Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Evaluation of Water Quality of the Benso Reclaimated Acid Mine Drainage Site in the Mpohor District

Yaw Anokye Barnieh
Kwame Nkrumah University of Science and Technology
Derrick Werekoh Asaah
werekoh59@gmail.com

Kwame Nkrumah University of Science and Technology
Eugene Ollennu
Kwame Nkrumah University of Science and Technology
Prof Esi Awuah
Kwame Nkrumah University of Science and Technology

Research Article

Keywords: Water Quality, Reclaimated, Acid Mine Drainage

Posted Date: November 20th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11350576/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Evaluation of Water Quality of the Benso Reclaimated Acid Mine Drainage Site in the Mpohor District

[1, 2]Yaw Anokye Barnieh, [2,5]Derrick Werekoh Asaah, [1, 3]Ollennu Eugene, [4] Prof. Esi Awuah

[1]Department of Civil Engineering, College of Engineering, Faculty of Civil and Geo Engineering Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.
[2]Genser Energy Ghana Limited, P.O. Box Stanbic Heights 215-South Liberation Road, Airport, Accra, Ghana.
[3]Yilo Krobo Municipal Assembly, P.O. Box SA 102, Somanya, Ghana.
[4]Department of Civil Engineering, College of Engineering, Faculty of Civil and Geo Engineering Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.
[5]Kwame Nkrumah University of Science and Technology, Faculty of Renewable Natural Resources, Department of Silviculture and Forest Management, Kumasi Ghana.

*Corresponding author's email: Werekoh59@gmail.com

Abstract

Extraction industry in Ghana is one of the most economically viable industry fetching huge returns to the country. However, over the years, the expansion of the extraction sector in Ghana have been associated with several social and environmental implications while environmental accidents from mines cost the country human lives and huge sums of money for rectification or remediation. Thus, the problem of acid mine drainage goes far beyond the existence of mining. Thus, after the official closure of a mine, the issue lingers on for long with negative implications existing for years. The study analyzed physico-chemical parameters of surface and ground water samples at Subriso, East Waste dump for Golden Star Wassa Limited to establish effectiveness of the Acid Mine Drainage (AMD) remediation method employed. Samples were collected from two major sources namely Surface flow (at 0 m) and Borehole (at 5 m and 10 m height). Electrical conductivity (EC) and *pH* were determined on the field by the *pH* meter and HANNA multi-parameter H19813 - 06 apparatus. Atomic Absorption Spectrometry (AAS) was utilized in analyzing heavy metals. Onsite results revealed that *pH* values of all waters analyzed fell within drinking water standards. Chemical

analysis on samples showed that heavy metals such as Sulfate (SO_4), Nitrate (NO_3), Cadmium (Cd), Copper (Cu), Lead (Pb), Chromium (Cr), Mercury (Hg) and Nickle (Ni) within the upstream were good for drinking water except Nitrogen Dioxide (NO_2) and Phosphate (PO_4). The study found out that shallow boreholes analyzed had heavy metal concentrations, falling within the drinking water standards except PO_4 which fell outside of range. For deep boreholes, all the metals analyzed fell within drinking water standards except Copper (Cu) which was not analyzed and PO_4 which fell outside of range. Sulfate concentrations (SO_4) decreased at (10 m) for deep boreholes, (0 m) for surface water and (5 m) for shallow boreholes. The study concluded that Sulfate (SO_4) concentrations in the water samples analyzed increased after the remediation; therefore, the AMD remediation was unsuccessful.

