

# Assessing the Impact of an Operating Tailings Storage Facility on Catchment Surface and Groundwater Quality in the Ellembele District of the Western Region of Ghana

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## Abstract

The study assessed the impact of an operating Tailings Storage Facility (TSF) of Adamus Resources Limited (Nzema Gold Mine) in the Ellembele District of the Western of Ghana on catchment surface and groundwater quality. Water samples were collected between June and December 2014 from seventeen (17) sampling sites including the TSF decant water (TSF-DW), three (3) streams, a water storage dam, a pond and eleven (11) groundwater monitoring boreholes within 500 m radius of the mine's Tailings Storage Facility. Samples were analyzed for pH, true colour, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), biological oxygen demand (BOD), dissolved metals (arsenic, cadmium, copper, mercury) and cyanide (weak acid dissociable cyanide (WAD), free cyanide and total cyanide) using standard procedures. The TSF-DW reported elevated arsenic, free cyanide and TSS concentrations above GHEPA guideline for effluent discharge. Elevated TSS and arsenic concentrations above GHEPA limits were reported in PWSD which is a pond uphill of the TSF and a receptor to effluents from illegal mining sites on the mine's concession. All other parameters recorded in surface and groundwater bodies studied were within WHO guideline limit for potable water. Results of the study suggest that the quality of surface and groundwater around the TSF has not been adversely affected even though the TSF is contaminated. Study findings suggest that well-engineered tailings dam of ARL with its effective liner and management systems may have provided a safe structure and prevented contamination of water resources within its catchment.

## 1. Introduction

Mining plays a key role in the socio-economic development of many countries and Ghana is a good example. Hinton, Veiga & Beinhoff (2003) outlined positive aspects of mining including creation of employment, contribution to government revenue, foreign currency earnings and increase of Gross Domestic Product (GDP). Mining operations generally produce many types of waste including tailings and waste rocks, many of which are dumped or contained in facilities near extraction or processing sites. Wastes generated from such mining operations are of grave concern to stakeholders such as mining companies, governments and communities owing to their potential detrimental impacts on water resources and the environment in general. Many mining operations also utilize large volumes of water for mineral processing, controlling dust, and meeting the diverse needs of workers on site (Acheampong, Adiyiah, & Ansa, 2013).

Mine tailings, which are solid-liquid slurry materials made up of fine-grained waste particles remaining after ore treatment (e.g., milling, flotation, separation, leaching), are often stored in a Tailings Storage Facility (TSF) and managed to optimize the amount of tailings stored as well as reduce potential adverse environmental impacts. According to Liu et al. (2008), the components of mine tailings depend to a large extent on the chemicals and the method used in the mineral extraction, as well as the geology of the mined ore been processed. Tailings from mineral processing, in particular, serve as a main source of contamination of catchment surface and groundwater resources (Roussel, Néel, & Bril, 2000). The liquid component of tailings is made up of water and chemicals used in ore processing. Contents of TSFs could therefore be highly contaminated and are therefore not discharged directly into the environment in conformity with international best practice for mining industries. It is therefore imperative to properly manage tailings as they constitute a major source of release of many trace elements and other contaminants into the environment (Armah et al., 2010).

For gold bearing ore, a greater part of ore processed ends up as tailings or process waste that must be discarded (Paull, Banks, Ballard, & Gillieson, 2006). After mineral concentrate has been separated from ore, the unrecoverable and uneconomic metals, minerals, chemicals, organics and process water are sent via a pipeline as slurry to a secured storage facility or dam at the mine site (Tailings Storage Facility or TSF or Tailings Management Facility or TMF) (Vick, 1990). Tailings usually include metal precipitates resulting from neutralization sludges or residues from pressure leaching processes. Such materials may exhibit long-term chemical stability concerns and need to be disposed in secure, lined facilities. A TSF or TMF is a large area usually located in a natural hollow or valley.

Tailings storage facilities are important and indispensable components in the mining and processing of minerals. Depending on methods used in construction, geology of mine sites, climate, nature of ore mined and/or treated, and overall management, tailings storage facilities may exact variable impacts on the immediate surrounding environment. According to Vick (1990), seepage of some process water from Tailings Storage Facilities may be inevitable irrespective of the facility's engineering design. Azcue, Mudroch, Rosa, & Hall (1994) also suggest that problems arise where excess seepage of process waste from the TSF impacts on the environment.

In Ghana, the mining industry contributes 40% of gross foreign exchange earnings and directly employs about 18,000 people, most of whom are Ghanaians (Hilson, 2005). The sector also contributes to development through implementation of Corporate Social Responsibility (CSR) programmes for host communities and the general public at large.

Because of the important role mining plays in the economy of Ghana, the government and regulatory agencies such as the Environmental Protection Agency (EPA) and Minerals Commission closely monitor the activities of mining companies to ensure the country maximizes the benefits and minimize risks or negative impacts including pollution of the environment that may result from mining operations.

Many large-scale mining companies in Ghana, such as Adamus Resources Limited located in the Ellembele district of Ghana, often operate in areas also inhabited by local communities within the catchment areas of the mine. Communities such as Tarkwa, Nsuta, Teberebie, Teleku-Bokazo and New Abirem are, for example, also located in the proximities of mining operations.

Groundwater contamination is of grave concern where it feeds surface streams or lakes, and where the groundwater is a source of drinking water and other domestic uses by people living close to a mine (Smedley, Edmunds, & Pelig-Ba, 1996).

Adamus Resources Limited which is a subsidiary of Endeavour Mining of Canada, operates a surface gold mine in the Ellembele District in the Western Region of Ghana. The company has a Tailings Storage Facility (TSF) which receives effluents from processing of sulphide (mainly arsenopyrite-rich) ore. The mine and its TSF are located in an area that is also inhabited by local communities that depend on surface and groundwater resources in the proximity of the mining and ore processing activities.

Several studies have reported high metal concentrations in water, soil, food and biological tissues around settlements close to tailings dams in Obuasi, Prestea and Tarkwa townships of Ghana (Smedley et al. (1996); Ahmad & Carboo (2000); Akabzaa, Banoeng-Yakubu, & Seyire (2005). However, studies on the impact of TSF on catchment water bodies are unavailable in the Ellembele District of Ghana, as mining operations have only recently started in the area. In addition, communities close to Adamus Resources Limited (ARL) which is the first large scale mining firm to operate in the area depend largely on surface and groundwater for drinking, subsistence agriculture and other domestic uses. This study therefore assessed the quality of surface and groundwater resources in the proximity of ARL's tailings facility to determine whether, after four years of active mining and ore processing, there are perceptible impacts on the surface and underground water resources.

