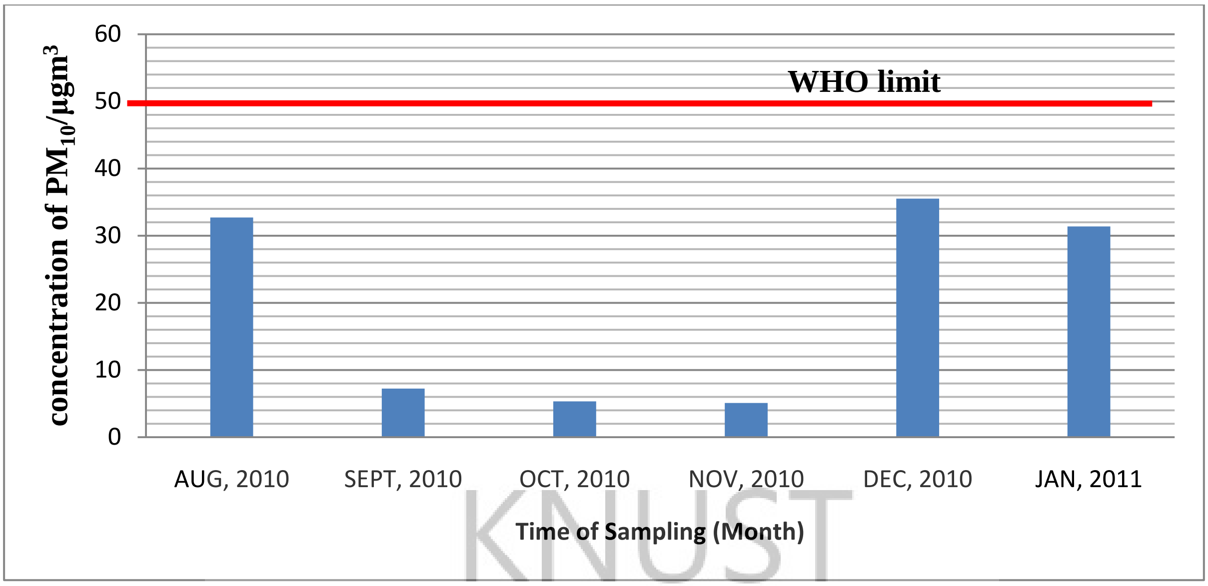


Figure 4.6: Concentration of suspended dust (PM_{10}) in the ambient air at Mpohor Police Station

Ambient air quality at the Mpohor Police Station throughout the study period was within the WHO air quality guideline concentrations (Figure 4.6). The overall average was 19.5 µg /m³ (appendix 2). The absence of exceedances within the period of six months with a maximum of 35.5 µg/m³ (December, 2010) shows that though mining impacts on the ambient air quality, the level of impact is within the tolerable limit of WHO air quality guideline.

Comparison of PM_{10} concentrations at different locations within the HBB project area

The results of the concentrations of suspended dust at different locations within the HBB mining concession area at the various sampling sites were compared using box-plots as shown in figure 4.7.

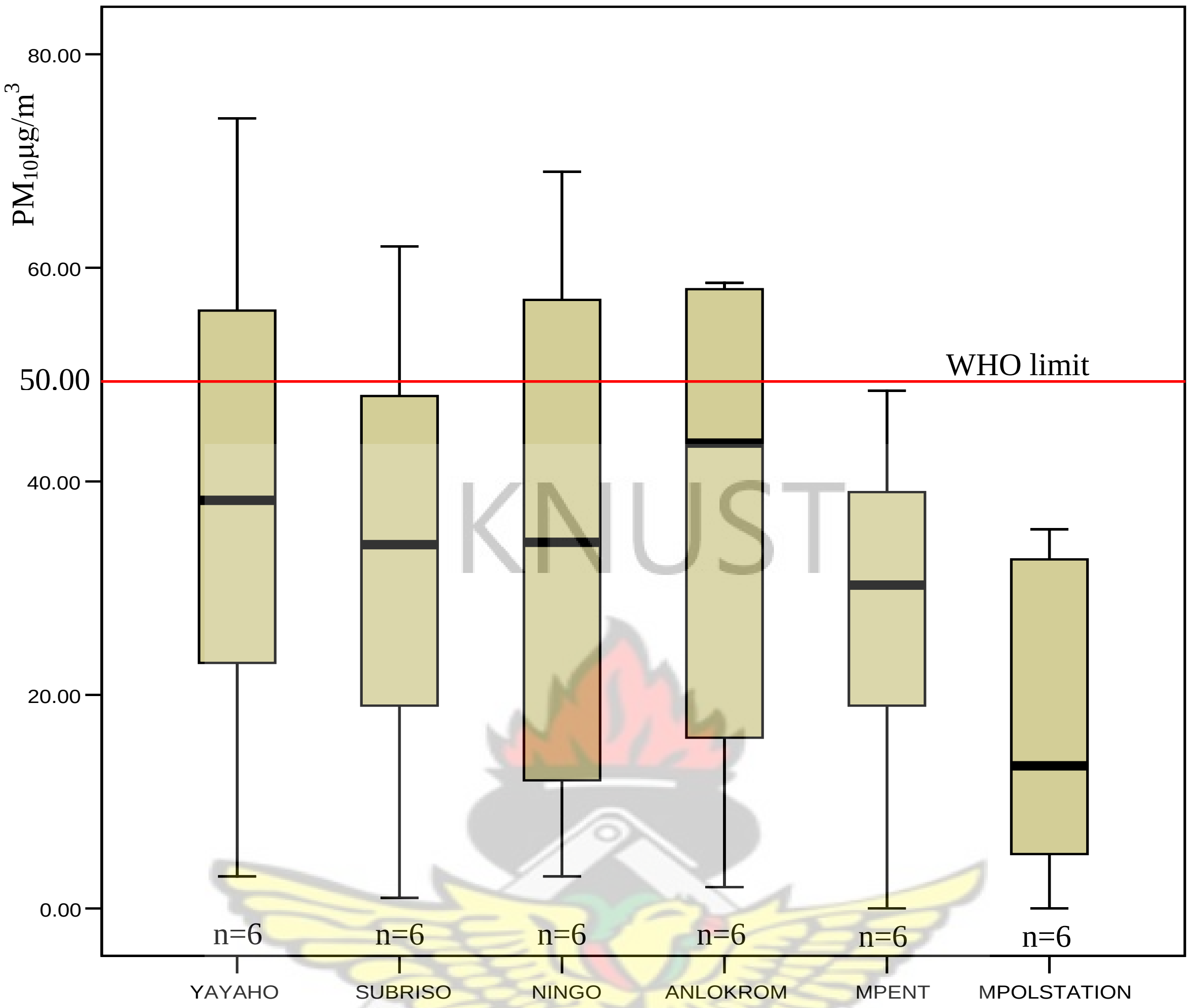


Figure 4.7: Distribution of PM_{10} concentrations at the different locations within the HBB project site

PM_{10} values recorded during measurements ranged from 5.1 μg/m^3–74.0 μg/m^3 (Figure 4.13). The box-plots (Figure 4.13) also show that the maximum PM_{10} exceedance occurred at Yayaho sampling site, and all the interquartile ranges overlapped, with the Yayaho maximum results being higher than the maximum results from Subriso, Ningo and Anlokrom sampling locations. Statistically, the suspended dust levels do not vary much from one sampling location to the other. However, the Anlokrom data set is skewed to the higher ranges while Mpohor Police station is skewed towards the lower ranges. The rest are symmetrically distributed.

Deposited dust (Dust fallout)

Airborne particulate matter comprises a mixture of organic and inorganic substances, made up of different sizes and shapes. Monthly laboratory analyses of dust fallout samples collected from the sampling sites (Yayaho, Subriso, Ningo, Anlokrom, Mpohor Pentecost Area and Mpohor Police Station Area) over the six-month period are shown in tables 4.8 to 4.13.

