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Original Research Paper

Mine water and the environment: a case study at Central African Gold Bibiani Limited, Ghana

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The quantity and quality of input and output water at the various stages of mining is of critical importance in monitoring the dynamics of mine water. This study was undertaken to assess the quantity and physic-chemical quality of water sources for ore processing, the process water pond and surface waters in the Central African Gold (CAG) Mine concession area. Water samples were analysed for levels of some physic-chemical parameters: pH, conductivity, total dissolved solids, iron, arsenic and cyanide. Results indicate that the main sources of water to the processing plant were the decant water (55.10%) and thickener overflow (34.55%). There was a general decline in water quality in this study as compared to the baseline study and most importantly deviated from levels prescribed by the Ghana EPA standard and the WHO guideline for both effluent discharge into the environment and drinking water, calling for measures to ward off any possible human and environmental health problems.

Keywords: Central African Gold, water, quantity, quality, pollution, Ghana EPA, WHO.

INTRODUCTION

The importance of extracted mineral to socio-economic development cannot be under- reckoned. It provides important incomes to nations, improved services and increase employment in local communities. In fact it is a critical factor that serves as an element of the foundation of resource utilization. This important attribute is likely to be unending if best resource management practices for environmental sustainability are adhered to by society. If the relationship between mining and the environment is directed towards sustainability through adoption of best management practices, the full benefit of mining can be realized.

Mining operations use water for mineral processing and metal recovery, dust control and supply of water needs of workers on site (Lottermoser, 2012). Groundwater, surface water and rainwater have been used as sources of water for mining. Metallurgical plants employ processing methods that may be categorized into flotation, gravitational, washing, magnetic separation, crushing and sorting, carbon-In- leach (CIL), Carbon-In-Pulp (CIP), heap leach etc each of which uses water. Although a large mining operation may use a

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considerable amount of water, the minerals industry consumes a relatively small quantity of water at national and global levels (Rankin, 2011). Environment Canada (2004) observed that in 2005, mining accounted a 4% of consumed water while coal and nuclear electric power generation consumed and 60% and manufacturing, municipal water supplies and agriculture consumed 18.5%, 9.5% and 8% respectively.

The amount of water required by a mine varies depending on its size, the mineral being extracted, and the extraction process used. For instance, metal mines that chemically process ore to concentrate minerals such as copper and gold use much more water than non-metal mines such as coal, salt, or gravel mines (Environment Canada, 2012). According to Lottermoser (2012), mine waste may be inert or benign, and therefore unlikely to cause water contamination or pollution. A typical instance of this observation is the Shibdon Pond in England from which abandoned coal mine drainage has supported the development of a wetland. This notwithstanding, mining may pollute water in mining environment due to the chemicals used for mining. Water pollution by mining poses serious threat to the health of the local communities (e. g. reproduction disorders and mortality) as well as the environment near and some extended ones. Biodiversity may also be decreased by pollution due to mining.

In the mining environment, pollution may occur from entry of mine water, mining water, mill water, process water, leachate, effluent and mine drainage water. The contaminants include heavy metals, cyanide, phosphate, carbonates, sulphides, sulphates, arsenic and its complexes, nitrogen and its compounds (Economopoulos, 1993). During underground operations, groundwater causes flooding of pits. The solution to this problem has usually been pumping the water out for storage above ground. Rivers have been dammed to ensure availability of water.

In response to environmental concerns and government regulations, the mining industry worldwide increasingly monitors water discharged from mine sites. A number of innovative water conservation practices are being developed and implemented to reduce water use. Although regulated mines have greatly improved their environmental performance, there still exist potential health and environmental threat. The use of liquid mercury, for example in informal or artisanal mining continues to pose a serious threat to water quality in some areas of the world. Monitoring environmental violations and enforcing the rules that combat those violations has been difficult due to a lack of resources and the widely scattered and inaccessible nature of Artisanal mining (McMahon, *et al*., 1999).

In its operations, the Central African Gold (CAG) Bibiani Mine uses four water sources for ore processing namely thickener overflow, levees, mine dewatering and decant water all of which converge in a pond, the Process Water Pond (PWP) which may serve as make-up or recycling pond. Typically, all the mine water in metal mines is collected and stored in tailings before being treated and released to surface water if necessary. The physicochemical and biological qualities of water sources for ore processing as well as the process water pond and surface waters in the mine concession which are of human and environmental concern are not known.