## **2. Study Area**

The Nzema Gold Mine is located in the Ellembele district of the Western Region of Ghana and is approximately 280 km west of the capital, Accra, and less than 20 km from the coast at Essiama. The mine is accessed from Accra via the main coast highway to Takoradi and from there by sealed road (77.6 km) to the village of Teleku- Bokazo and then by 10 km of untarred road. The current project setting consists of the following concessions; Salman, Akanko and Ebi-Teleku-Bokazo, which covers a total area of 92.3 sq. km (9,230 ha). The mine footprint is estimated to disturb an area totaling approximately 0.4 % of the total land take. The project falls within the Nzema East and Jomoro Traditional Areas and is situated in the Wet Evergreen Forest Zone with an average annual rainfall of about 2000 mm (Knight Piesold, 2007). The project lays within three major drainage systems namely the

Ankobra River to the east, the Amansuri lagoon to the west and the Biare catchment that flows to the south into the Atlantic Ocean.

The site is largely transformed as a result of extensive human induced degradation. The main land uses include subsistence and cash crop farming, logging and illegal artisanal mining. There are six distinct communities within the Project area, namely Teleku-Bokazo, Anwia, New Aluku, Salman, Akanko and Duale (Ichino & Nathan, 2013). Additionally, a number of smaller satellite communities also exist within the project catchment area. The location of the study area is shown in Figure 1.

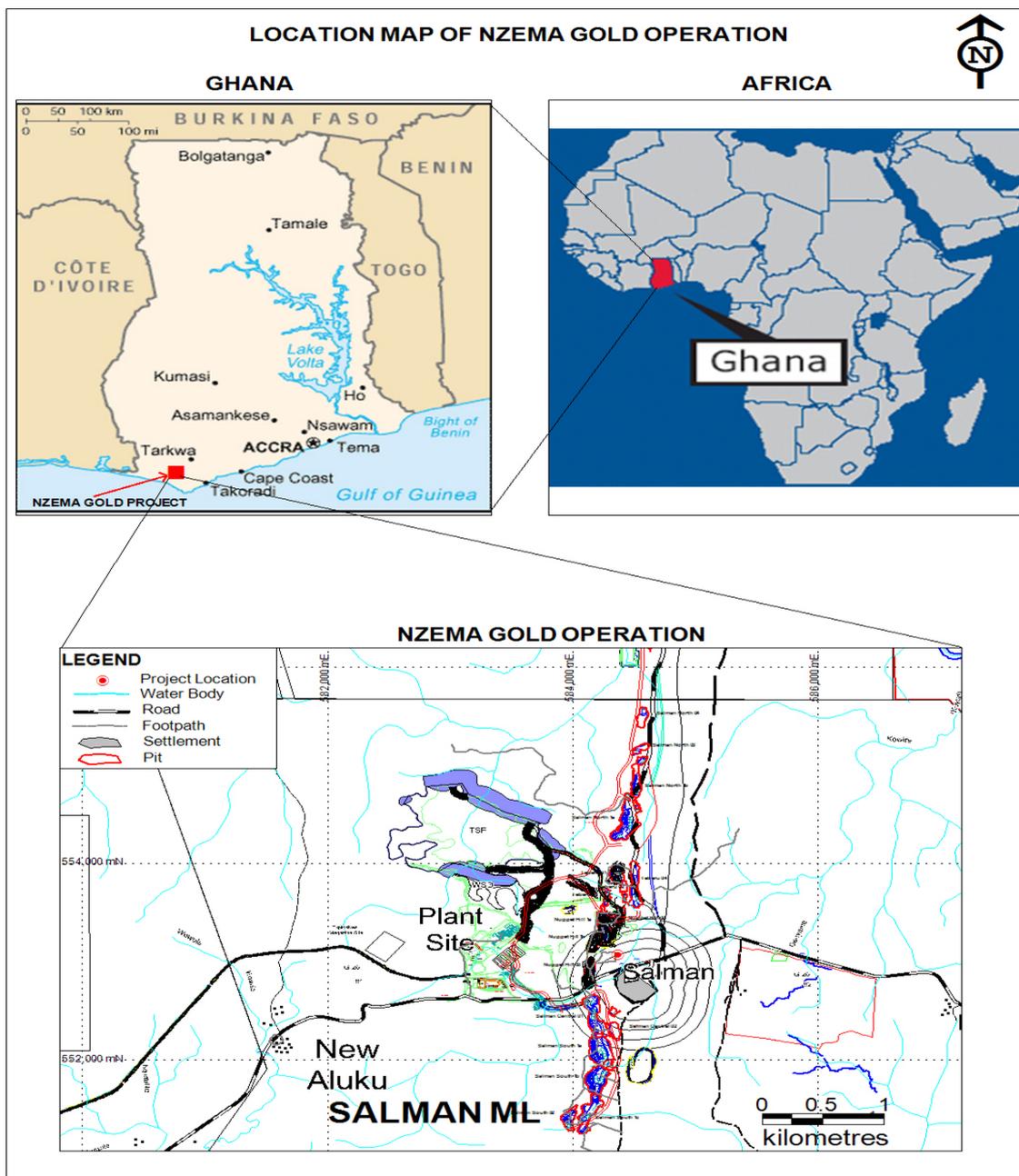


Figure 1. Map of study area showing key areas of mining operations

Source: Knight Piesold (2007).

### 2.1 Local Geology and Soils

Basement exposure is generally poor within the Project area and is largely restricted to road cuttings, a few stream beds, prospecting pits and trenches, and drill pads (Dzibodi-Adjimah, 1993). Laterite and mottled clay zones are locally developed on ridges, and saprolite typically extends to 10 – 30 metres beneath surface and locally as much as 80 m. The eastern part of the Project is largely underlain by Birimian volcanic and volcanoclastic rocks assigned to the Ashanti Belt, the western part mainly by Birimian metasedimentary rocks of basin and basin margin affinity in the southeastern corner of the Kumasi Basin (Dzibodi-Adjimah, 1993).

The Birimian volcanics are thought to be faulted against the Tarkwaian Group immediately northeast of the current tenure, and a small area of quartz-rich fluvial rocks immediately east of Axim may also belong to the Tarkwaian. A large biotite granite body is exposed in the western part of the Project area and probably belongs to the Cape Coast suite (Leube, Hirdes, Mauer, & Kesse, 1990). Two large, magnetically zoned Dixcove-type granitoid batholiths intrude the volcanics at the eastern edge of the Project, and curved magnetic ridges adjacent to these intrusives could represent contact aureoles (Dzibodi-Adjimah, 1993). Several narrow granitoid dykes and fault slivers up to 13 kilometres long and 700 metres thick of uncertain affinity are scattered through the Project area, and some near-circular geophysical features (electromagnetic resistors with weakly magnetic edges) between 1.5 and 2.0 km diameter, northeast of Anwia may represent subsurface plutons (Knight Piesold, 2007). Two north-striking doleritic dykes are known from geophysics and drilling in the Nkroful-Anwia area.