Yayaho dust fallout

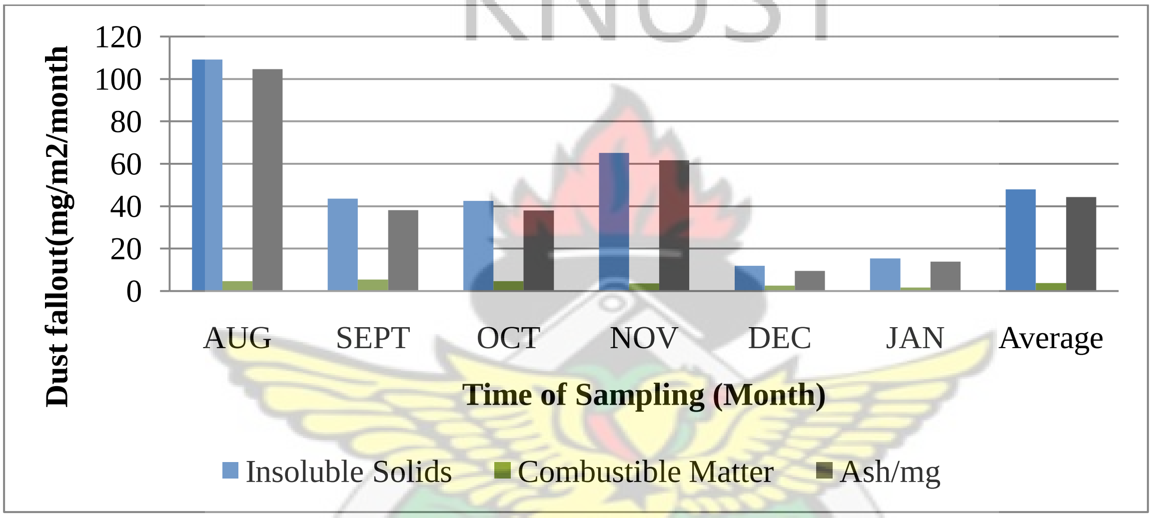


Figure 4.8: Dust fallout rate from the ambient air at Yayaho

IS = CM + Ash (mineral content)

IS – Insoluble solids; **CM** – Combustible matter (organic part of dust)

Yayaho recorded an average rate of 44.2 mg/m^2/month of deposited dust, which constituted the second maximum average dust deposition rate for the HBB project area during the period. The total deposited insoluble solid of 109.2 mg/m^2/month recorded in August, 2010 (Figure 4.8) was the highest. However the deposited dust results from Yayaho were within the international threshold limit of 4 g/m^2/month, indicating that nuisance dust in the Yayaho ambient air is within the allowable limit of WHO.

Subriso dust fallout

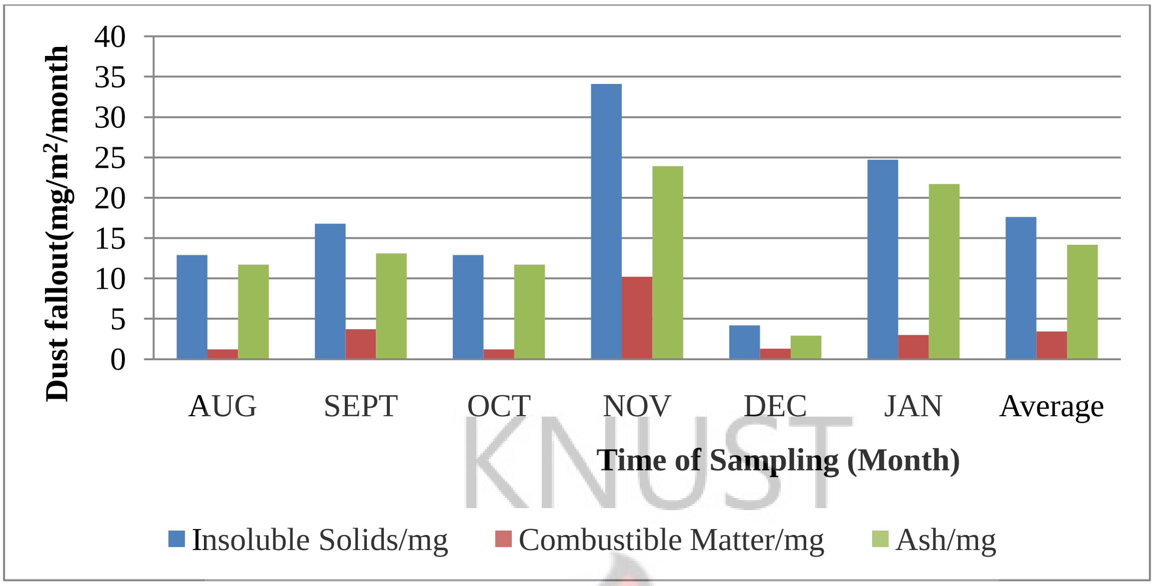


Figure 4.9: Dust fallout rate from the ambient air at Subriso

Subriso recorded the least average deposit of insoluble dust at a rate of 17.6 mg/m^2/month (Figure 4.9). The maximum deposition rate of 34.1 mg/m^2/month occurred in November 2010 and the minimum of 4.2 mg/m^2/month in December (Figure 4.9).The results indicate that total insoluble solids collected per month had very small components of combustible matter and a high mineral content (ash).

Generally the results show that the impact of coarse dust attributable to mining activities fell below international limit of 4gm^{-2}/month.

Ningo dust fallout

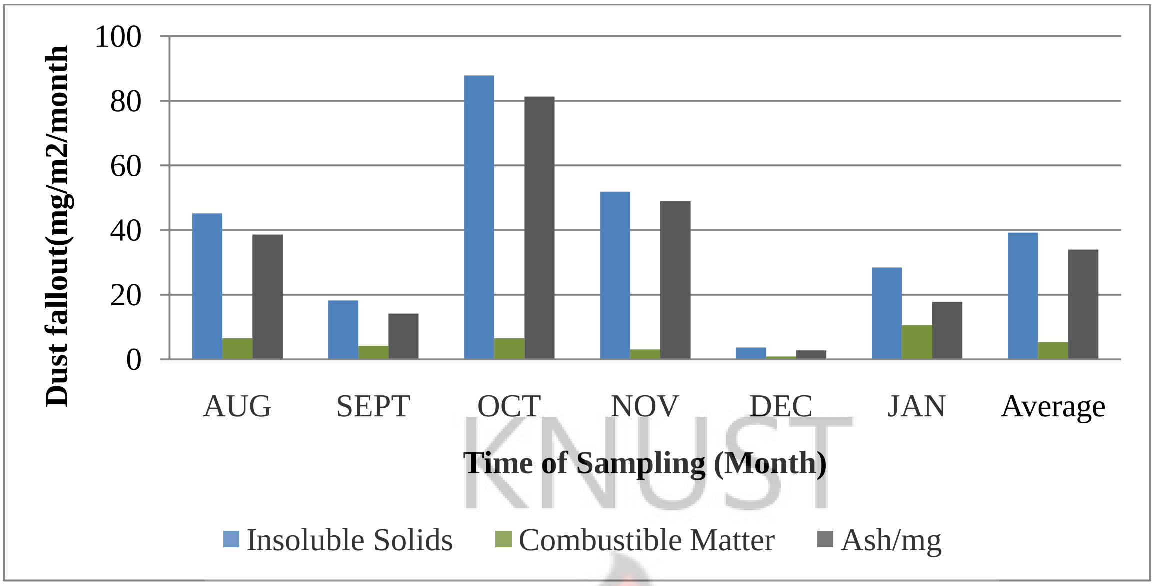


Figure 4.10: Dust fallout rate from the ambient air at Ningo

Ningo recorded the third highest mean deposited insoluble dust rate of 39.2 mg/m^2/month (Figure 4.10). Results from the dust fallout reflect low coarse dust levels from August to November 2010. The maximum dust fallout occurred in the month of October 2010, which constituted the second highest deposited dust in the HBB project area in the month of October after Yayaho. The deposited dust was within the international threshold limit of 4 g/m^2/month.

Anlokrom dust fallout

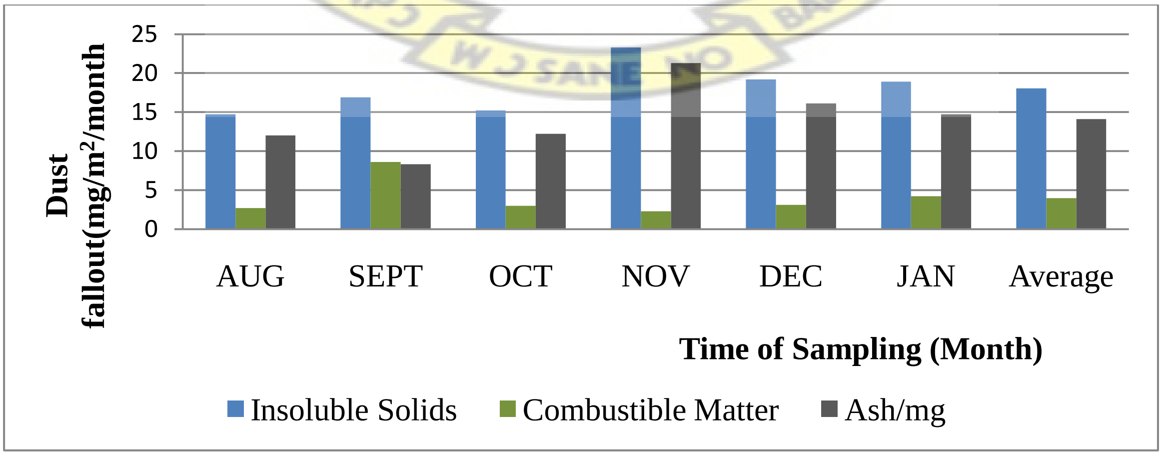


Figure 4.11: Dust fallout rate from the ambient air at Anlokrom

Anlokrom recorded the penultimate mean deposited insoluble dust of 18 $mg/m^2/month$. Results from the dust fallout reflected low dust fallout levels in August and October 2010, which later increased in the month of November 2010. There was a decrease in the month of December 2010 (19.2 $mg/m^2/month$), and a further decrease in January 2011 (18.0 $mg/m^2/month$). The deposited dust results were within the international threshold limit of 4 $g/m^2/month$.