Keywords: **Water Quality, Reclaimated, Acid Mine Drainage**

Introduction

Ghana's involvement in the extraction and trading of minerals such as gold, bauxite, manganese, petroleum salt, etc. has increased over the years. With Ghana being a principal contributor to global gold production and contributing around 80.5 tons of gold annually, the importance of the extraction industry in Ghana cannot be overemphasized. This industry has been known to make significant contributions of about 5 % to the country's GDP. Out of 37 % of total mineral export, gold exportation alone makes up about 95% of the total mineral exportations of the country (Akabzaa and Damani, 2001). Subsequently, Corrosive Mine Drainage (CDM) is a fundamental biological problem confronting mining businesses. This occurs when pyrite is uncovered and responds with atmospheric oxygen and water to produce sulphidic acid and dissolved iron. This deluge can dissolve certain toxic metals and flow into both surface and groundwater sources thereby contaminating them. Notwithstanding the pollution of water bodies by CDM, it inhibits the development of both aquatic flora and fauna; and corrodes surfaces of infrastructures and its flow path among others.

An example is the cyanide spill that occurred on a Goldfields mine concession in the year 2001. While the spillage defiled the primary wellspring of drinking water for the individuals of Abekoase and Huni in Wassa West district. It took prompt reporting and continual monitoring of the river to be able to protect the lives of residents in these communities (Ghana web, 2001). Hence, there is the need for the government to

continue monitoring closely, the activities of mining companies in Ghana to ensure the right procedures are followed coupled with the minimization of negative impacts that comes with their operations. Additionally, waste rocks that are generally acidic in nature have low pH, iron and sulphate bearing and typically produced when rocks bearing sulphidic minerals are presented to the air along the lines drained by water (Jennings et al., 2008). Therefore, this waste has been a major problem to the precious metal and coal mining industry all over the globe while numerous remote mining locals suffer the heritage of acid seepage after the exhaustion of mineral deposits. The creation of harmful waste through oxidation of sulphide rocks (e.g. pyrite) is illustrated in the equation below:

$FeS2 + O2 + H2O \rightarrow Fe(OH)3 + SO42- + H+$

Sulphidic rocks (mostly iron sulphate) composition combines water in the environment with oxygen to deliver ferric hydroxide and watery sulphuric acid compound. The accompanying compound responses represent key strides in corrosive producing procedures when pyrite responds to water within the sight of oxygen. Once more, it features the significance of the arrangement of ferric hydroxide (Fe (OH) 3) in the creation of corrosive conditions. When pyrite is presented into the atmosphere, it decays in water in dissolvable parts creating acids and chemically shown below;

$FeS2 + 3.5\ O2 + H2O \rightarrow Fe2+ 2SO42- + 2H+$ and the moderately, diminished water solvent segments (Fe2+) are additionally oxidized; within the sight of the created corrosiveness shown below;

$Fe2+ + 0.25\ O2 + H+ \rightarrow Fe3+ + 0.5\ H2O$. Further, the development of ferric iron in water brings about the precipitation of ferric hydroxide; and creation of hydrogen ions which make the solution corrosive illustrated below;

$Fe3+ + 3H2O \rightarrow Fe(OH)3 + 3H+$. The escape of Ferric hydroxide from water beyond pH 3.3 after the framework adequately circulates in air, encouraging transformation of dissolvable ferrous iron into solvent ferric iron. Illustrated in the above chemical reactions, this procedure is very vital in corrosive creation levels. Thus, after sulphides have been oxidized, it makes it difficult to do away with ferric hydroxide precipitation (Murphy et al., 1997) which leads to the oxidation of extra pyrite by ferric iron. This is produced by the underlying oxidation responses in the chemical reactions earlier illustrated. This cyclic proliferation of acid creation by iron happens quickly and proceeds till the pyrite is depleted occurring in the absence of oxygen shown in the seen below.