There is no formal subdivision of the Birimian Supergroup in the Southern Ashanti area but several lithologically and geophysically distinct units can be identified and three litho-structure domains are recognised: Avrebo, Salman and Anwia. The soils of the Project area have developed over the sediments of the Lower Birimian rocks and belong to the Boi Soil Association (Knight Piesold, 2007). The soils are deeply weathered and intensively leached of bases rendering them acidic and low in fertility. The series members of the Association within the Project site according to a study by Knight Piesold (2007) are the Omappe, Boi, Bremang and Oda series. The commonest features of the soils of the site are their great depths, strong brown to yellowish colour, acidic reaction, moderate fertility levels, high nutrient levels, clayey texture, sticky and plastic consistence and high contents of hard fresh quartz gravels and stones resulting from the weathering of quartz veins embedded in the subsoil (Dzibodi-Adjimah, 1993).

### 2.2 Design and Construction Background of the Nzema Tailings Storage Facility

The TSF was constructed in the year 2010 and is a cross-valley type impoundment located immediately due north of the plant site. It was designed by Knight Piesold (KP) Consulting to store tailings at a maximum capacity of 18 million tonnes. The storage is created by the construction of a main confining embankment across the valley some 2 km downstream of the treatment plant site (Knight Piesold, 2007). Tailings are deposited into the facility by multi-point spigot discharge from the main embankment and small east-west trending saddle dam. This deposition pattern will result in a tailings surface that slopes downwards to the south where the supernatant pond is formed remote from confining embankments (Vick, 1990). A series of decant towers are constructed in the southern part of the facility from which supernatant water are reclaimed and returned to the plant site.

An under-drainage system is constructed within the basin area to minimize seepage to the local groundwater (Azcue et al., 1994). The system comprises a series of drainage pipes, surrounded by sand drainage material laid on the basin floor. Water intercepted and collected by the system is drained to a sump located immediately upstream of the main embankment. A groundwater drainage system is also in place and this comprises a 160 mm diameter drain-coil pipe in a 1m<sup>2</sup> cross-section of clean crushed granite aggregate which is surrounded by geo-textile and backfilled with compacted clay prior to constructing the impervious compacted clay soil liner.

The technical justification for the ground water drainage system is based on the principles of groundwater hydrology, namely that the water table in the hills surrounding the TSF is draining by gravity through the fractured and weathered rocks to come to surface in the stream bottoms and then drain by gravity on surface (Rico, Benito, Salgueiro, Díez-Herrero, & Pereira, 2008). The groundwater is conveyed under the soil liner by a drainage system to avoid uplift and penetration of the liner. The ground water drain is expected to yield less and less water over time as the recharge area is progressively reduced by the increasing area of the liner in the catchment and as the stored water in the hills is slowly drawn down over time (Davies, 2002). Water intercepted and collected by the ground water drain system is drained to a sump located immediately upstream of the main northern embankment.

Emergency spillways are constructed at each stage of facility development in the vicinity of a north-south trending saddle dam. A final spillway has been located in the small saddle, some 400 m south west of the plant site. The decant system for the facility comprises series of decant towers. The towers are located in the southern part of the facility. The two towers were constructed from pre-fabricated slotted concrete pipe and surrounded by coarse free

draining rock-fill (Knight Piesold, 2007). A submersible pump is installed to pump water back to the plant via a High Density Poly-Ethylene (HDPE) reclaim line along the decant access road. The pump and return water line systems is capable of removing water from the pond at a rate equivalent to maximum plant demand.

The tailings delivery pipeline comprises a solid HDPE pipeline some 4,000 m long, located on the downstream side of the TSF access road. The alignment of the pipeline is such that any leakages from the line, due to a rupture or pipe break, will flow directly into the TSF and thus be contained. The TSF pipeline containment bund is fully lined with felt pad membrane. The future embankment raise is a downstream method.

### 3.3 Materials and Methods

#### 3.1 Study Design and Statistical Methods

Water samples were collected between June and December 2014 from seventeen (17) sampling sites including the TSF decant water (TSF-DW), three (3) streams, a water storage dam, a pond and eleven (11) groundwater monitoring boreholes within 500 m radius of the mines Tailings Storage Facility. Water samples were collected on monthly basis consecutively from first week of June 2014 to the first week of December 2014. The sampling matrix was designed to capture both dry and wet seasons to ascertain the quality of water in the two key seasons experienced over the project area. The data obtained were subjected to descriptive statistical analysis (95% confidence limit) and a correlation matrix was generated for parameters analyzed within the different media. Analysis of variance (ANOVA) was used to determine the variation amongst the various parameters sampled from the various sampling sites. All measurements were conducted at 5% level of significance. Microsoft Excel 2010 and EQwin data management software were used in statistical analysis conducted in the study

#### 3.2 Locations of Groundwater Monitoring Borehole and Surface Water Sampling Sites

Ground and surface water sampling locations were carefully selected to reflect the potential impacts of ARL's TSF on water resources within its catchment. Closeness of these sampling sites to the TSF makes them susceptible to pollutants through leachates and seepage from the facility.

Four (4) groups of two monitoring boreholes and three single deep boreholes have been strategically installed by the mine at the northern and eastern embankment to monitor possible seepage of contaminants from the TSF. Each monitoring borehole pair consists of one shallow borehole, extending through approximately 5 - 10 m of the near surface horizon and one deep borehole terminating at approximately 25 m. The monitoring boreholes comprise 100 mm PVC pipe, with a 3m slotted tip wrapped in geotextile. The boreholes are all capped with plastic material and locked to avert possible contamination of its content from external sources. In all, there are eleven (11) groundwater monitoring boreholes located at various points down gradient of the operating TSF of Nzema Gold Mine, which were sampled.

The shallow boreholes are designed to detect seepage flowing within the surface sediment whilst deep boreholes monitor the chemical composition of groundwater. Locations of the monitoring boreholes were informed by initial hydrological studies conducted prior to operation of the TSF by an independent engineering firm (Knight Piesold) and recommendations from the Environmental Protection Agency (EPA) of Ghana. The water storage Dam (WSD) shares boundary with the southern embankment of the Tailings Storage Facility. Pond besides Water Storage Dam (PWSD) is a pond 80 m uphill of the TSF at the south and 8 m away from the WSD. It used to be a stream that traverses the existing location of the TSF and the WSD before its construction and was later dammed by the mine to make way for the construction of the TSF and the WSD. It is stagnant and does not have any vertical flow. TSF North-West Stream (TSF-NWS) is located just at the toe of the TSF northwestern embankment about 10 m away from the facility. It recharges from a cocoa farm located on a hill at the west of TSF and drains eastwards. The stream channel is about 4 m wide and 0.5 m deep and flows in a dendritic pattern.