Mpohor Pentecost Area dust fallout

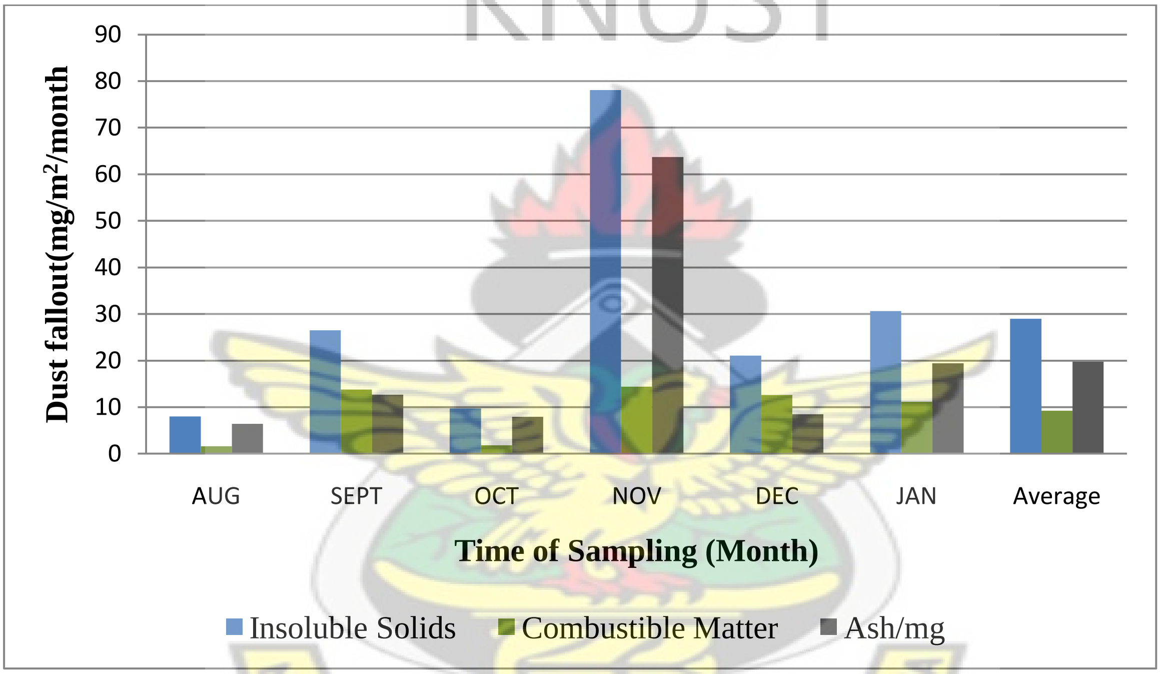


Figure 4.12: Dust fallout rate from the ambient air at Mpohor Pentecost Area

Mpohor Pentecost area recorded the fourth highest mean deposited dust of 29 $mg/m^2/month$. Results from the dust fallout reflect low dust fallout levels in August and October, 2010 (Figure 4.12), which increased in the month of November, 2010 (78.1 $mg/m^2/month$). However there was a sharp decrease in December (21.1 $mg/m^2/month$) relative to November. The deposition rate for January, 2011 (30.6 $mg/m^2/month$) was higher than all the previous months except for November.

Generally the deposited dust results shows that nuisance dust in the Mpohor Police Station area ambient air was well below the allowable limit of 4 g/m^2/month.

Mpohor Police Station dust fallout

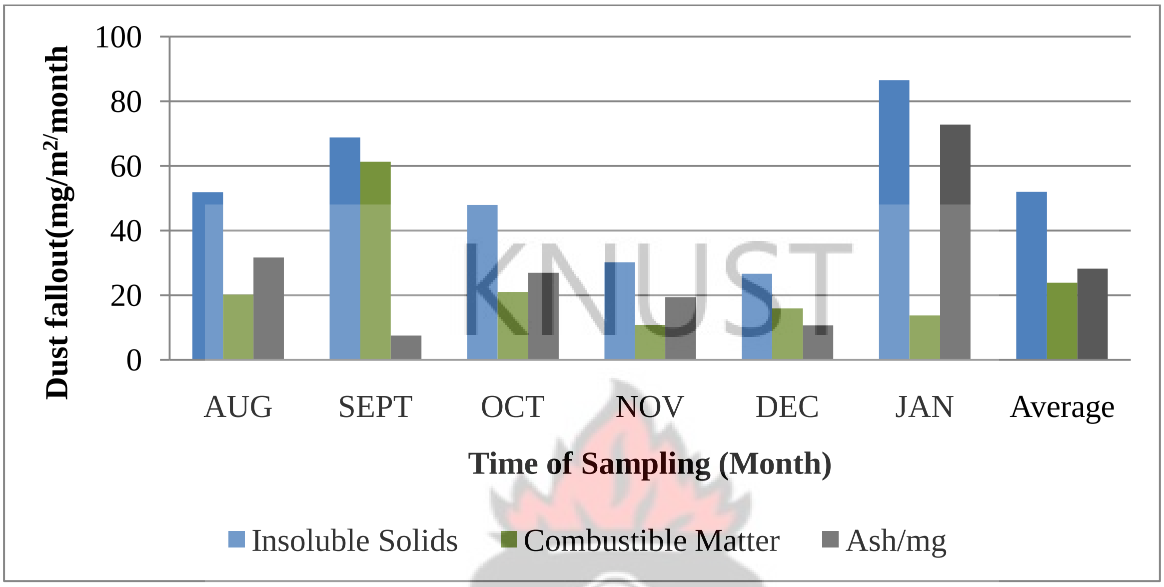


Figure 4.13: Dust fallout rate from the ambient air at Mpohor Police Station

This area recorded the highest average deposit of insoluble dust fallout at a rate of 52 mg/m^2/month. However the collected dust contained a sizeable fraction of combustible matter of 23.8 mg, a little below the ash content of 28.2 mg. The deposited dust results show that nuisance dust in the Mpohor Police Station area ambient air was below the allowable limit 4 g/m^2/month.

Comparison of inorganic dust at different locations within the HBB concession area

The results of the concentrations of dust fallout at different locations within the HBB mining concession area at the various sampling sites were compared using box-plots as shown in figure 4.14.