METHODOLOGY

Study area

The study was carried out in the concession of Central African Gold (CAG) at Bibiani in the Western Region of Ghana. CAG operates an open pit, underground mine and tailing reclamation using conventional CIL method for the treatment of the ore is the study area. The concession area falls within the wet semi-equatorial climatic zone of Ghana. Its area of CAG is approximately 55.7 km^2 (21.5 square miles) and closely enjoined with the town of Bibiani in the Western Region of Ghana. The area is characterised by an annual double maxima rainfall pattern occurring from March and reaches one peak in May to July. The mean rainfall for the months May, June and July are 199mm, 191mm and 135mm respectively. It decreases rapidly in August and increases to the second peak in October. This trend could also be noticed in the general flow balances for each year. The monthly mean rainfall in October was 201mm. About 72 to 87% of the total rainfall occurs in seven months from March to July, September and October. The mean annual rainfall of Bibiani ranges from 1,274mm to 1,473mm. The wet semi-equatorial climatic type is determined by the movement of the Inter-Tropical Convergence Zone (ITCZ). This zone oscillates annually about the equator attracting air masses from both the north and south. The northern air masses locally called "Harmattan" originating from the sub-tropical Azores anticyclones and its extension over the Sahara Desert brings hot and dry weather. However, the southern air masses, known as the "Monsoon", originating from the sub-tropical anticyclones in the South Atlantic, brings cool and moist weather and essentially dictates the weather in the area (Ghana Meteorological Services, 2008). Among the study stations are in the concession are the rivers Mpokwampa, Mensin, Kyirayaa and Pamunu and the process water pond.

The Mensin River (SW4) is the principal river draining the CAG concession. It receives flow contributions from

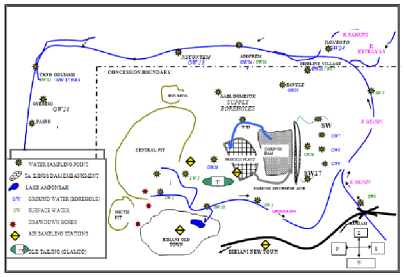

Figure 1 A schematic diagram sampling sites in CAG's for s water quality analyses.

Plate 1 A section of the Kyirayaa River

Plate 2 A section of the Pamunu River

Plate 3 A stagnant section of River Mpokwampa

Plate 4 A stagnant section of the Mensin River

the Mpokwampa River (SW3). The Mensin stream drains into the Kyirayaa which empties into the Pamunu River. The Pamunu enters the Tano River downstream from the Aboferem village and upstream from Tanodumase which then flows into the Atlantic Ocean (CAG's EIS, 1997).

Determination of outflow from Process Water Pond

The outflows from the PWP were estimated by adding the inflows from the sources of water namely; Mine dewatering, Levees, decant water and thickener.

Sampling

Water samples for this study were specifically taken from the rivers Mpokwampa, Mensin, Kyirayaa, Pamunu and Tano, rivers which were considered in CAG's Environmental Impact Statement, and some processing plant units. Replicate composite samples were taken from the rivers Mpokwampa, Mensin, Kyirayaa, Pamunu (Plates 1, 2, 3 and 4) and Tano, some stagnant waters (Levees 2 and 4) in old mine pits as well as from processing plant consisting of process water entering the mill, mill discharge hopper, thickener overflow, Carbon-In-leach (CIL) feed, CIL Tank 01 and tailing discharge onto the tailings dam. Compliance water quality monitoring sites made up of Raw Water Pond, Decant Water and water from the Seepage Collection Sump were also sampled. One litre of water samples were taken from each sampling site, split into two 500 ml portions and stored in plastic bottles covered with black polyethylene material for total iron (Fe) and Arsenic (As) determination and white polyethylene material for free cyanide determination.

Samples for cyanide analyses was preserved by adding two pellets of NaOH and each sample for Fe and As analyses preserved by adding 0.5 ml of concentrated HNO_3 immediately after sampling. The pH of each sample was measured *in-situ* using a Palintest Micro 500 pH meter. Conductivity, Temperature and TDS of each sampling point was measured using a HACH Sension5 2100P colorimeter.