Angajale Stream (ANG) is located further northeast of the TSF and flows to join other streams which finally end up in the Ankobra River. It is monitored by the mine for surveillance purposes on monthly basis. The Angajale stream flows downstream of the TSF in north-eastern direction. The stream passes through the Angajale and Akango communities. It serves as the main source of water for farming and domestic use for the community folks.

Sampling point coded BAN-T is a perennial stream that flows in an easterly direction down gradient of the TSF North Embankment. It flows through Akango to join the Ankobra River. All surface and groundwater bodies studied were within 500 m radius of the TSF.

#### 3.3 Sample Collection and Analysis

Prior to collection of water samples, the Horiba Multi-parameter (U-52) probe which was used for in-situ surface and groundwater quality analysis was calibrated with 500 ml of HORIBA 100-4 pH standard solutions,

as per the equipment's operating manual. Standard latex gloves were always worn and disposed of after sampling at each sampling site to avoid cross contamination. Proper purging before collection of samples is key to successful ground water sampling. This ensures that water sampled is of good quality and reflects natural conditions (Singh, Malik, Mohan, & Sinha, 2004). In that regard, purging was done with the aid of portable generator set and submersible pump. Boreholes were purged for 5-10 minutes. In some instances, bailers were used when the generator set was faulty. Surface water samples were taken from below the surface (75 mm minimum) of the surface water in flowing streams. Care was taken not to include any surface film in the water collected. Containers were slowly and gently filled to avoid contamination of sampled water and disturbance of the water during sampling. Samples bottles were made to face the flow direction of water bodies. Air bubbles were eliminated and the bottles capped tightly to prevent contamination and water spilling. In order to avoid errors and mix-ups of samples, sample bottles were labeled with permanent, legible markings with information on the following: Sample location or code; date and time; Parameters for analysis and Preservatives, if any (Parizek, & Lane, 1970). Preservation methods are limited to: pH control, chemical addition, and refrigeration. The following parameters were preserved as follows: Metals: - Conc. HNO<sub>3</sub> to pH < 2, after filtering with 0.45-micron filter; Cyanide: - NaOH to pH > 12 (filter if turbid or TSS present).

Samples were packed upright in a cooler with ice packs to maintain the temperature of the samples just above freezing. A sample submission form ("chain of custody form") was filled out with all of the above information plus comments pertinent to the sample and transported to the laboratory for analysis.

### 3.4 In-situ Measurements

TDS, pH, BOD and electrical conductivity were measured in-situ using Horiba multi parameter probe (Model No. Horiba 500, S/N). The probe was rinsed with distilled water after every measurement to avoid cross contamination. The most stable reading displayed by the probe was taken to be the actual reading. All samples collected were sent to SGS Mas laboratory at Tema for analysis. Analyses of water samples were carried out in line with strict laboratory standards and internationally accepted protocols.

### 3.5 Analysis for Cyanide (CN)

The titrimetric method was used for the analysis of CN species. A blank solution was titrated against standardized 0.1M AgNO<sub>3</sub> solution using p-dimethylamino benzalrhodanine indicator solution, until the colour of the indicator changed from canary yellow to salmon blue. The blank titre was recorded and subsequently used. 100 ml of the sample was titrated against 0.1 M AgNO<sub>3</sub> using 5ml of p- dimethylaminobenzalrhodanine as an indicator to the end point. Concentrations of total cyanide in the water samples were determined by distillation of the sample to which 10 ml of conc. HCl and 10 ml of 12 % w/v hydroxylamine hydrogen chloride solution had been added to generate hydrogen cyanide gas (HCN), which was absorbed into 2 M NaOH solutions. The resulting sodium hydroxide solution was further diluted to 250 ml out of which 100 ml was titrated against standardized 0.1 M AgNO<sub>3</sub> solution using 5 ml of p-dimethylaminobenzalrhodanine indicator to the salmon blue end point (Kuhn & Young, 2005). Concentrations of free and total cyanide in the samples were calculated as follows:

$$\text{CN}^- \text{ mg/l} = (\text{A}-\text{B})/100 \text{ ml} * (250/1000) \text{ ml}$$

where A = sample titre volume of AgNO<sub>3</sub> and B = blank titre volume of AgNO<sub>3</sub>

### 3.5 Total Suspended Solids Analysis (TSS)

The photometric (non-filterable residue) method was used. 500 ml of sample was blended at high speed for two minutes. This was poured into a 600 ml beaker, stirred and 25 ml immediately poured into a sample cell. The stored programme number for suspended solids, 630, was entered. The wavelength was set to 810 nm. A sample cell was filled with 25 ml de- mineralized water (blank). This was placed in the cell holder and standardized. Next the sample was placed into the cell holder and the reading taken in mg/l suspended solids.

### 3.6 Dissolved Metals

Metals in the water samples collected were determined using atomic absorption spectro-photometer (AAS), AAS 220 model. The samples for AAS were first digested with nitric acid before analysis. In the laboratory, the acidified samples were filtered using Whatman's filter paper. The 0.45µm membrane filter paper was used because the analyte of interest in this work is the total dissolved metals. The filtered samples and the unfiltered samples were stored in the refrigerator at 4 °C for further analysis (Serfor-Armah, Nyarko, Dampare, & Adomako, 2006).

## 4. Results and Discussion

### 4.1 Quality of the Tailings Decant Water

The water quality parameters of Tailings Decant Water (TSF-DW) were mostly within Ghana EPA guideline

limits for effluent discharge.

The pH of TSF-DW ranged from 7.4 to 8.9. Mean pH of 8.2 was within the GHEPA effluent guideline limit of 6-9. Electrical conductivity ranged from 1340 to 1630  $\mu\text{S}/\text{cm}$  with a mean value of 1507.1  $\mu\text{S}/\text{cm}$  which was slightly above the GHEPA guideline limit of 1500  $\mu\text{S}/\text{cm}$  for effluent discharge.

Total Dissolved Solid (TDS) varied from 861 to 1040 mg/l. The mean TDS of 964.5 mg/l reported in this study was well within the GHEPA guideline limit for effluent discharge.

Biochemical Oxygen Demand (BOD) recorded in TSF-DW was below the laboratory detection limit in the entire study. Values of true colour ranged between <3 and 40 TCU with a mean value of 9.40 TCU which was far below the GHEPA guideline limit for effluent discharge.