$FeS2 + 14\ Fe3+ + 8H2O \rightarrow 15Fe2+ + 2SO42- + 16H+$

Therefore, when sulphidic minerals are presented to oxidizing agents (air and water), iron sulfides responds while the water transports the resulting elements into surface water and groundwater. Additionally the moving water further reacts with different minerals within the media and breaks down more extensive scope of elements (Murphy et al., 1997). Mine wastes waters usually inhabit these metals; iron, aluminum, manganese, copper, lead, zinc, cadmium and different elements, which are corrosive (Taylor et al., 1997). Hence, metal toxicity. A sensitive problem for decrease in ecological contamination in previous years has animated dynamic proceedings with studies and documentation on the toxicology of heavy metals. Consequently, all metals can create poisons when ingested in adequate amounts except a few which produce less harmfulness at low fixations. Hence, heavy metals produce many poisonous substances in life forms by producing complexes with natural mixes (Soghoian, 2008; Hoekman, 2008).

Some metals produce complexes with other materials in living life. These complexes impact massively on some significant enzymes and certain protein structures (Hoekman, 2008). Acidic waste greatly affects the biology of streams and influence utilizations of conduits downstream of mining activities. In line, acidic environments lead to damaging amphibian biological systems, riparian communities and potentially human well-being. In water, aquatic species subjected to metals and H+ particles in breathing lead to debilitated breath causing intense toxicity. Research conducted on the dissemination of fish in Pennsylvania streams influenced by acid mine waste by Cooper and Wagner (1973), discovered that fish are seriously affected at pH of 4.5 to 5.5. From the study results, ten species exhibited some resistance to corrosive states of pH 5.5 and beneath; 38 species were discovered living in waters with pH extending from 5.6 to 6.4 while 68 species were discovered distinctly at pH levels more noticeable than 6.4 (Murphy et al., 1997). In effect, acid mine seepage destroys vegetation establishment and poses restoration challenges. Its conditions have remarkable impediments on the vegetation types that can be utilized for recovery and best-case scenario, a reason for a bombed restoration program (Murphy et al., 1997).

Studies conducted on pyrite oxidation and acid mine drainage have revealed innumerable management practices when employed. This minimizes the negative consequences emanating from acid rocks. Acid rock drainage has become one of the most challenging waste management issues most mining companies have to deal with

in present times. It is not surprising that various extensive research has been devoted to the mechanisms of pyrite oxidation while various protocols are being executed to minimize the ripple effect of pyrite oxidation even after the successful closure of mines (Foli et al., 2011; Barton and Karathanasis, 1999). Mining exercises discharge vaporous materials, particulate matter, and residue, among different poisonous substances which add up to ecological contamination and debasement. Therefore, one of the major inorganic contaminations of the above is the impact of overwhelming metal contamination to nature. Substantial metals including manganese, arsenic, zinc, lead, mercury and vanadium, are regular at mining locales (Hanson et al., 2007; Obiri, 2007). Operational territories that are considered as significant wellsprings of metals incorporate tailings depositional destinations, plants locales, squander rock stockpiling destinations, open pit facilities and effluent discharge sites.

Precipitation overflows from and around these operational territories of mines possibly cause soil and water contamination in view of the poisonous materials that are discharged into the earth. Mining causes the decimation of biological systems, commotion contamination, sullying of water bodies and land surfaces when there is corrosive seepage (Bitala, 2008). The above conditions fill in as significant supporters of deforestation, causing demolition and disintegration of vegetation and agrarian land and loss of natural surroundings for feathered creatures and creatures in general (Akabzaa and Darimani, 2001). In mining, water, vaporous profluent, and waste stone are created during mining exercises, from investigation to genuine mining stages, which contain contaminants, for example, substantial metals, mining, treatment synthetic substances and corrosive producing sulfides which are harmful when they come into contact with the environment. For example, AngloGold Ashanti Limited in Obuasi, spilled tailings materials at the Eastern mass of the Sansu Tailing Facility in the 1999s. Likewise, the Boete slurry pipeline and hydra-fill pipeline from Sansu tailings, siphoned into the Kwesi Mensah shaft brought about soil and water contamination, influencing households. These contributed fundamentally to heavy metal contamination (AGA, 2008).