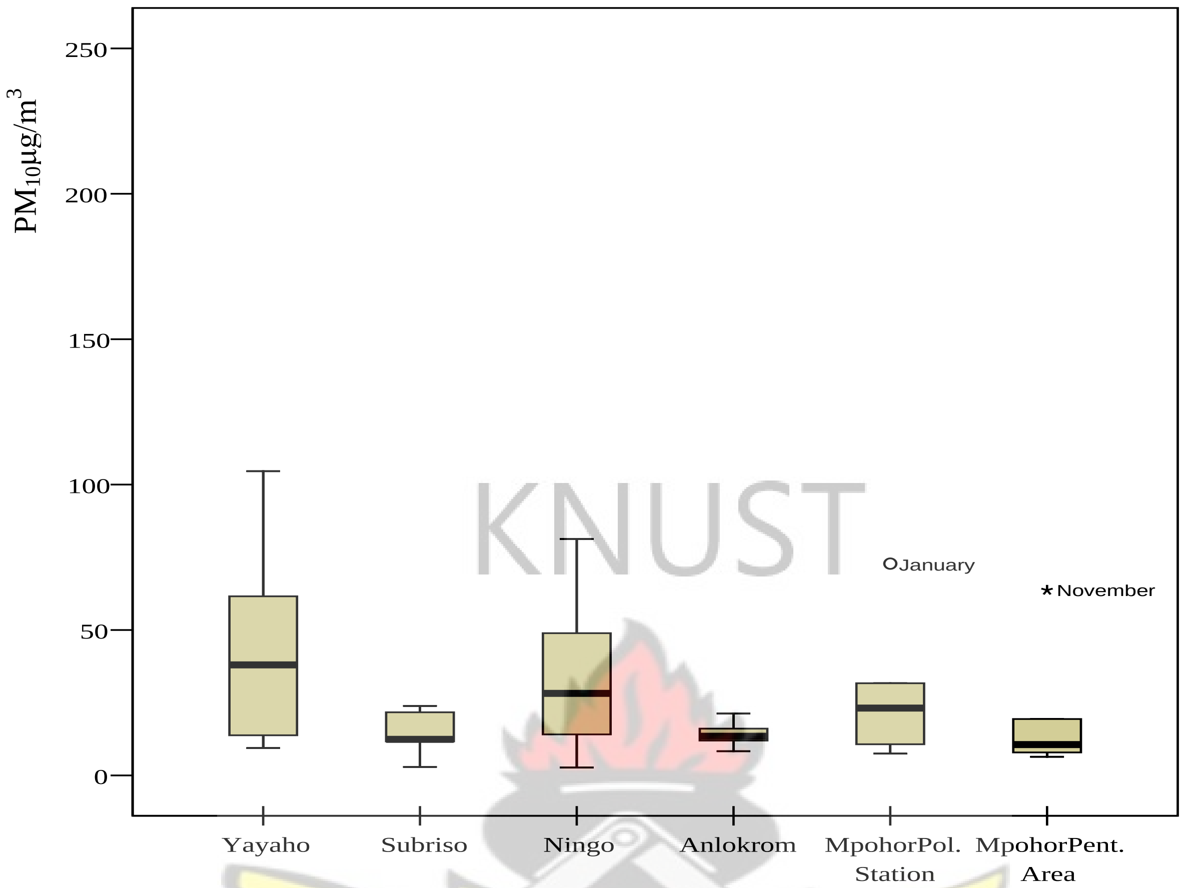


Figure 4.14: Distribution of inorganic dust at the different locations within the HBB concession area

Figure 4.14 shows that ash content (inorganic dust) recorded during the period ranged from 2.70 mg/(m^2/month) to 104.60 mg/(m^2/month) at Ningo and Yayaho respectively, with no exceedances. Statistically, the distribution of inorganic dust levels at Subriso, Anlokrom and Mpohor Pentecost Area do not vary much. Moreover Subriso, Ningo, Anlokrom, and Mpohor Pentecost area data sets are skewed to the lower ranges while Mpohor Police station is skewed towards the higher ranges. Contrastingly, Yayaho dust fallout shows a symmetrical distribution.

CHAPTER FIVE

DISCUSSION

This study indicates that surface mining had significant impact on the ambient air quality of the Huni-Butre and Benso mining concession area at Mpohor Wassa East District in the Western Region of Ghana. This was due to the high levels of suspended dust recorded in the selected mining communities with some of the communities recording dust values above the WHO air quality threshold limit. There were higher PM_{10} concentrations in mining locations compared with non-mining locations, and a further evidence of relatively high percentages of inorganic dust in the ambient air compared with low organic fractions at the same sampling sites.

These findings agree with work done by Ogola *et al*. (2002) on air quality evaluation in the Migori Gold Belt, Kenya. Ogola *et al*. (2002) posited that concentrations of particulate matter in mining communities reached their maximum levels during the month with the minimum rains, which is similar to other works by Soni and Agarwal (1997), Ghose and Majee (2000), Nanda and Tiwary (2001) and Reddy and Ruj (2003) for Indian coal mining areas. This study also recorded higher dust levels in the month of November, a relatively drier month in Ghana.

Mining and its allied activities during the entire period of this study were uniform, suggesting that no particular month experienced excessive mining operations. Hence deviations in a particular month could be attributed more to meteorological parameters and possibly to dust management practices (Reddy and Ruj, 2003). The build-up of dust concentrations to the higher levels in the study area could be the result of the calm winds that characterises the area due to the surrounding forests. There is therefore a restricted mixing depth due to a stable atmospheric lapse rate, and thus results in little dilution of pollutants which facilitates the build up of dust concentrations (Chaulya *et al*., 2002).

The levels of both suspended dust and inorganic dust fallout decreased with increasing distance from the mining and its allied activities (Chaulya *et al*., 2002).

Suspended Particulate matter

The study shows that PM_{10} emission due to surface mining at the HBB concession area vary from other studies published on mining from other parts of the world. Zhang *et al.* (2005) reported that the PM_{10} content in air samples collected in the Dachang town, South China exceeded the Chinese standard by nearly tenfold, though the place experiences high rainfall (1200 – 1600 mm). These differences in the results could have come from the landscape. Unlike the present study area, Dachang town is surrounded by hills with an altitude between 200 and 500 m which drastically reduces air movement coupled with heavy vehicular traffic (Zhang *et al.,* 2005).

Another study of contrasting interest was by Kaonga and Kgabi (2009) who reported that PM_{10} concentration values in the Marikana Mining Area of Rustenburg, South Africa, in the month of November ranged between 3 – 10 μg/m^3 which were quite low compared to laid down International Air Quality Standards. Such low results could be attributed to the air sampler (Dekati cascade impactor version 2.1) used to collect the dust samples. The sampler samples aerosol particle sizes selectively thereby restricting only particles of size 10 μm to be collected, unlike the dusttrak (used in this research) which collects all dust samples below or equal to 10 μm. Another reason could be due to the high winds and very low temperatures in the Marikana area compared to the HBB concession area.

Possible sources of suspended dust at the HBB concession area could be the mining pits, waste dumps, emissions from the haul roads, excavation, crushing and screening. Others are materials transfer, drilling, vehicle movement on unpaved roads, dust from tailings storage facilities, waste dumps and other stock piles. A total of 241 blasts were carried out at the mine pits during the period of study and this could also have contributed to the high suspended dust in the area. The PM_{10} concentration in the ambient air could not be attributed much to dust storms from regions beyond the HBB project area due to the low wind speed (1.2 km/h). A dust storm could occur at a wind speed equal to or above 24 km/h (Alonso *et al.,* 2002) which never occurred during the period of study. The low wind speed and high temperatures, coupled with decline in rainfall contributed significantly to the exceedances (Stanton *et al.,* 2006), and the results are similar to that reported by Aberkane *et al.* (2004). The simultaneous exceedances in all the four sites in the month of November could have come from the above factors. The number of exceedances at Subriso and Anlokrom respectively did not breach the WHO air quality guidelines and the results are similar to that reported by Grant *et al.* (2005) and Liebenberg *et al.* (2006).

Deposited dust (Inorganic content)

Only inorganic part of deposited dust and not the combustible part could be attributed to mining operations (Standards Australia, 2006). The relatively high mineral content in the collected samples indicate that mining and its related activities contribute significantly to atmospheric dust particles (Liebenberg *et al.,* 2006). Nevertheless the levels of inorganic dust recorded in the HBB concession area were below International Standard of 4 g/m²/month (Standards Australia, 2006) which also agrees with work by Grant *et al.* (2005). The mean annual rainfall for the area is 1500mm which ranges from 1300 to 2000mm. The wet period in the district is between March and July while November to January is relatively dry (Kwamena and Benneh, 1977). Hence the low levels of dust fallout may be due to the site's continuous rainfall and dust suppression (spraying water) on the haul roads by the mining company. Incidences of relatively high dust fallout rates could be attributed to activities near the dust gauge bottles and the unsealed haul roads. Other reasons could be due to the low wind speed and high temperatures (Stanton *et al.,* 2006). An increase in dust fallout was noted for the month of November which was a comparatively drier month. The mining company might have depended on the abundant rains in the preceding months and reduced its dust suppression activities.

Inorganic dust results from the Mpohor Police Station Area deviated from the trend. The place recorded the highest deposited insoluble dust with high organic matter. This indicates that other activities not related to mining also contribute greatly to the dust fallout at the Mpohor Police Station Area. Vehicular movements along the adjacent Mpohor-Benso unsealed road could be a contributory factor for the inorganic deposited dust, while pollens, dead insects, agricultural activities from farmers and domestic activities from the surrounding communities could have also contributed to the organic particles (Aleksandropoulou *et al*., 2011). Yayaho recorded the maximum average inorganic dust, and this could be the result of the busy unsealed haul road that links Benso to Wassa; and the Subriso East pit.