Total Suspended Solids values ranged between 19 mg/l and 105mg/l with mean of 55.29 mg/l which was above the GHEPA guideline limit of 50 mg/l.

Total cyanide (CN-t) concentration recorded in TSF-DW ranged between <5 and 1.55 mg/l. Mean CN-t concentration of 0.586 mg/l was below the recommended GHEPA threshold of 1 mg/l. However, Free Cyanide (CN-f) concentration in the TSF-DW varied between <0.005 and 1.04mg/l with a mean concentration of 0.38mg/l which was above the recommended regulatory (GHEPA) limit of 0.2 mg/l.

Values of weak acid dissociation cyanide (CN-WAD) recorded during the sampling period ranged between <0.005 and 1.04mg/l with a mean of 0.342 mg/l and was well below the GHEPA effluent discharge limit of 0.6 mg/l.

Arsenic concentration in TSF-DW ranged from 0.17 to 5 mg/l. Mean arsenic concentration of 1.26 mg/l far exceeded the GHEPA guideline limit of 0.1 mg/l in TSF-DW. Arsenic concentration exceeded regulatory guideline limits in all months sampled.

Values of copper recorded ranged from 0.058 to 0.35 mg/l with a mean concentration of 0.15 mg/l which was far below the GHEPA guideline limit of 5 mg/l for effluent discharge.

Mercury concentrations recorded in TSF-DW ranged between <0.0001 and 0.0002 mg/l with a mean of 0.002 mg/l and was well within the GHEPA guideline limit of 0.006 mg/l.

Concentration of cadmium in TSF-DW varied from 0.0001 to 0.0004 mg/l. Mean cadmium concentration in TSF-DW was 0.0002mg/l and was well within the GHEPA guideline limit of 0.1mg/l for effluent discharge.

#### *4.2 Water Quality of Groundwater Monitoring Boreholes within 500 m Radius of the TSF*

Values recorded for pH, electrical conductivity, total dissolved solids and total suspended solids in groundwater samples within 500 m radius of the TSF were consistent with baseline values of the project site and also well within their respective regulatory guidelines.

Similarly, arsenic and copper also recorded values within the WHO guideline limits for potable water and also consistent with the baseline data. Biochemical oxygen demand, true color, cadmium, arsenic and cyanide (free, total and WAD) recorded values that were below their respective laboratory detection limits. Table 2 presents further details of groundwater quality data of the study.

Table 2. Physical and chemical parameters of groundwater monitoring boreholes within 500 m radius of the TSF

pH					Electrical conductivity ( $\mu\text{s}/\text{cm}$ )					Total Dissolved Solids (mg/l)				
Monitoring bore	Mean	SD	Range	P-value	Monitoring bore	Mean	SD	Range	P-value	Monitoring bore	Mean	SD	Range	P-value
TSFMBB02A	6.13	0.18	5.8-6.3		TSFMBB02A	129.43	13.44	108-152		TSFMB02A	84.29	9.45	70-99	
TSFMB02B	6.34	0.16	6-6.5		TSFMB02B	190.85	23.84	168-237		TSFMB02B	124	16.83	109-154	
TSFMB03A	7.05	0.22	6.7-7.3		TSFMB03A	441.85	89.74	277-557		TSFMB03A	285.86	61.44	180-357	
TSFMB03B	7.64	0.15	7.5-7.9		TSFMB03B	373.71	6.32	366-385		TSFMB03B	242.29	5.5	233-250	
TSFMB04A	6	0	6		TSFMB04A	114.71	5.42	106-120		TSFMB04A	74.57	3.82	69-78	
TSFMB04B	6.03	0.05	6-6.1	4.79E-26	TSFMB04B	128.14	24.08	110-173	2.35E-35	TSFMB04B	82.86	17.26	70-113	4.83E-35
TSFMB05	7.16	0.17	6.9-7.3		TSFMB05	362.71	75.59	179-405		TSFMB05	252.71	9.89	236-263	
TSFMB06	6.83	0.12	6.7-7		TSFMB06	190.85	13.07	179-210		TSFMB06	124.29	9.14	116-137	
TSFMB07	6.91	0.45	6.2-7.4		TSFMB07	208.56	5.07	201-215		TSFMB07	135.71	3.64	131-140	
TSFMB08A	6.44	0.4	6-7.1		TSFMB08A	134	3.16	129-139		TSFMB08A	87.14	2.12	84-90	
TSFMB08B	6.46	0.3	6.1-6.9		TSFMB08B	187	13.18	165-207		TSFMB08B	121.43	9.4	107-135	
Total Suspended Solids (mg/l)					Dissolved Arsenic (mg/l)					Dissolved Copper (mg/l)				
Monitoring bore	Mean	SD	Range	P-value	Monitoring bore	Mean	SD	Range	P-value	Monitoring bore	Mean	SD	Range	P-value
TSFMB02A	10.57	19.04	<1-53		TSFMB2A	0.00057	0.00012	0.0005-0.0007		TSFMB2A	0.001	NA	<0.0001-0.001	
TSFMB02B	8.29	4.57	14-Feb		TSFMB2B	0.0009	0.00014	0.0008-0.001		TSFMB2B	0.001	0	<0.0001-0.001	
TSFMB03A	5.43	3.69	12-Jan		TSFMB3A	0.00254	0.00401	0.0005-0.0097		TSFMB3A	0.002	0.001	0.001-0.003	
TSFMB03B	4.43	1.9	7-Feb		TSFMB3B	0.00633	0.004	0.0021-0.013		TSFMB3B	0.00186	0.00069	0.001-0.003	
TSFMB04A	8.43	7.21	19-Jan		TSFMB4A	0.0005	NA	0.0005-0.0005		TSFMB4A	0.00267	0.00116	0.002-0.004	
TSFMB04B	23.86	37.75	<1-102	0.0062	TSFMB4B	0.00055	7.07E-05	0.0005-0.0006	0.107592	TSFMB4B	0.00165	0.00191	0.0003-0.003	0.14669
TSFMB05	29.57	16.59	<1-53		TSFMB05	0.0008	0.00042	<0.00010-0.0012		TSFMB05	0.0015	0.00071	0.001-0.002	
TSFMB06	7.57	7.98	<1-18		TSFMB06	0.00126	0.00067	0.0001-0.0018		TSFMB06	0.001	0	0.001	
TSFMB07	4.71	5.56	<1-16		TSFMB07	0.0006	0	0.0006-0.0006		TSFMB07	<0.001	NA	<0.0001	
TSFMB08A	2.29	2.81	<1-8		TSFMB8A	0.00088	0.00056	0.0005-0.0017		TSFMB8A	<0.001	0	<0.0001-0.002	
TSFMB08B	5	0.79	<1-2		TSFMB8B	0.00063	0.00015	0.0005-0.0008		TSFMB8B	0.001	0	<0.0001-0.001	

Note. TSFMB=Tailings Storage Facility Monitoring Borehole, NA=Not Applicable

### 4.3 Physical and Chemical Parameters of Surface Water within 500 m radius of the TSF

#### 4.3.1 Arsenic

Arsenic concentration in surface water within 500 m radius of the TSF varied from 0.001 to 0.021 mg/l. The highest mean concentration of arsenic recorded in surface water was above the WHO (2011) guideline limit for potable water in PWSD whereas the lowest was recorded in BAN-T and TSFNWS respectively. The difference ( $P>0.05$ ) between the means of surface water studied were statistically insignificant. Figure 2 presents dissolved arsenic concentration in surface water compared with the baseline mean (0.003 mg/l) and WHO (2011) guideline for potable water.