Notwithstanding the above, it is mandatory by law to ensure release of assets or resources back to communities after the completion of operations on any mining land, hence the need to ensure all discharges are safe and potable usage by the indigenes. Sealing methods or encapsulation procedures have been employed in the management and prevention of AMD on mining sites even after closure. In regard, sealing with dry

cover works aims to reduce AMD by reducing the availability of oxygen which in turn inhibits actions of microbial oxidation of sulphide materials. This eventually reduces water flow and slows down the drainage of water production. This activity enhances the gradual release of metals thereby diluting the toxicity of drainage water with time. However, after seven years of applying the sealing method of managing AMD on the Subriso East waste dump, no scientific investigations have been conducted on the nature of water bodies at the mined site and its surroundings. Hence, the study investigates the physicochemical variables of water bodies examining the trend of sulphate transport and comparison of pH and heavy metals to WHO drinking water standards of the Benso Reclamation Acid Mine Drainage site in the Hwini-Butre and Subriso East waste dump, Mpohor District of the Western Region, Ghana.

Methodology

Study Area Description

The study was conducted at Golden Star Wassa Limited (GSWL), a gold mining company in the Mpohor District of the Western Region, Ghana. Mpohor is the administrative capital of the district which is found at the mid-southern part of the Region. The population of inhabitants in the region is roughly 236, 000 and fundamentally made of the initial Wassa clan (Avotri et al., 2002). The area exists in the principal gold belt of Ghana that extends from Axim in the southwest, to Konongo in the Upper East (Kortatsi, 2004). The research was conducted at Hwini-Butre and Benso (HBB) concession of GSWL in the Western Region, which is approximately 35 km NNW of the Takoradi Harbour and 20 km SE of Tarkwa. The Benso Township is roughly 5 km from the Benso mine site toward the south and around 2 km west of the Hwini Butre mining site.

The area is said to be in the wet semi-tropical climatic zone of Ghana which is described by a yearly two-fold maxima precipitation design. The first and highest pinnacle happens in June, while the subsequent and lowest pinnacle happens in October. Approximately 53 % of all down pour in the locality fall from March to July. Average yearly precipitation is roughly 2608 mm (most extreme) and least estimations of 1449 mm, respectively (Kortatsi, 2004). The mean yearly precipitation differs broadly from

year to year. The territory is very stuffy and relatively warm with temperatures between 26 – 30 °C (Dickson and Benneh, 1980).

The study was conducted in three stages namely; pre-field, field and post-field stages. The following procedures were used in conducting the study;

Reconnaissance Study: Focused on the identification and representative distribution of the sample points, considered the possible sources of pollution and collection secondary data on the quality of water before the construction of the waste dump.

Detailed Study: This entailed sampling of five boreholes and one surface water, measurement of their positions using GPS, labeling of samples, packaging of samples and transportation of samples to the laboratory. It also included field measurements of the physical parameters of the sampled waters.

Laboratory Analysis: Focused on analysis of the chemical parameters of the groundwater. The location of the study area and the Golden Star Wassa Limited operational areas is shown in Fig. 1.