Determination of iron concentration in water sample

The atomic emission spectroscopy was used to analyze concentration of iron in the samples. The solution was filtered into a volumetric flask and subjected to acetylene flame aspiration in air. The percentage iron content was calculated from the formula:

Table 1. Contribution of sources to the PWP in the period 2004 – 2007

Source	2004	%	2005	%	2006	%	2007	%	Average %
TO (m^3)	187243.0	3.61%	2837842.0	43.96%	2614631.0	44.04%	2411325.0	46.62%	34.56%
LV (m^3)	25670.8	0.50%	684246.0	10.60%	884340.0	14.89%	11766.0	0.23%	6.55%
DW8 (m^3)	562198.4	10.84%	94494.0	1.46%	100503.0	1.69%	60266.0	1.16%	3.79%
TDI (m^3)	4410852.0	85.05%	2839290.0	43.98%	2338100.0	39.38%	2689370.0	51.99%	55.10%
Total (m^3)	**5185964.2**	**100.0**	**2839290.0**		**5937574.0**		**5172727.0**	**100.0**	**100.0**

$$\%Fe = \frac{\text{sample absorbance}}{\text{standard absorbance}} \times \frac{\text{volume of solution} \times \text{dilution factor} \times \text{standard conc.}}{\text{weight of sample} \times 10^6} \times 100$$

Determination of arsenic concentration in water sample

The compound arsine (AsH_3) was generated from the water sample through a reaction of arsenic and sodium borohydride. It was then passed through a lead acetate-laden chamber and a solution of pyridine and silver diethyldithiocarbamate which led to the formation of a red coloured complex compound. This was then subjected to photometric analysis

Determination of cyanide concentration in water sample

In determining the concentration of cyanide in water samples, 25 ml of the sample was pipette into a conical flask and 2 to 3 drops of indicator added. The necessary dilution was performed in cases of higher concentration. It was then titrated against a standard solution of a Silver Nitrate (0.025N $AgNO_3$) and the titre recorded. The concentration of NaCN in mol/dm³ was obtained from titre value × 0.0005 mol/dm³ and results converted to ppm as:

$$\frac{\text{titre value} \times 0.0005}{\text{volume used}}$$

RESULTS AND DISCUSSION

Process Water Pond (PWP)

The sources of water for the process water pond were the thickener overflow (TO), levees (LV), mine dewatering (DW8) and decant water (TD1). The average percentage contributions of each source of water to PWP were in the following manner: TD1 supplied about 55.10% of the total water for the processing plant due to the zero effluent discharge system used by the CAG, followed by TO (34.56%). LV (6.55%) and DW8 (3.79%) (Table 1).

This observation may be explained by the direct entry of the thickener overflow into the processing pond The only exception is the situation where there is de-siltation of the processing pond in which case, this is directed onto the tailings dam. Levees Water, considered as emergency water supply to the processing plant contributes 6.55% of the total amount of water. DW8 contributes the lowest amount of water, that is, 3.79%. This may be due to the fact that the source of this water was disused pits which were to ease operations and also to avoid destruction of equipment especially in the underground pit.

Water consumption for tailings reclamation treatment was higher that Underground/Pit Ore treatment for the same amount of plant throughput. In tailings reclamation, water used was for washing of the tailings and processing, thereby increasing the water consumption. Old tailings reclamation started in 2005 to augment the underground/pit ore, so in 2004 there was no Old Tailings reclamation. These may explain why in 2004, although Plant throughput was the highest (2.48×10^6 tonnes/year), the water consumption was not the (5.19×10^6 m³/year).

Water Quality in the PWP

Water Quality in the Process Water Pump PWP (Physical and Chemical)

pH

pH is a critical operational water quality parameter. The pH (7.7-8.5) recorded in this study for PWP (Figure 2) could be described as slightly alkaline and was within the Ghana EPA standards (6 – 9) for effluent discharge into the environment and the WHO guideline value (6.5 - 9.5) for drinking-water. pH of most raw water sources lies within the range of 6.5 - 8.5 (DWAF, 1996d). The recorded pH in the study suggests that water from the PWP was safe to human health and did not exert any negative effect on human and the environment.