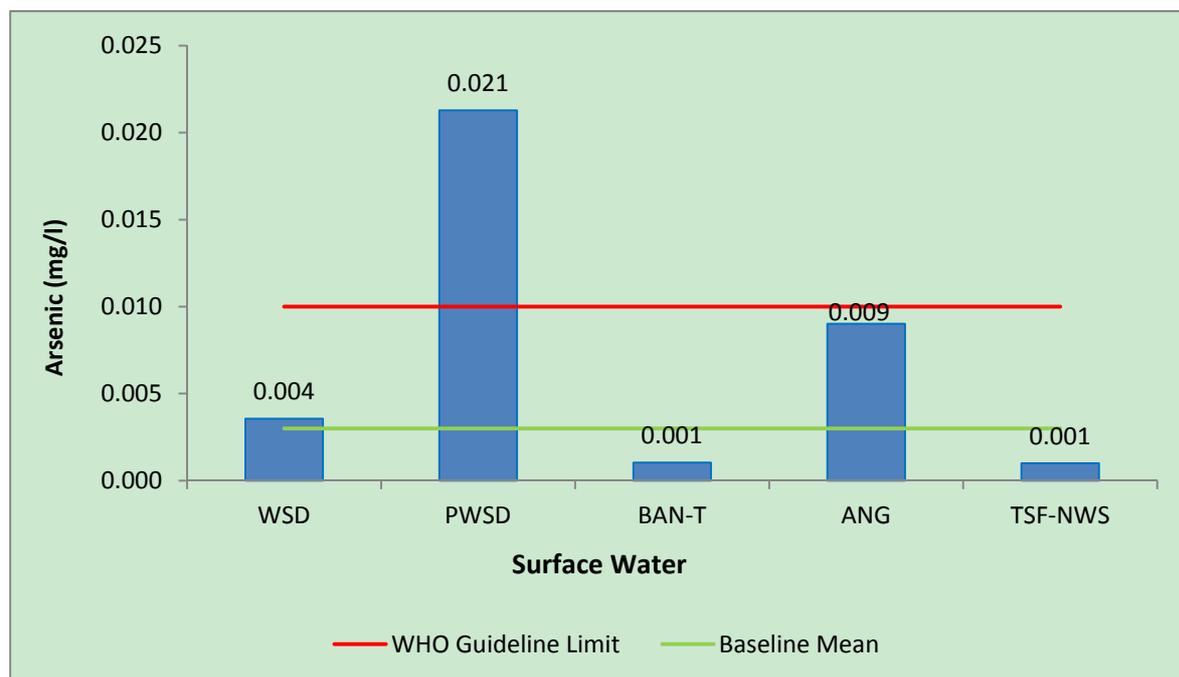


Figure 2. Arsenic Concentration of Surface Water within 500m radius of TSF compared with WHO (2011) Guideline and Baseline mean

#### 4.3.2 Copper

The maximum concentration of copper (0.0035 mg/l) was recorded at PWSD while the minimum was (0.001 mg/l) recorded at BAN-T. Statistically, the difference ( $P > 0.05$ ) between the mean values of the various surface water sampling sites were insignificant. Mean copper concentration of 0.0020 mg/l was consistent with the baseline mean and also within the WHO guideline limit of 2 mg/l for surface water.

#### 4.3.3 Cyanide (Total, Free and WAD), Mercury and Cadmium

Cyanide (Total, free and WAD), mercury and cadmium concentrations recorded in surface water around the TSF were all below their respective laboratory detection limits during the study.

#### 4.4 Pearson's Product Moment Correlation between Parameters

##### 4.4.1 TSF Decant Water

Pearson's product moment correlation matrix was carried out to determine the degree, strength or direction of the relationship between the parameters in TSF-DW. The results revealed that pH had moderate positive relationship with mercury, with a correlation coefficient ( $r$ ) of 0.56. Electrical conductivity had a highly significant positive correlation with dissolved arsenic, cadmium and copper (EC-As,  $r = 0.5$ ), EC-Cd,  $r = 0.6$ ), EC-Cu,  $r = 0.72$ ). EC also correlated moderately positive with free cyanide (EC- CN-f,  $r = 0.58$ ). There was a strong positive correlation between TDS and cadmium as well as TDS and copper (TDS-Cd,  $r = 0.67$ , TDS-Cu,  $r = 0.71$ ) respectively. However, a very weak negative correlation was reported between TDS and mercury (Hg) (TDS-Hg,  $r = -0.0122$ ). There was also a moderate positive correlation between TDS and free cyanide as well as TDS and arsenic (TDS- CN-f,  $r = 0.56$ , TDS-As,  $r = 0.48$ ) respectively. True colour had a weak negative correlation with dissolved Arsenic, cadmium, WAD and free cyanide. Correlations between TSS and cadmium as well as dissolved mercury were weak and negative respectively. (TSS-Cadmium,  $r = -0.29$ , TSS-Hg,  $r = -0.018$ ).

##### 4.4.2 Groundwater

A very strong negative correlation between groundwater pH and copper (pH-Cu,  $r = -0.699$ ) was recorded. No defined relationship could be established between groundwater pH, mercury and cadmium because the concentrations of these metals in groundwater samples were below their respective detection limits. Pearson's product moment correlation revealed that EC had a weak positive correlation with copper (EC-Cu,  $r = 0.29$ ). The relationship between EC and arsenic was however weak and negative (EC-As,  $r = -0.22$ ). TDS had a strong positive correlation with copper (TDS-Cu,  $r = 0.65$ ). The correlation between TDS and arsenic was very weak and

negative (TDS-As,  $r = -0.097$ ). There was no defined relation between TDS and cyanide (Free, WAD, and Total). This is because cyanide was not detected in groundwater.