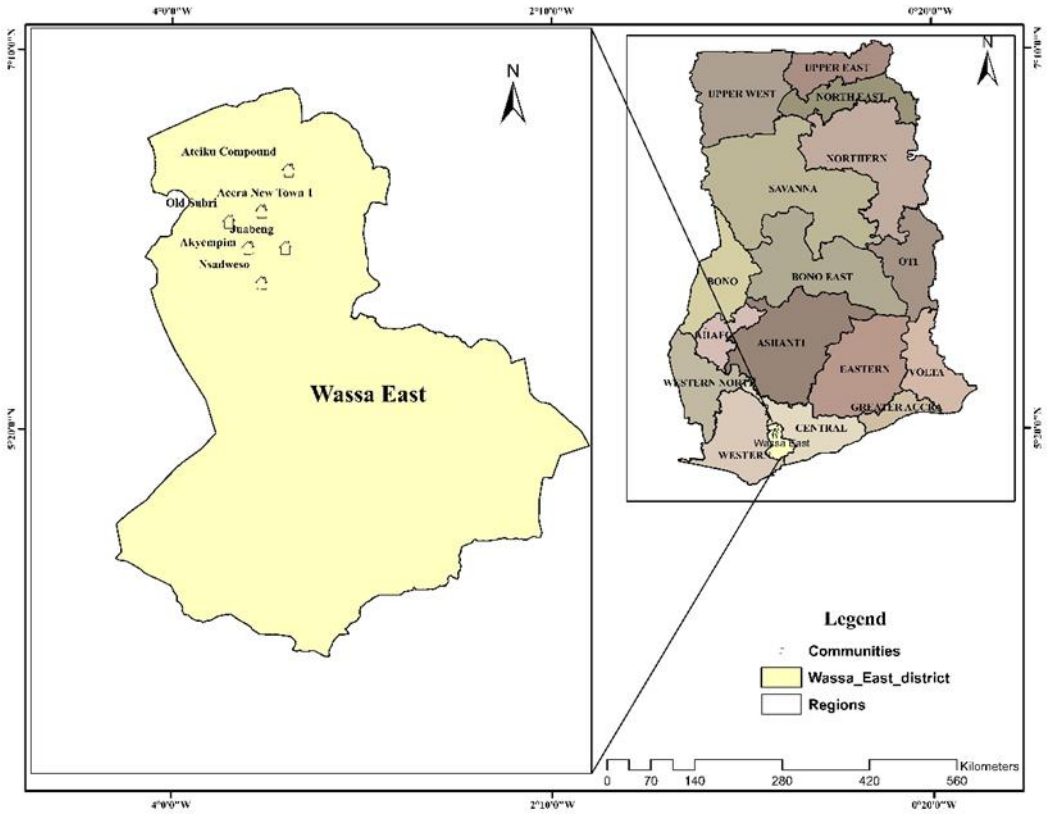

Figure 1: Map Location of Golden Star Wassa Limited Operational Areas
(Source : Author's construct, 2020)

Reconnaissance Study

A total of seven points were sampled for collection. Six of these points comprised monitoring boreholes found at the toe of the East Waste Rock Dump and surface water from the Subri River (0 m). The boreholes comprised of shallow and deep depths of 5 m and 10 m respectively. Samples were taken from the upstream and downstream sections of the Subri River. Boreholes and surface water were sampled and monitored continuously on monthly basis for seven months (from August, 2015 to February, 2016). Coordinates of boreholes and surface waters were picked with the Garmin e-Trex hand held Global Positioning System (GPS) receiver and the coordinates were used to generate the Site Sampling Map. Sampled waters were collected using a Bailer for the boreholes and transferred into 500 ml pre conditioned high density polyethylene bottles. They were conditioned by initial washing with five percent nitric acid, and rinsed severally with de-ionized water to ensure the sample bottles were free from contaminants.

Surface water samples were collected directly by fetching from a river using well rinsed 500 ml bottles. Each bottle was immersed below the water surface and samples from the various sampling points were allocated with a unique identity. Samples earmarked for ion analysis were filtered on site cellulose filters with the aid of a funnel. Bottles and caps for collection of major ions were rinsed five times with the filtered water from the respective boreholes and surface water, after, filled to the brim and caped. Samples were kept in an ice chest containing ice blocks and transported to the laboratory for analysis.

Detailed Study

Field Measurements (pH and electrical conductivity) variables were measured using the HANNA multi-parameter H19813-06 analyzer. Total suspended solids were determined using In Site IG 1350 meter. There was a first calibration for pH using solutions of pH 4 and pH 10 buffers. For electrical conductivity, electrodes were immersed in solution of 0.1M KCl of conductivity 1413.0 µs/cm and appropriately calibrated. Readings were taken by dipping the probe into sampled water and the readings recorded at every sampling point. Dissolved oxygen (D.O), salinity and oxygen reduction potential (ORP) were determined using the HANNA multi-parameter H19146-04 analyzer. The parameters were analyzed in-situ (on field analysis) to obtain true field representative values of persisting conditions for the samples.