CONCLUSION AND RECOMMENDATION

Over the six-month study period, it can be concluded that surface mining impacts negatively on the air quality within the Huni-Butre and Benso area of the Western Region of Ghana. The levels of suspended dust in some of the communities within the area are above the WHO guidelines limits, while the levels of dust deposition rates in all the studied areas fall far below threshold limits. The increase in ambient air PM_{10} in relation to the surface mining activities represents potential health risk to people in the mining locations especially Yayaho, Subriso and Ningo.

Recommendations

Although Golden Star mine is committed to reducing emissions by employing environmentally clean technologies, this should be reviewed periodically.

- Ambient air quality guidelines and targets should be developed for the mining companies in Ghana, taking into consideration risks to health, technological feasibility, economic considerations, and other political and social factors. The guidelines used in this study could be adopted in the interim.
- Mining companies should implement best practice mitigation measures for known dust generating sources. These should include: Chemical suppressants on permanent haul roads, in addition to water sprays to optimise water utilisation on non-permanent unsealed roads; water sprays at material transfer points; and full or semi-enclosure of crushing and screening operations.
- Dump locations and ROM pads should be sited such that they are out of the prevailing wind direction, so that the prevailing wind will not result in emissions blowing towards farms and residential areas.
- Baseline studies should include air quality impact assessment for future surface mining prospects.
- A permanent continuous on-line PM_{10} sampler should be implemented at Yayaho.

- For future research, it would be advisable that a weather station be placed at each sampling site to capture changes in winds speed and directions that may influence air borne particulate concentrations. In addition, videoing of dust plumes at each location could be a powerful tool for confirming which mine pits or activities are related to PM_{10} concentrations at each site.
- The surfaces of haul roads, in particular those that are frequently used (and near to sensitive areas) should be hard surfaced.
- Speed of vehicles on the haul roads should be restricted around the sensitive receivers to reduce dust emissions.
- A comprehensive quantitative assessment of the state of air quality in the area should be conducted.

Considerations for future studies

A future study worth considering would be to assess the mitigation methods used by the mining companies to determine how effective or ineffective some methods are.

Another further course of study would be to do a comparative analysis of the four directions at each sampling location and to do comparisons between results in line with the prevailing wind direction.

REFERENCES

Aawaar, G. (2006). *The Economic Impact of Mining Sector Investment in Ghana* (Undergraduate Dissertation). Faculty of Social Sciences, Kwame Nkrumah University of Science and Technology, Ghana.

Aberkane, T., Harvey, M. and Webb, M. (2002). Annual air quality monitoring report 2000. *Environment Canterbury Report* U04/58.

Abramson, L.S. (2004). *Health Effects of Particulate Air Pollution*. Houston: Shell Centre for sustainability, Rice University, USA.

Acheampong, E. (2004). *Impact Assessment of Mining Activities by Ashanti Goldfields-Bibiani Limited on the Environment and Socio-Economic Development of Bibiani.* (Undergraduate Dissertation), Faculty of Social Sciences, Kwame Nkrumah University of Science and Technology, Ghana.

Adadey, K. (1997). *The Role of the Mining Industry in the Economy of Ghana*. Accra: ISSER, University of Ghana.

Agyapong W. A., Amanor J. A. and Acheampong E. O. (1992, November). *Selective open pit gold mining at Ashanti Goldfields, Obuasi, Ghana.* Paper presented at the 9th International Geological Conference. Accra: Geological Society of Africa.

Akabzaa, T. (2000). *Boom and Dislocation: Environmental Impacts of Mining in the Wassa West District of Ghana.* Accra: Third World Network Africa.

Akabzaa, T. and Darimani, A. (2001). *Impact of Mining Sector Investment in Ghana: A case study of the Tarkwa Mining Region.* Draft Report for SARPRI. Pp. 1-64.

Aleksandropoulou, V., Torseth, K. and Lazaridis, M. (2011). *Water, Air and Soil Pollution,* 219(1-4): 507-526.

Almbauer, R. A., Oettl, D., Bacher, M. and Sturm, P. J. (2000). Simulation of the air quality during a field study for the city of Graz, *Atmospheric Environment,* 34: 4581-4594.

Alonso, R., Biland, L., Bytnerowicz, A., Chavez, P., Gillette, D. and Johns, B. (2003). *The potential for fugitive dust problems at the Salton Sea.* Salton Sea Science Office Workshop (Panel report). La Quinta, California.

American Gas Foundation (2008). *Literature Review of Indoor Ultrafine Particles and Residential Gas Appliances.* Irvine, California: Wilson Environmental Associates.

Amonoo-Neizer, E. H. and Amekor E. M. K. (1993). Determination of total arsenic in environmental samples from Kumasi and Obuasi, Ghana. *Environmental Health Perspectives*, 101(1): 44–49.

Anderson, F. J. (1991). *Natural Resources in Canada; Economic Theory and Policy*. (2nd ed). Ontario: Nelson.

Armstrong, A. T. (2008). *Gold Strike in the Breadbasket: Indigenous Livelihoods, the World Bank, and Territorial Restructuring in Western Ghana* (Development Report No 18). Oakland, CA: Institute for Food and Development Policy. Pp 1 – 50.

Aryee, B.N.A. (2001). Ghana's Mining Sector: Its contribution to national economy. *Resource Policy*, 27: 1-15.

Atkinson, R.W., Anderson, H.R., Sunyer, J., Ayres, J., Baccini, M., Vonk, J.M., Boumghar, A., Forastiere, F., Forsberg, B., Touloumi, G., Schwartz, J., Katsouyanni, K. and (2001). Acute effects of particulate air pollution on respiratory admissions: Results from APHEA 2 project. Air Pollution and Health: European Approach. *American Journal of Respiratory and Critical Care Medicine*, 154:1860-1866.

Australian EPA (2007). *Protocol for Environmental Management*: *Mining and Extractive Industries.* Australia, Victoria, Publication 1191.

Auty, R.M. (1993). *Sustaining Development in Resource Economies*: *The Resources Curse.* London: Routledge.

Awudi, B. K. (2002). *The Role of Foreign Direct Investment (FDI) in the Mining Sector of Ghana and the Environment.* A Paper Presented at the Conference on Foreign Direct Investment and the Environment, Paris. Accra: Friends of the Earth.

Babut, M., Sekyi, R., Rambaud, A., Potin-Gautier, M., Tellier,S., Bannerman, W. and Beinhoff, C. (2003). Improving the environmental management of small-scale gold mining in Ghana: a case study of Dumasi. *Journal of Cleaner Production*. 11(2): 215-221.

Baker, M. D., Henretig, F. M. and Ludwig, S. (1988). Carboxyhaemoglobin levels in children with nonspecific flu-like symptoms. *Journal of Paediatrics*, 113: 501–504.

Balakrishna, G. and Pervez, S. (2009). Source Apportionment of Atmospheric Dust Fallout in an Urban-Industrial Environment in India. *Aerosol and Air Quality Research*, 9(3): 359-367.

Barning, K. (1992). Mineral Investment Policy in Ghana and its Impact on the Mining Development, *Proceedings of symposium on gold mining in Ghana.* Accra: Minerals Commission.

Baron, P. A. and Willeke, K. (2001). *Aerosol Measurement: Principles, Techniques and Applications*. New York: Van Nostrand Reinhold. Pp 5 -20.

Bauer, S. E. and Koch, D. (2005). Impact of heterogeneous sulphate formation at mineral dust surfaces on aerosol loads and radiative forcing in the Goddard Institute for Space Studies general circulation model. *Journal of Geophysics*, 110: D17202.

Blacksmith Institute (2007). *Blacksmith 2007 Annual Report.* New York: Blacksmith Institute. Pp 3 – 15.

Bockhorn, H. (2000). Ultrafine particles from combustion sources: Approaches to what we want to know. *The Royal Society*, 358: 1775.

Bourke, P., Arthur, J., Marshall,N., MacIntyre,J., Wasel, S. M.and Urbaez, E. (2007). *First time disclosure of mineral reserves: Hwini-Butre and Benso properties southwest Ghana* (Technical report). Denver, Colorado, USA: Golden Star Resources Ltd. Pp 20 -100.

Bridge, G. (2004). Contested terrain: Mining and the Environment. *Annual Reviews of Environmental Resources*, 29:205–59.

Brimblecombe, P. (1996). *Air composition and chemistry* (2nd Ed). Melbourne, Australia: Press Syndicate of Cambridge University Press.