The extent, duration and timing of the changes are factors that govern the significance of pH changes to aquatic biota. Adverse effects of pH result from

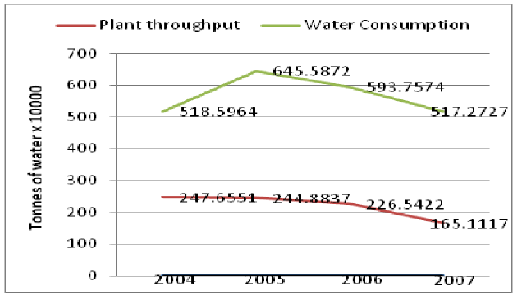

Figure 2. Annual plant water throughput compared with consumption for 2004-2007

Table 2. Levels of water quality parameters measure in the PWP

Destination	As (mg/l)	Fe (mg/l)	CN (mg/l)	(pH)	Conduct. (µS/cm)	Temp. (ºC)	TDS (mg/l)
Mine Dewatering (DW8)	1.94	0.37	N/A	7.3	3400	30.5	1565
Raw water pond (RWP)	4.02	0.23	<0.03	8.4	2850	33.5	1226
Levees 2 (LV2)	1.94	0.48	<0.03	7.9	2950	32.6	1291
Levees 4 (LV4)	3.33	1.36	<0.03	8.3	2350	32.1	1033
Process water pond (PWP)	4.02	23.83	0.13	8.5	4430	30.6	2060
Mill discharge water (P1)	2.22	24.29	0.07	8.2	4190	30	1966
Tank 1 (P4)	9.58	33.6	250	10.9	7610	32.2	3500
Tailings discharge (TD)	2.08	560.72	95	9.8	5750	32.3	2620
Decant water (TD1)	5.27	5.5	<0.03	8.6	4530	31.4	2080
Mpokwampa River (SW3)	0.83	0.47	<0.03	7.0	3990	30	1868
Mensin River	0.97	21.96	<0.03	6.3	411	27.7	187.7
SW3+SW4	1.52	1.22	<0.03	7.0	1056	30.3	467
SW5+Kyirayaa	1.8	1.15	<0.03	7.5	1275	29.3	581
SW7+Pamunu	1.11	1.05	<0.03	7.2	649	28.8	292
Thickener overflow	N/A	N/A	N/A	8.0	4310	32	1949

solubilization of toxic heavy metals and protonation or de-protonation of other ions. Acidification is normally the result of different types of pollution, namely: low-pH point-source effluents from industries, nearly always acid, leading to the pH of receiving streams dropping to below 2; and acid precipitation resulting largely from atmospheric pollution (DWAF, 2006). At pH 6.5 - 8.0 there is likely to be strongly influences on corrosion and scaling processes which may cause considerable damage to industrial equipment and structures (Kim *et. al.,* 2011). Industrial processes usually function optimally in well-defined pH ranges, with most having an optimum working range around neutral point (pH 7).

The pH of the surface waters ranged from 6.3 (in SW4) to 7.5 (in SW7) (Table 2). This signified that SW4 was slightly acidic. A comparison of the pH recorded in this study and the baseline levels indicate relatively increasing acidity in SW3, SW4 and SW5 while SW7 and SW10 indicated increased alkalinity (Figure 3). For surface water,. The relative proportions of the major ions, and in consequence the pH, of natural waters, may be determined by geological and atmospheric influences. Elevated pH values can be caused by increased biological activity in eutrophic systems. The pH may also affect the availability and toxicity of constituents such as trace metals, non-metallic ions, and essential elements. Small changes in pH often cause large changes in the concentration of available metallic complexes and can lead to significant increases in the availability and toxicity of most metals (DWAF, 2006).

Total Dissolved Solids (TDS)

The level of total dissolved solids in the PWP was 2060 mg/l (Table 2). This was above the 1000 mg/l prescribed by both the WHO recommended guideline value and Ghana EPA for drinking water. It was also higher than the baseline value (Figure 4). Higher TDS levels cause changes in ecosystem structure and function. TDS less than 600 mg/l is generally described as good but at levels greater than 1200 mg/l it is not (McCutheon *et al.* 1993). Water in the PWP may therefore be detrimental to the health of the environment.