Laboratory Analysis:

Secondary data on quality of water before the commencement of remediation processes of waste dump of study area were collected from the Environmental Team of GSWL. Samples were transported from the GSWL laboratory from Wassa to the SGS Laboratory at Tema for sample preparation and analyses. At the SGS laboratory, all six samples was analyzed for the following: Sulphate (SO42-), Alkalinity, Arsenic (As), Manganese (Mn), Iron (Fe), Zinc (Zn), Copper (Cu), Cadmium (Cd), Mercury (Hg) and lead (Pb). For Sulphate determination, NexION 2000 ICP MS (mass spectrophotometer) was used in detection of sulphate in the water samples. 10 ml of sample was filtered using a 0.45 μm membrane filter into a sample cell (bottle). One Sulphur Ver 4 Reagent Powder pillow content was added to samples. Sampled cell was stopped and shaken for half a minute. An additional 30 seconds was observed while sample is undisturbed. The blank, standard samples were read at a wavelength of 450 nm.

Alkalinities were also determined using 100 ml of water sample, measured into 250 ml flask with pH measurements. Three drops of Bromocresol green indicator were added, and sample titrated with 0.02 NaH2SO4 until color changed from blue to yellow reaching an endpoint pH of 4.5. Total volume of acid used to obtain endpoint was recorded. Total alkalinity computed was; Alkalinity (mg CaCO3/L) =A x N x 50,000 / ml Sample where;

"A" represents the total volume (mL) of the standard acid used.

"N" represents the normality of the standard acid used.

"50, 000" is a conversion factor to change the normality into units CaCO3/L (Standard Methods, 1992).

For Metal analysis, Varian 220 Spectra AA model of Atomic Absorption Spectrometer (AAS) was used in determining concentrations of selected metals (Arsenic, Manganese, Iron, Zinc, Copper and Cadmium). Instrument used was calibrated using standard solutions of various elements. Selected elements were determined in wavelengths as follows: As = 193.7 nm, Mn = 279.3 nm, Fe = 284.3 nm, Zn = 213.9 nm, Cu = 324.8 nm and. Cd = 228 nm. 100 ml of water sample was measured into sample bottle. Bottle was rinsed three times with sample before actual sample was placed in sampled bottle. 1 ml of concentrated HNO3 was added to the sample using calibrated dispenser. Sample was shaken and allowed to stand close to an hour for digestion. Filtration was done using a 0.45μm membrane filter. Sample was fed to the AAS analyzer for analysis.

Statistical analysis of data was conducted using Microsoft Office Excel and Statistical Package for Social Science (SPSS – version 19). Additionally, Pearson correlation matrix and cluster analysis were employed for possible correlations among measured parameters. Coefficients of correlation were grouped into classifications using parameters given by Hinkle et al., (2003). See table 1.

Table 1: Interpretation Size of a Correlation Coefficient (Hinkle et al., 2003)

Size of correlation (±)	**Interpretation of Correlation**
0.90 - 1.00	Very high
0.70 - 0.90	High
0.50 - 0.70	Moderate
0.30 - 0.50	Low
- 0.30	Negligible

For hierarchical cluster analysis, Ward's Method was employed for hierarchical cluster analysis of sampled water collected at different depths (upstream 0 m, shallow borehole 5 m and 10 m for deep). Squared Euclidean distance was the interval employed to establish dissimilarities in variables. The Z-score was used as standardized transformed value while orientation of data was vertical. Cluster membership employed was single solution and three (3) numbers of clusters were selected employing the phonon line.