Cakmak, G. D., Schins, R. P., Shi, T., Fenoglio, I., Fubini B. and Borm, P. J. (2004). In vitro genotoxicity assessment of commercial quartz flours in comparison to standard DQ12 quartz. *International Journal of Hygiene and Environmental Health*, 207**:** 105-113.

Campbell, S.W., Evans, M.C., and Poor, N.D. (2002). Predictions of Size-resolved Aerosol Concentrations of Ammonium, Chloride and Nitrate at a Bayside Site Using EQUISOLV II, *Atmospheric Environment*, 36: 4299-4307.

Chakradhar, B. (2004). Fugitive Dust Emissions from Mining Areas. *Journal of Environmental Systems*, 31(3): 279-288.

Chakradhar, B. (2008). Fugitive dust emissions from mining areas. *Journal of Environmental Systems*, (31): 3, 279-3,288.

Chaudhari, P. R. and Gajghate, D. G. (2000). Assessment of air pollution effect on plants – A review. *Indian Journal of Environmental Protection*, 20(12): 925–933.

Chaulya, S. K., Chakraborty, M. K., Ahmad, M., Singh, R. S., Bondyopadhay, C., Mondal, G. C. and Pal, D. (2002). Development of empirical formulae for determination of emission rate from various open pit coal mining operations. *Water, Air and Soil Pollution*, 140: 21–55.

Chaulya, S.K. (2005). Air Quality Status of Open Pit Mining Area in India. *Environmental Monitoring and Assessment*, 105: 369–389.

Coakley, G. J. (1999). The minerals industry of Ghana, Area Reports: International 1997, Africa and the Middle East. Volume III. Pp 3-30.

Colls, J. (1997). *Air Pollution: An Introduction*. New York: Spon press.

Combes, R.S. and Warren, D.A. (2005). Characterizing and Controlling Industrial Dust: A case study in small particle measurement. *Environmental Monitoring and Assessment,* 106: 43-58.

CPCB (2007). *A Draft of Conceptual Guidelines and Common Methodology for Air Quality Monitoring, Emission Inventory and Source Apportionment Studies for Indian Cities*. New Delhi: Central Pollution Control Board.

Crabbe, H., Beaumont, R. and Norton, D. (2000). Assessment of air quality, emissions and management in a local urban environment. *Environmental Monitoring Assessment*, 65(1–2): 435–442.

Cuclis, A. and Fraser, M. (2004). *Particulate Matter: Composition and Sources.* Rice University, Houston,USA. Pp 1-10.

Derwent, R. G.and Malcolm, A. L. (2000, October 15). Photochemical generation of secondary particles in the United Kingdom. *The Royal Society*, 358: 1775.

Dockery, D.W. and Pope, C.A. (1994). Acute Respiratory Effects of Particulate Air Pollution. *Annual Review of Public Health*, 15: 107-132.

Dominici, F., Zanobetti, A., Zeger, S., Schwartz, J. and Samet, J.M. (2004). Hierarchical Bivariate time series models: A combined analysis of the effects of particulate matter on morbidity and mortality. *Biostatistics*, 5(3): 341-360.

Donaldson, K. and Tran, C. L. (2002). Inflammation caused by particles and fibres. *Inhalation Toxicology*. (14): 5-27.

Donaldson, K., Beswick, P.H. and Gilmour, P.S. (1998). Free Radical Activity associated with the Surface of Particles: A Unifying Factor in Determining Biological Activity? *Toxicology Letters*, 88: 293-298.

Donaldson, K., Stone, V., Borm, P.J., Jimenez, L.A., Gilmour, P.S. and Schins R.P. (2003). Oxidative stress and calcium signalling in the adverse effects of environmental particles (PM_{10}). *Free Radical Biology and Medicine*, 1;34(11): 1369-1382.

Donkor, K. (1997). *Structural adjustment and mass poverty in Ghana.* London: Ashgate. Pp 1-20.

Environment Australia (1998). *Best Practice Environmental Management in Mining.* Series 0642194181, Australia: Canberra.

Frampton, M.W. (2001). Systemic and cardiovascular effects of airway injury and inflammation: Ultrafine particle exposure in humans. *Environmental Health Perspective,* 109: 529-532.

Franck, U., Herbarth, O., Wehner, B., Wiedensohler, A. and Manjarrez, M. (2003). How do the indoor size distributions of airborne submicron and ultrafine particles in the absence of significant indoor sources depend on outdoor distributions? *Indoor Air*, 13(2): 174-181.

Franck, U., Tuch, T., Manjarrez, M., Wiedensohler, A. and Herbarth, O. (2006). Indoor and outdoor submicrometer particles: Exposure and epidemiologic relevance ("the 3 indoor Ls"), *Environmental Toxicology*, 21(6): 606 – 613.

Ghose, M. K. (1989). Pollution due to air borne dust particles in coal mining, its monitoring and abatement measures. *Mine technology*, 10(1): 91–95.

Ghose, M. K. and Majee, J. (2000). Assessment of dust generation due to open pit coal mining – an Indian case study. *Environmental Monitoring and Assessment*, 61(2): 255–263.

Grant, U., Hulme, D., Moore, K. and Shepherd, A. (2005). *Chronic poverty report 2004-05*. Manchester, UK: University of Manchester, Institute for Development Policy and Management. Pp 4 – 25.

Gulumian, M., Semano M. and Vallyathan, V. (2005). *Surface activity of silica dusts collected from different mines in South Africa.* IOHA, 19 - 23. Pilanesberg, South Africa.

Guttikunda, S. (2009). Air Quality Management in Delhi, India: Then, Now and Next. Air Quality Management in Delhi, India, *SIM-Air Working Paper Series*, 22:1-8.

Hall, D. J. (1994). Design for a Deposit Gauge and a Flux Gauge for Monitoring Ambient Dust: *Atmospheric Environment*, 28(18): 2963-2979.

Harrison, R. M. and Yin, J. X. (2000). Particulate matter in the atmosphere: Which particle properties are important for its effects on health? *Science and Total Environment*, 249: 85-101.

Heaney, P. J. and Banfield, J. F. (1993). Structure and chemistry of silica, metal oxides, and phosphates, *Reviews in Mineralogy and Geochemistry,* 28: 185.

Heckerling P.S., Leikin J.B., Terzian, C.G. and Maturen, A. (1990). Occult carbon monoxide poisoning in patients with neurologic illness. *Clinical Toxicology*, 28: 29–44.

Hilson, G. M. and Nyame, F. (2006). Gold mining in Ghana's forest reserves: A report on the current debate. *Area*, 38(2): 175-185.

Hind, W. C. (1982). *Aerosol Technology, Properties, Behaviour, and Measurement of Airborne Particles.* New York: Wiley.

Hnizdo, E. (1992). Health risks among white South African gold miners – dust smoking and chronic obstructive pulmonary diseases. *South Africa Medical Journal*, 81(10): 512-517.

Hodzic, A., Bessagnet, B. and Vautard, R. (2006). A model evaluation of coarse-mode nitrate heterogeneous formation on dust particles. *Atmospheric Environment*, 40: 4158–4171.

Honey, L.F. and McQuitty, J.B. (1979). Some physical factors affecting dust concentrations in a pig facility. *Canadian Agricultural Engineering* 21(1): 9-14.

Http://mpohorwassaeast.ghanadistricts.gov.gh

Http://www.ghanadistricts.com.

Hudson, T. L., Fox, F. D. and Plumlee, G. S. (1999). *Metal mining and the environment*. Virginia: American Geological Institute. Pp 5 – 18.

Hughes, J. and Donald (1994). *Pan's Travail: Environmental Problems of the Ancient Greeks and Romans.* Baltimore: John Hopkins University.

Ibald-Mulli, A., Wichmann, H.E., Kreyling, W. and Peters, A. (2002). Epidemiological evidence on health effects of ultrafine particles. *Journal of Aerosol Medicine*, 15(2): 189-201.

Kaonga, B. and Kgabi, N. A. (2009). Atmospheric Particulate Matter in the Marikana Mining Area of Rustenburg, South Africa. *European Journal of Scientific Research*, 34(2): 271-279.

Kissell, F. N. (2003). *Handbook for Dust Control in Mining* (Information Circular/DHHS No. 2003-147), Cincinnati, OH, USA: NIOSH-Publications.

Kwamena, D. B. and Benneh, G (1977). *Ghana Geography*. London: Longman.

Lee, D. and Ferguson, C. (2009). Air pollution and health in Scotland: a multicity study. *Biostatistics*, 10(3): 409-423.

Liebenberg-Enslin, H., Krause, N. and Annegarn, H.J. (2006). *Modelling of wind eroded dust transport in the Erongo Region, Namibia*. Namibian Ministry of mines and energy, Namibia. 1-8pp.