#### 4.4.3 Surface Water

Pearson's product moment correlation revealed that surface water pH had a very weak negative correlation with copper (pH-Cu,  $r = -0.16$ ). The relationship between pH and other metals studied as well as cyanide could not be established because the values recorded were below detection limits. The electrical conductivity of surface water recorded a weak positive correlation with copper (EC-Cu,  $r = 0.27$ ). The relationship between electrical conductivity of surface water and other metals as well as with cyanide could not be defined owing to the same reason above. There was a strong positive correlation between TDS and copper (TDS-Cu,  $r = 0.88$ ) as shown in Appendix D. Surface water true colour had a weak negative correlation with dissolved copper (Colour- Copper,  $r = -0.34$ ).

### 5. Discussion and Conclusion

#### 5.1 Physical Parameters

The mean pH of 8.2 reported in ARL's TSF Decant Water (TSF-DW) was in agreement with a report by Acheampong et al. (2013) on TSF-DW at Bibiani mine. The slightly alkaline pH of the TSF water could be attributed to addition of lime during the beneficiation process at the mine. The mean pH of ground and surface water (6.67 and 6.63 respectively) within the catchment of the TSF were near neutral and within the WHO guideline limit for potable water. This suggests that pH of the TSF-DW has not adversely affected the surrounding water bodies and their life forms. Additionally, the slightly alkaline pH of the TSF-DW describes ARL's tailings as non-acid generating and therefore presents less risk of catchment water bodies being polluted as a result Acid Mine Drainage (ARD).

According to Shinoda, Nakagawa & Tamamushi, (2013), electrical conductivity of water depends on the quantity of dissolved salts present and for dilute solutions, it is approximately proportional to the total dissolved solid (TDS) content. The presence of dissolved salts in water increases its electrical conductivity and varies based on temperature. High electrical conductivity in the TSF-DW (1147.6  $\mu\text{S}/\text{cm}$ ) with relatively low mean EC of 116.8  $\mu\text{S}/\text{cm}$  and 223.8  $\mu\text{S}/\text{cm}$  recorded for surface and groundwater respectively suggests that TSF-DW does not have any perceptible impact on surrounding water bodies as far as EC is concerned. The high content of EC in TSF-DW could be attributed to free ions originating from reagents such as HCl which were used in the ore treatment process.

The high TDS of 964.6mg/l in the TSF-DW was above the WHO limit of 500mg/l for potable water. Low and acceptable amount of TDS in surrounding ground and surface water suggest no detrimental impacts. Biochemical oxygen demand is an estimate of the quantity of oxygen used by microorganisms such as aerobic bacteria in the oxidation of organic matter (Preininger, Klimant, & Wolfbeis, 1994). Mean Biochemical Oxygen Demand (BOD) in all media studied were below detection limit. This observation suggests that organic contamination was non-existent in the media studied. Results from the study suggest that true colour of TSF-DW and water bodies within its catchment are independent of each other.

There is no WHO guideline available for TSS. Spikes in TSS recorded in June and July for TSF-DW could be attributed to washouts from bare embankment of the TSF during the rainy season as observed during the sampling regime. Slurry discharge into the TSF could also contribute to the high TSS in TSF-DW. The PWS sampling sites is located uphill of the TSF and a receptor to effluents from illegal mining sites on ARL's concession. High TSS in PWS could possibly be as a result of effluent discharge from the illegal mining sites located uphill. Water bodies with high TSS could harbor pathogens that may be harmful to humans and therefore not suitable for drinking (Noble, Lee, & Schiff, 2004). High TSS could also reduce the rate of photosynthesis in aquatic environment.

#### 5.2 Chemical Parameters

##### 5.2.1 Cyanide

Cyanide is a toxic substance that renders tissues incapable of oxygen exchange (Shifrin, Beck, Gauthier, Chapnick, & Goodman, 1996). Elevated concentrations of cyanide in water is hazardous to man and wildlife, particularly migrating bats and waterfowls (Eisler, Clark, Wiemeyer & Henny, 1999). Cyanide contamination of the TSF-DW could be attributed to its use as a process chemical by Adamus Resources Limited as recounted by Acheampong et al. (2013) at Bogoso mine. High free cyanide concentration relative to other cyanide species (Total, and WAD) could possibly be attributed to excessive use of cyanide at the process plant relative to the rate at which they are broken down by natural processes.

Significant concentration of cyanide in the TSF with non-detection in water bodies around the facility suggests that cyanide in the TSF-DW has not impacted on catchment water resources. This could possibly be attributed to adherence to the industry's best practices as observed at ARL during this study.

### 5.2.2 Arsenic, Cadmium, and Mercury

Arsenic (As) is an identified carcinogen, mutagen, and teratogen and it is associated with increasing risk of bladder, kidney, liver and lung tumors (Kortatsi et al., 2008). Chronic and acute poisoning by arsenic due to exposure to elevated concentrations is a common occurrence. High arsenic concentration in TSF-DW could be attributed to leaching of the element by cyanide from arsenopyrite ore mined by ARL (Armah et al., 2010). Welch, Lico, & Hughes (1988) reported that arsenic is an important auxiliary contaminant in mine waters, particularly where the ore bodies contain arsenopyrite as is the case at ARL.

Low arsenic concentration in groundwater although TSF-DW recorded high concentrations could be attributed to arsenic's ability to bind strongly to soil and therefore does not travel downward toward aquifers very quickly (Woo & Choi, 2001). Low arsenic in groundwater could also be attributed to effective liner application systems of ARL's TSF as suggested by Vick (1990). Findings from the study suggest that TSF has no impact on surrounding water bodies with respect to arsenic contamination. The spike in arsenic concentration seen in PWS is an isolated case and may be due to influx of effluents from uphill-illegal mining activities during the rainy season.

Cadmium and Mercury are important factors in aquatic monitoring studies. This is because they have been found to be toxic to fish and other aquatic organisms (Essumang, Dodoo, Obiri, & Yaney, 2007). Even though significant concentration of dissolved mercury and cadmium (below GHEPA limit for effluent discharge) was reported in the TSF-DW, the concentrations of these metals in surface and groundwater within 500 m radius of the TSF were all below their respective laboratory detection limits. The results suggest that concentration of mercury and cadmium in the TSF-DW has not affected the quality of water within the vicinity of the facility.

High levels of copper are associated with nausea, abdominal pain, or vomiting in humans (Pizarro et al., 1999). Concentrations of copper in groundwater (0.0015 mg/l) were greater than that of surface water (0.0020 mg/l). This notwithstanding, TSF-DW has no impact on catchment water bodies with respect to copper contamination as per the results obtained from the study.