Results

Summary statistics for the Subri upstream (0 m) water samples before and after remediation are presented in Table 2.

Parameter	**BEFORE (2011/2012)**							
	Mean	Median	Std. Deviation	Variance	Skewness	Kurtosis	Minimum	Maximum
Ph	6.923	7.020	0.562	0.316	-0.142	-1.621	6.120	7.700
EC	70.300	57.000	25.153	632.678	1.526	0.827	52.000	117.000
Temp	24.750	24.600	0.844	0.712	0.377	-0.988	23.600	26.200
TSS	48.444	45	18.049	325.778	1.393	2.389	27.000	88.000
TDS	35.600	28.500	12.738	162.267	1.396	0.466	26.000	59.000
SO_4	4.420	1.950	4.548	20.686	0.919	-0.572	0.800	13.000

NO_3	0.766	0.865	0.575	0.330	-0.238	-1.602	0.006	1.530
NO_2	0.050	0.043	0.048	0.002	2.013	4.758	0.005	0.170
Cd	0.002	0.002	0.000	0.000	-3.162	10.000	0.001	0.002
Cu	0.021	0.020	0.008	0.000	1.089	5.085	0.006	0.040
Pb	0.010	0.010	0.002	0.000	-3.162	10.000	0.005	0.010
Hg	0.001	0.001	0.000	0.000	-	-	0.001	0.001
Cr	0.010	0.010	0.002	0.000	-3.162	10.000	0.005	0.010
Ni	0.019	0.020	0.005	0.000	-3.162	10.000	0.005	0.020
PO_4	0.029	0.020	0.017	0.000	1.964	3.152	0.020	0.070
AFTER (2016/2017)								
Parameter	Mean	Median	Std. Deviation	Variance	Skewness	Kurtosis	Minimum	Maximum
pH	7.449	7.450	0.490	0.240	1.649	4.214	6.870	8.650
EC	110.800	104.000	26.046	678.400	1.105	0.156	84.000	156.000
Temp	25.751	26.150	1.919	3.682	0.184	0.465	23.000	29.410
TSS	30.600	34.000	12.545	157.378	-0.331	-1.406	14.000	47.000
TDS	55.400	52.000	13.023	169.600	1.105	0.156	42.000	78.000
SO_4	5.110	2.500	5.199	27.034	0.707	-1.203	0.700	14.000
NO_3	1.565	0.445	2.268	5.144	2.109	4.547	0.006	7.250
NO_2	1.142	0.200	2.048	4.196	1.763	1.378	0.005	5.080
Cd	0.000	0.000	0.001	0.000	1.779	1.406	0.000	0.002
Cu	0.007	0.003	0.008	0.000	1.092	-0.674	0.001	0.020
Pb	0.003	0.001	0.004	0.000	1.662	1.109	0.001	0.010
Hg	0.000	0.000	0.000	0.000	1.035	-1.224	0.000	0.001
Cr	0.003	0.001	0.004	0.000	1.750	1.341	0.001	0.010
Ni	0.006	0.003	0.008	0.000	1.615	1.061	0.001	0.020
PO_4	0.052	0.050	0.045	0.002	2.318	6.279	0.02	0.170

Table 2: Samples Before and After Remediation at Subri Upstream (depth 0 m)