Lomer, M. C. Thompson, R. P. and Powell, J. J. (2002). Fine and ultrafine particles of the diet: influence on the mucosal immune response and association with Crohn's disease. *Proceedings of the Nutrition Society*, 61(1): 123-30.

Medina, R.M., Zanobetti, A. and Schwartz, J. (2006). The Effect of Ozone and PM_{10} on Hospital Admissions for Pneumonia and Chronic Obstructive Pulmonary Disease: A National Multicity Study. *American Journal of Epidemiology*, 163(6): 579-588.

Meenalbal, T. and Akil, K. (2000). Ambient air quality at selected sites in Coimbatore city. *Indian Journal of Environmental Protection,* 20(1): 49–53.

Nanda, S. N. and Tiwary, S. N. (2001). Concentration of SPM in the Burla-Hirakud-Sambalpur region (Orissa). *Indian Journal Environmental Protection,* 21(3): 193–202.

Nelkon, P. and Parker, M. (1982). *Advanced level physics*. (5th ed). London: Heinemann.

Noller, B. N., Bloom, H., and Arnold, A. P. (1981). Sampling and analysis of metals in atmospheric particulates by graphite furnace atomic absorption spectrometry. *Progress in Analytical Atomic Spectroscopy*, 4: 81–189.

Ogola, J. S., Mitullah, W. and Omulo, M. (2002). Impact of Gold mining on the environment and human health: A case study in the Migori Gold Belt , Kenya. *Environmental Geochemistry and Health,* 24**:** 141–158.

Ooki, A. and Uematsu, M. (2005). Chemical interactions between mineral dust particles and acid gases during Asian dust events (2005). *Journal of Geophysical research*, 110(D03201): 13.

Palmgren, F., Wåhlin, P., Kildeso, J., Afshari, A. and Fogh, C. L. (2003). Characterisation of particle emissions from the driving car fleet and the contribution to ambient and indoor particle concentrations. *Physics and Chemistry of the Earth*, 28(2003): 327-334.

Pechacek, N. (2003). *Toxicological review of results of ambient air mobile monitoring* [Technical Report]. El Paso, Mexico: Texas Commission on Environmental Quality, Toxicology Section.

Pohjola, M. A., Rantamäki, M., Kukkonen, J., Karppinen, A. and Berge, E. (2004). Meteorological evaluation of a severe air pollution episode in Helsinki on 27-29 December 1995. *Boreal Environmental Resources*, 9: 75-87.

Pope, C.A. (2000, August). Epidemiology of Fine Particulate Air Pollution and Human Health: Biologic Mechanisms and Who's at Risk. *Environmental Health Perspectives Supplements*, 108(S4): 1-64.

Pope, C.A. and Burnett, R.T. (2002). Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. *Journal of the American Medical Association*, 287: 1132 – 1141.

Reddy, G. S. and Ruj, B. (2003). Ambient air quality status in Raniganj-Asansol area, India. *Environmental Monitoring and Assessment*, 89: 153–163.

Ristovski, Z., Morawska, L., Thomas, S., Hitchins, J., Greenaway, C. and Gilbert, D. (2000). Particle emissions from natural gas engines. *Journal of Aerosol Science*, 31: 403-413.

Sasakawa, M., Ooki, A. and Uematsu, M. (2003). Aerosol size distribution during sea fog and its scavenge process of chemical substances over the northwestern North Pacific. *Journal of Geophysical Research-Atmospheres*, 108 (D3): 4120.

Schwartz, J. (1994). Total suspended particulate matter and daily mortality in Cincinnati. *Environmental Health Perspective*, 102: 186-189.

Seinfeld, J.H. and Pandis, S.N (1998). *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change.* New York: John Wiley and Sons, Inc. Pp 1 – 15.

Sinha, S. and Banerjee, S.P. (1997). Characterisation of haul road in Indian open cast iron ore mine. *Atmospheric Environment.* (31): 2809–2814.

Sioutas, C. Delfino, R J. And Singh, M. (2005). Exposure assessment for atmospheric ultrafine particles (UFPs) and implications in epidemiologic research. *Environmental Health Perspectives*, 113(8): 1-12.

Soni, D. K. and Agarwal, A. (1997). Characterisation of dust emission in coal mining activities – Case study. *Indian Journal of Environmental Protection.* 17(11): 80–814.

Standards Australia (2006). *Methods for sampling and analysis of ambient air – Gravimetric method:* AS/NZ 3580.10.1:2003. Sydney: Wellington.

Stanton, D. W., Belle, B. K., Dekker, K. J. J. and Du Plessis, J.J.L. (2006). *South African Mining Industry Best Practice on the Prevention of Silicosis*. South Africa: Mine Health and Safety council.

Stephens, C. and Ahern, M. (2001). *Worker and Community Health Impacts Related to Mining Operations.* London: International Institute of Environment and Development World Business Council on Sustainable Development. Pp 25 – 50.

Stuckler, D., Basu, S., McKee, M. and Lurie, M. (2011). Mining and risk of tuberculosis in sub-Saharan. *Africa American Journal of Public Health*, 101(3):524-30.

Tillery, B.W., Eldon, D. E, and Ross, F. C. (2001). *Integrated Science.* New York: McGraw-Hill. Pp 500 – 502.

TSI Incorporated (2008). *Dusttrak aerosol monitor theory of operation*. Retrieved 2nd January, 2011 from http//www.tsi.com

Tsikata, F.S. (1997). The Vicissitudes of Mining Policy in Ghana. *Resources Policy*, 23(2): 9-14.

United States Geological Survey (2006). *2004 Minerals Yearbook.* Reston, VA, USA: Geological survey publications. Pp 1 – 20.

United States Geological Survey (2008). *2006 Minerals Yearbook.* U.S. Reston, VA, USA: USGS Geological Survey Publications. Pp 8-15.

USEPA (2004). *Air Quality Criteria for Particulate Matter.* Washington DC, USA: United States Environmental Protection Agency.

USEPA (2007). *National Ambient Air Quality Standards.* Washington, DC: U.S. EPA Office of Air Quality Planning and Standards.

Vallius, M. (2005). *Characteristics and sources of fine particulate matter in urban air.* University of Kuopio, Helsinki, Finland: National Public Health Institute, A6/2005. 79 pages.

Vermeire, P.A. (1997). Higher Asthma Occurrence in an Urban than a Suburban Area: Role of House Dust Mite Skin Allergy. *Euro Respiration Journal*, 10: 1460-1466.

Warner, P. O. (1976). *Analysis of Air Pollution.* New York: Wiley.

Weber-Fahr, M. and van der Veen, P. (2002 , April). Sustainable Development- Not a tough choice but a must for the mining industries. *International Council on Mining and Metals (ICMM) Newsletter*. Pp 1-6.

Weichenthal, S., Dufresne, A., Infante-rivard, C. and Joseph, L. (2007). Indoor ultrafine particle exposures and home heating systems: a cross-sectional survey of Canadian homes during the winter months. *Journal of Exposure Science and Environmental Epidemiology*, 17(3): 288-97.

Wheeler, A. J., Williams, I., Beaumont, R. A. and Manilton, R. S. (2000). Characterisation of particulate matter sampled during a study of children's personal exposure to air borne particulate matter in a UK urban environment. *Environmental Monitoring Assessments,* 65(1–2): 69–77.

WHO (2000). *Air quality guidelines for Europe, (2nd ed).* Copenhagen, World Health Organization Regional Office for Europe, WHO Regional Publications, European Series, No. 91.

WHO (2003). *Health Aspects of Air pollution with Particulate Matter, Ozone and Nitrogen Dioxide.* Report on WHO working group, Bonn, Germany, 13–15 January, 2003. (WHO Regional Publications, European Series No. EUR/03/5042688).

WHO (2005). *WHO air quality guidelines global update 2005*. Report on WHO Working Group meeting. Bonn, Germany: WHO press.

WHO (2006). *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulphur dioxide: Global update 2005, Summary of risk assessment*. Switzerland: WHO press.

WHO (2008). *Air quality and health*. Copenhagen, World Health Organization Regional Office for Europe, (WHO Regional Publications, fact sheet No. 313).

Wilson, A. L. and Karpukhin, (2008). *A. Literature review of indoor ultrafine particles and residential gas appliances*. Irvine, California: Wilson Environmental Associates

Wilson, D. J. and Buffa, J. A. (2000). *College physics.* NJ: Prentice Hall.

Wilson, W. E. and Suh, H. (1997). Fine particles and coarse particles: Concentration relationships relevant to epidemiologic studies. *Journal of Air Waste Management Association,* 47: 1238-1249.