### 5.3 Relationships between Parameters

Free ions of Cd, Cu, CN-f and As could account for the high EC recorded in TSF-DW and these ions could be originating from a single source (the ore) as per the results of the correlation analysis.

The strong positive correlation between arsenic in TSF-DW with cyanide total, free and WAD (As/CN-T,  $r = 0.855$ , As/CN-F,  $r = 0.85$ , As/CN-WAD,  $r = 0.934$ ) suggests that arsenic in the TSF-DW is leached from arsenopyrite ore by cyanide.

## 6. Conclusion

Concentration of key Ghana Environmental Protection Agency (GHEPA) conventional pollutants in ARL'S TSF decant water was above the agency's guideline limit for the mining sector. This indicates that the TSF-DW of ARL is contaminated. However, the concentration of Ghana Environmental Protection Agency (GHEPA) conventional pollutants in surface water and groundwater monitoring boreholes within 500 m radius of the tailings dam were generally within acceptable GHEPA, Ghana Water Company, and World Health Organization (WHO) guidelines.

Concentration of pollutants recorded for surface and groundwater monitoring boreholes were also consistent with baseline data from the mine. The TSF of ARL therefore has no perceptible impact on the quality of surface and groundwater within its vicinity.

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## Appendices

### Appendix A: Baseline Mean of Surface and Groundwater

	BASELINE MEAN												
	pH	EC ( $\mu$ S/cm)	TDS (mg/l)	TSS (mg/l)	BOD (mg/l)	Col. (TCU)	As (mg/l)	Cu (mg/l)	CN-WAD (mg/l)	CN-f (mg/l)	CN-t (mg/l)	Cd (mg/l)	Hg (mg/l)
GW	6.8	312	218.6	11.2	<5	<5	0.005	0.0024	<0.01	<0.01	<0.01	<0.01	<0.01
SW	6.6	203.8	36.6	22	<5	5	0.003	0.0026	<0.01	<0.01	<0.01	<0.01	<0.01

Note. GW = Groundwater, SW=Surface water

Appendix B: Pearson’s Product Moment Correlation between Parameters Analyzed in the TSF

	Color (TCU)	EC (µS/cm)	pH	TDS (mg/l)	TSS (mg/l)	As-D (mg/l)	Cd-D (mg/l)	Cu-D (mg/l)	CN-t (mg/l)	CN-f (mg/l)	CN-WAD (mg/l)	Hg-D (mg/l)
Color (TCU)	1											
EC (µS/cm)	0.29495634	1										
pH	0.420989673	0.580416816	1									
TDS (mg/l)	0.31901237	0.999596535	0.593463126	1								
TSS (mg/l)	-0.466428821	-0.282076979	-0.058371166	-0.29638023	1							
As-D (mg/l)	-0.105150416	0.499112053	0.021833318	0.485835995	0.48411389	1						
Cd-D (mg/l)	-0.058404965	0.67446824	0.371305329	0.669252883	-0.297720225	0.046364152	1					
Cu-D (mg/l)	0.02820054	0.724199838	0.245545632	0.713875518	0.302884413	0.869753834	0.486569586	1				
CN-t (mg/l)	0.173896045	0.447964118	-0.101124583	0.443277962	0.110366707	0.855803744	-0.187608735	0.632472645	1			
CN-f (mg/l)	-0.236985306	0.585111147	0.094179997	0.56825964	0.449166411	0.850357061	0.492871173	0.958593748	0.52304438	1		
CN-WAD (mg/l)	-0.18895113	0.285836964	-0.319601342	0.269440039	0.460039481	0.934780109	-0.107784126	0.729405878	0.85771618	0.7523006	1	
Hg-D (mg/l)	0.393240824	-0.141421356	0.5625	-0.122709136	-0.018507931	-0.301021062	-0.495073771	-0.454299411	-0.1407465	-0.5871781	-0.459235264	1

Note. RED=Significant Correlation, NR=No Established Relationship

Appendix C: Pearson’s Product Moment Correlation between Parameters Analyzed in Groundwater around the TSF

	Color (TCU)	EC (µS/cm)	pH	TDS (mg/l)	TSS (mg/l)	As-D (mg/l)	Cd-D (mg/l)	Cu-D (mg/l)	CN-t (mg/l)	CN-f (mg/l)	CN-WAD (mg/l)	Hg-D (mg/l)
Color (TCU)	1											
EC (µS/cm)	NR	1										
pH	NR	-0.326835407	1									
TDS (mg/l)	NR	0.800411761	-0.67712895	1								
TSS (mg/l)	NR	-0.35984769	-0.406743894	0.245079415	1							
As-D (mg/l)	NR	-0.218870108	-0.187184192	-0.097366941	0.274535635	1						
Cd-D (mg/l)	NR	0.264924337	-0.723711055	0.777705685	0.790527901	0.082312	1					
Cu-D (mg/l)	NR	0.294796757	-0.699117613	0.645719031	0.46544283	0.505545	0.681782999	1				
CN-t (mg/l)	NR	NR	NR	NR	NR	NR	NR	NR	1			
CN-f (mg/l)	NR	NR	NR	NR	NR	NR	NR	NR	NR	1		
CN-WAD (mg/l)	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	1	
Hg-D (mg/l)	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	1

Note. RED=Significant Correlation, NR=No Established Relationship

#### Appendix D: Pearson's Product Moment Correlation between Parameters Analyzed in Surface water around the TSF

	Color (TCU)	EC ( $\mu\text{S}/\text{cm}$ )	pH	TDS (mg/l)	TSS (mg/l)	As-D (mg/l)	Cd-D (mg/l)	Cu-D (mg/l)	CN-t (mg/l)	CN-f (mg/l)	CN-WAD (mg/l)	Hg-D (mg/l)
Color (TCU)	1											
EC ( $\mu\text{S}/\text{cm}$ )	0.220481	1										
pH	0.130198	-0.315455099	1									
TDS (mg/l)	-0.30634	0.007393158	-0.145030092	1								
TSS (mg/l)	-0.36722	0.358360729	0.014011621	0.849372	1							
As-D (mg/l)	-0.6539	-0.443416829	-0.430898348	0.466533	0.15703	1						
Cd-D (mg/l)	NR	NR	NR	NR	NR	NR	1					
Cu-D (mg/l)	-0.34469	0.278650617	-0.169704958	0.881353	0.846698	0.361274808	NR	1				
CN-t (mg/l)	NR	NR	NR	NR	NR	NR	NR	NR	1			
CN-f (mg/l)	NR	NR	NR	NR	NR	NR	NR	NR	NR	1		
CN-WAD (mg/l)	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	1	
Hg-D (mg/l)	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	1

Note. RED=Significant Correlation, NR=No Established Relationship

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