Although the highest TDS level was recorded in SW3 and was above the limits for drinking water by Ghana

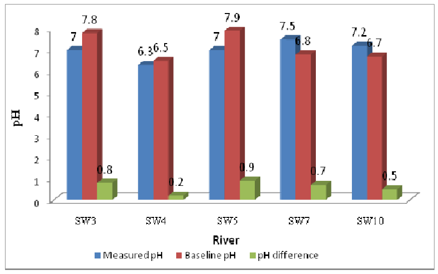

Figure 3 Measured and Baseline pH compared

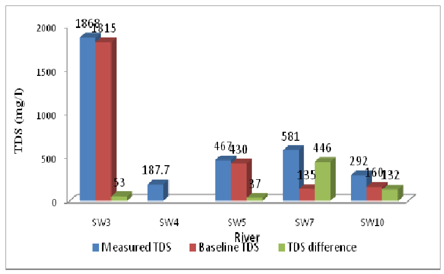

Figure 4 Measured and Baseline TDS concentrations compared

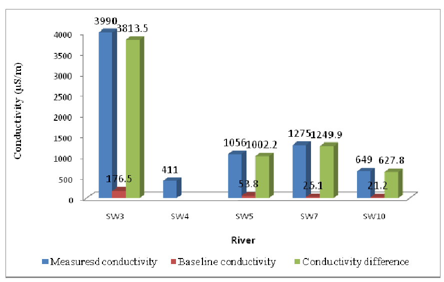

Figure 5 Measured and Baseline conductivities compared

EPA and WHO, the levels of TDS in each of the water bodies increased, with the highest incremental change occurring in SW7. The high level of TDS in SW3 i.e. 1868mg/l may be attributed to a spring source which originated from past mining activities and contained storm water stored over the years and underground water that flowed through dewatering pits of the old underground mine structure. Natural waters contain varying quantities of TDS as a consequence of the dissolution of minerals in rocks, soils and decomposing plant material. Increases in total suspended solids may also result from anthropogenic sources, including, discharges from mining operations. Mining activities including removal of vegetation and discharge mine waste could explain the TDS levels recorded.

Conductivity

The conductivity of the PWP (4430 µS/cm) was highest (Table 2) and exceeded the Ghana EPA limit for effluent discharge (750 µS/cm) and drinking water (1500 µS/cm). In the rivers, electrical conductivity ranged from 411µS/cm (SW4) to a maximum of 3990 µS/cm (SW3) with the latter recording the highest incremental change (3813.5 µS/cm) (Figure 5).

Higher values were recorded in this study than in the baseline study for the rivers (figure 5). Although effluents from the plant were treated before discharged into the rivers, the treatment processes might not be effective. This may explain the observed higher TDS levels in this study than the baseline values. However, with the exception of SW3 which recorded conductivity value (3990 µS/m) exceeding the limit of Ghana EPA standard (1500µS/m) for drinking water, the levels in the rivers were within the acceptable limit suggesting no health threats. Disposal of mine drainage effluent into surface water or ground-water can cause serious impacts on water quality for all uses. Increased mineral salts, which cause increase in salinity, in rivers may arise from

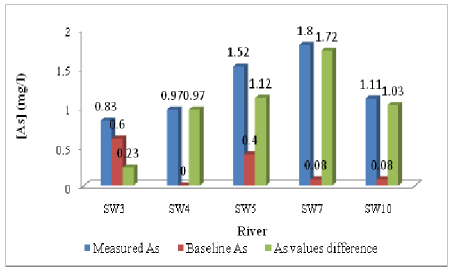

Figure 6 Measured and Baseline Arsenic concentrations compared

several sources including release of mining (Chapman, 1996).

Total Arsenic

A concentration of 4.02 mg/l, higher than the Ghana EPA standards for effluent discharge (1mg/l) was recorded in the waters of the PWP (table 2) and also higher than the baseline value (Figure 6). The high levels of As in the process water can have adverse effect on cyanidation in Carbon-In-leach unit of the processing plant. Karimi *et. al.,* (2010) stated that base metals including arsenic and antimony, consume cyanide during cyanidation of ores. Exposure of As, a chemicals of great health concern in some natural waters may occur through occupation, food ad drinks prepared with As contaminated drinking water (MANCE, 1987). ADWG (1996) that notes soluble arsenic salts are readily absorbed by the gastro-intestinal tract. After absorption inorganic arsenic binds to haemoglobin, and is deposited in the liver, kidney, lungs, spleen, and skin According to the USEPA (2002) arsenic I classified as "very toxic and relatively accessible" to aquatic organisms.