Wolf, E. R. (1982). *Europe and the people without history*. Berkeley: University of California Press. Pp 25 - 30.

Xiong, C. and Friedlander, S. K. (2001). Morphological properties of atmospheric aerosol aggregates. *Proceedings of the National Academy of Sciences*, 98(21):11851–11856.

Yatin, M., Tuncel, S., Aras, N.K., Olmez, I., Aygun, S. and Tuncel, G. (2000). Atmospheric trace elements in Ankara, Turkey: 1. Factors affecting chemical composition of fine particles. *Atmospheric Environment*, 34: 1305-1318.

Yelpaala, K. (2004), *Mining, Sustainable Development and Health in Ghana: The Akwatia Case-Study,* Brown University, Rhode Island, U.S.A.

Zhang, X.Y, Tang, L.S., Zhang, G. and Wu, H.D. (2005). Heavy Metal Contamination in a typical mining town of a minority and mountain area, South China. *Bulletin of Environmental Contamination and Toxicology*, 82: 31–38.

APPENDICES

Appendix 1: Percentiles of PM_{10} concentrations at different locations

	Location	5%	10%	25%	50%	75%
Weighted Average	Yayaho	23.00	23.00	26.75	42.87	60.50
	Subriso	19.00	19.00	24.25	38.28	51.50
	Ningo	12.00	12.00	22.08	40.00	60.00
	Anlokrom	16.00	16.00	35.50	43.74	58.15
	M. Pent. Area	19.00	19.00	23.50	32.00	41.38
	M. Police Station	5.100	5.10	5.25	19.27	33.40

Appendix 2: Descriptive statistics for PM_{10} concentrations at different locations

Location	Descriptive		Statistic	Std. Error
Yayaho	Mean		44.4550	8.12082
	95% confidence interval for mean	Lower Bound	23.5798	
		Upper Bound	65.3302	
	5% Trimmed Mean		44.0056	
	Median		42.8650	
	Variance		395.686	
	Std. Deviation		19.89186	
	Minimum		23.00	
	Maximum		74.00	
	Range		51.00	

Location	Descriptive		Statistic	Std. Error
	Interquartile range		33.75	
	Skewness		.452	.845
	Kurtosis		-1.348	1.741
Subriso	Mean		38.5933	6.66113
	95% Confidence Interval for Mean	Lower Bound	21.4703	
		Upper Bound	55.7163	
	5% Trimmed Mean		38.3815	
	Median		38.2800	
	Variance		266.224	
	Std. Deviation		16.31638	
	Minimum		19.00	
	Maximum		62.00	
	Range		43.00	
	Interquartile Range		27.25	
	Skewness		.276	.845
	Kurtosis		-1.389	1.741
Ningo	Mean		40.5750	8.96608
	95% Confidence Interval for Mean	Lower Bound	17.5270	
		Upper Bound	63.6230	
	5% Trimmed Mean		40.5833	
	Median		40.0000	
	Variance		482.344	

Location	Descriptive		Statistic	Std. Error
	Std. Deviation		21.96233	
	Minimum		12.00	
	Maximum		69.00	
	Range		57.00	
	Interquartile Range		37.91	
	Skewness		.003	.845
	Kurtosis		-1.777	1.741
Anlokrom	Mean		43.6817	6.31615
	95% Confidence Interval for Mean	Lower Bound	27.4455	
		Upper Bound	59.9178	
	5% Trimmed Mean		44.3907	
	Median		43.7450	
	Variance		239.362	
	Std. Deviation		15.47134	
	Minimum		16.00	
	Maximum		58.60	
	Range		42.60	
	Interquartile Range		22.65	
	Skewness		-1.212	.845
	Kurtosis		2.043	1.741
Mpohor Pentecost Area	Mean		32.5833	4.35587
	95% Confidence	Lower Bound	21.3862	

Location	Descriptive		Statistic	Std. Error
	Interval for Mean			
		Upper Bound	43.7805	
	5% Trimmed Mean		32.4537	
	Median		32.0000	
	Variance		113.842	
	Std. Deviation		10.66966	
	Minimum		19.00	
	Maximum		48.50	
	Range		29.50	
	Interquartile Range		17.88	
	Skewness		.321	.845
	Kurtosis		-.643	1.741
Mpohor Police Station	Mean		19.5233	6.13925
	95% Confidence Interval for Mean	Lower Bound	3.7419	
		Upper Bound	35.3048	
	5% Trimmed Mean		19.4370	
	Median		19.2700	
	Variance		226.142	
	Std. Deviation		15.03803	
	Minimum		5.10	
	Maximum		35.50	
	Range		30.40	

Location	Descriptive	Statistic	Std. Error
	Interquartile Range	28.15	
	Skewness	.024	.845
	Kurtosis	-3.210	1.741

Appendix 3: Percentiles of ash content (inorganic dust) at different locations

	Location	5%	10%	25%	50%	75%
Weighted Average	Yayaho	9.4000	9.4000	12.7000	38.0000	72.3500
	Subriso	2.9000	2.9000	9.5000	12.4000	22.2500
	Ningo	2.7000	2.7000	11.2500	28.2000	57.0000
	Anlokrom	8.3000	8.3000	11.0750	13.4500	17.4000
	Mpohor Police Station	7.5000	7.5000	9.9000	23.1500	41.9750
	Mpohor Pentecost Area	6.4000	6.4000	7.5250	10.6000	30.4750

Appendix 4: Descriptive statistics for ash content at different locations

Location	Descriptive		Statistic	Std. Error
Yayaho	Mean		44.2333	14.33296
	95% Confidence Interval for Mean	Lower Bound	7.3893	
		Upper Bound	81.0774	
	5% Trimmed Mean		42.8148	
	Median		38.0000	
	Variance		1232.603	

Location	Descriptive		Statistic	Std. Error
Yayaho	Std. Deviation		35.10844	
	Minimum		9.40	
	Maximum		104.60	
	Range		95.20	
	Interquartile Range		59.65	
	Skewness		1.070	.845
	Kurtosis		.985	1.741
Subriso	Mean		14.1667	3.11840
	95% Confidence Interval for Mean	Lower Bound	6.1506	
		Upper Bound	22.1828	
	5% Trimmed Mean		14.2519	
	Median		12.4000	
	Variance		58.347	
	Std. Deviation		7.63850	
	Minimum		2.90	
	Maximum		23.90	
	Range		21.00	
	Interquartile Range		12.75	
	Skewness		-.075	.845
	Kurtosis		-.414	1.741
Ningo	Mean		33.9000	11.71685
	95% Confidence Interval	Lower Bound	3.7809	

Location	Descriptive		Statistic	Std. Error
	for Mean			
		Upper Bound	64.0191	
	5% Trimmed Mean		33.0000	
	Median		28.2000	
	Variance		823.708	
	Std. Deviation		28.70031	
	Minimum		2.70	
	Maximum		81.30	
	Range		78.60	
	Interquartile Range		45.75	
	Skewness		.859	.845
	Kurtosis		.216	1.741
Anlokrom	Mean		14.1000	1.80610
	95% Confidence Interval for Mean	Lower Bound	9.4573	
		Upper Bound	18.7427	
	5% Trimmed Mean		14.0222	
	Median		13.4500	
	Variance		19.572	
	Std. Deviation		4.42403	
	Minimum		8.30	
	Maximum		21.30	
	Range		13.00	

Location	Descriptive		Statistic	Std. Error
	Interquartile Range		6.33	
	Skewness		.590	.845
	Kurtosis		.818	1.741
Mpohor Police Station	Mean		28.1667	9.68723
	95% Confidence Interval for Mean	Lower Bound	3.2648	
		Upper Bound	53.0685	
	5% Trimmed Mean		26.8352	
	Median		23.1500	
	Variance		563.055	
	Std. Deviation		23.72877	
	Minimum		7.50	
	Maximum		72.80	
	Range		65.30	
	Interquartile Range		32.08	
	Skewness		1.664	.845
	Kurtosis		3.134	1.741
Mpohor Pentecost Area	Mean		19.7667	8.99376
	95% Confidence Interval for Mean	Lower Bound	-3.3525	

Location	Descriptive		Statistic	Std. Error
		Upper Bound	42.8859	
	5% Trimmed Mean		18.0685	
	Median		10.6000	
	Variance		485.327	
	Std. Deviation		22.03013	
	Minimum		6.40	
	Maximum		63.70	
	Range		57.30	
	Interquartile Range		22.95	
	Skewness		2.215	.845
	Kurtosis		5.031	1.741