The concentration of arsenics in all the rivers; Kyirayaa (1.8 mg/l), Pamunu (1.11 mg/l) Mensin (0.97 mg/l) and mg/l), Mpokwamp (0.83 mg/l) were also higher than the Ghana EPA standards for Ghana EPA standard of 0.05 and an Interim guideline maximum by the WHO guideline value of 0.01 mg/l WHO (2003). and 0.005 mg/l for freshwater aquatic life and none for recreation and aesthetics. Consumption of these by human and aquatic organisms may result in health disorders. Also they were not aesthetically polluted. The high level of arsenic may be due to treatment of tailings reclamation. Sludge from the former water treatment plant (which contained base metals and others minerals) were dumped on the tailings which was under reclaimation. The high values recorded in the rivers indicate unwholesomeness for consumption.

Iron

The total iron concentration in the PWP water was 23.83mg/l (table 2) a value above the Ghana EPA standards 10mg/l for effluent discharge. River water samples had generally higher Fe concentrations with the highest (21.96 mg/l) recorded from SW4 flowing along the southern to the eastern part of the concession and presently acted as a receptacle for all waste flows from the Bibiani Township as well as mining effluents from the old mine (CAG's EIS, 1997). Comparison of concentrations of Fe values recorded in the studied rivers with the Ghana EPA standard and WHO guideline value for drinking water (0.3mg/l) implied a possibility of health threat. The high levels of As may be due to same reason as the high level of As. The un-palatability of such water would probably prevent consumption (DWAF, 1996). Also the Water Stewardship Division (2008) asserted that the maximum concentration should not exceed 1.0 mg/L total iron and 0.35 mg/L dissolved iron to protect freshwater aquatic life from adverse effects of iron. Iron has frequently been used as an indication of natural changes in the trace metal carrying capacity of sediments (Rule, 1986). The results as indicated by this study may point to unfavourable habitat conditions for other sediment-dwelling organisms including benthic invertebrates.

Total cyanide

In this study, 0.13mg/l of cyanide recorded in the PWP water (Table 2). This was higher than the recommended maximum concentration in drinking but was lower than the recommended concentration (1mg/l) by the Ghana EPA standards for both drinking water and effluent discharge. Cyanide is a common reagent in gold extraction processes and large quantities of cyanide are found in gold mine tailing dams. According to DWAF (2006), most of the cyanide in water is in the hydrocyanic acid form which is largely un-dissociated at pH values of 8 or less and that hydrocyanic acid (HCN) is the most toxic form of cyanide reacts with water to release cyanide ions. Given the pH recorded in this study and the high concentration of iron and Arsenic the implication is that, escalated cyanide toxicity in the rivers may be imminent. Also cyanide in the environment is usually found complexed with metals. Sub-lethal concentrations of cyanide, in the presence of other contaminants, may elicit antagonistic, additive or synergistic effects. For example zinc and cadmium cyanide complexes are more toxic than either of the metals alone.

CONCLUSION

The outflows from the PWP consisted of mine dewatering, Levees, decant water and thickener. The main sources of water to the processing plant were the decant water (55.10%) and thickener overflow operating at the zero effluent discharge and thickener overflow (34.56%). Greater amount of water was consumed for reclamation treatment than that for underground/pit ore treatment. Slightly alkaline conditions (pH 8.5) existed in the PWP but did not constitute alkalinity hazard with reference to the Ghana EPA standard and the WHO guideline values. Water from the PWP was comparatively acidic than that recorded in the baseline study. Generally higher levels of conductivity, total dissolved solids, iron, cyanide and arsenic than the Ghana EPA standard and the WHO guideline values for both effluent discharge into the environment and drinking water were recorded in the study. This therefore suggests that the water in the PWP and the rivers appear to be of poor quality in terms of limits set by the Ghana EPA standard and the WHO guideline values and the baseline data and could therefore pose threat to human and the environment.

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