Results of the above posited that concentrations of SO4, NO3, NO2, Cd, Cu, Pb, Hg, Cr, Ni, and PO4 at the Subri upstream before (2011/2012) remediation vary from 0.800 to 13.000 mg/l, 0.006 to 1.530 mg/l, 0.005 to 0.170 mg/l, 0.001 to 0.002 mg/l, 0.006 to 0.040 mg/l, 0.005 to 0.010 mg/l, 0.001 to 0.001 mg/l, 0.005 to 0.010 mg/l, 0.005 to 0.020 mg/l and 0.020 to 0.070 mg/l individually. After remediation (2016/2017), the concentrations of SO4, NO3, NO2, Cd, Cu, Pb, Hg, Cr, Ni, and PO4 varies from 0.700 to 14.000 mg/l, 0.006 to 7.25 mg/l, 0.005 to 5.080 mg/l, 0.00 to 0.002 mg/l, 0.001 to 0.002 mg/l, 0.001 to 0.010 mg/l, 0.00 to 0.001 mg/l, 0.001 to 0.010 mg/l, 0.001 to 0.020 mg/l and 0.020 to 0.170 mg/l respectively. Comparatively, average concentrations of Cd, Cu, Pb, Hg, Cr and Ni in the upstream sample after remediation were far lower than those sampled before. Additionally, the mean concentrations of SO4, NO3, NO2 and PO4 after the remediation process were higher before remediation. The pH values at

the Subri upstream before remediation ranged from 6.120 to 7.700 with mean of 6.9 while after remediation pH values were from 6.9 to 6.5 with mean of 7.4.

Table 3: Summary statistics for the shallow monitoring borehole (5 m) before and after remediation are presented in Table 3.

Measured Physical and Chemical Variables in Water Samples before (2011/2012) and after (2016/2017) from Shallow Borehole (5m depth) before and after Remediation

BEFORE (2011/2012)								
Parameter	Mean	Median	SD	Variance	Skewness	Kurtosis	Minimum	Maximum
Ph	7.146	7.340	0.555	0.308	-0.205	-2.292	6.500	7.800
EC	268.400	252.000	37.859	1433.300	2.216	4.926	249.000	3360
Temp	26.220	26.200	0.466	0.217	0.309	1.605	25.600	26.900
TSS	10.600	16.000	9.737	94.800	-0.554	-3.260	0.000	19.000
TDS	134.00	126.000	19.039	362.500	2.217	4.931	124.000	168.000
SO4	1.380	2.000	0.907	0.822	-1.131	-0.372	0.000	2.000
NO3	0.640	0.150	0.767	0.588	0.621	-3.096	0.000	1.570
NO2	0.022	0.005	0.026	0.001	0.579	-3.285	0.000	0.050
Cd	0.010	0.010	0.010	0.000	0.025	-2.896	0.000	0.020
Cu	0.013	0.020	0.010	0.000	-0.756	-2.479	0.000	0.020
Pb	0.007	0.010	0.004	0.000	-1.258	0.312	0.000	0.010
Hg	0.001	0.001	0.001	0.000	-0.609	-3.333	0.000	0.001
Cr	0.007	0.010	0.004	0.000	-1.258	0.312	0.000	0.010
Ni	0.013	0.020	0.010	0.000	-0.756	-2.479	0.000	0.020
PO4	0.278	0.320	0.172	0.029	-1.240	2.254	0.000	0.460
AFTER (2016/2017)								
Parameter	Mean	Median	SD	Variance	Skewness	Kurtosis	Minimum	Maximum
pH	7.446	7.400	0.156	0.024	0.391	-1.720	7.270	7.650
EC	272.400	270.000	19.463	378.800	-0.189	-0.724	246.000	296.000
Temp	26.054	26.200	1.044	1.090	-1.055	1.763	24.400	27.200
TSS	3.800	2.000	4.382	19.200	0.491	-3.016	0.000	9.000
TDS	136.200	135.000	9.524	90.700	0.000	-1.252	124.000	148.000
SO4	7.600	5.000	6.731	45.300	1.697	3.017	2.000	19.000
NO3	3.588	3.990	1.443	2.084	0.215	-1.369	2.050	5.530
NO2	0.074	0.060	0.073	0.005	0.234	-3.044	0.005	0.150
Cd	0.001	0.001	0.000	0.000	-	-	0.001	0.001

Cu	0.002	0.001	0.003	0.000	2.236	5.000	0.001	0.007
Pb	0.013	0.005	0.021	0.000	2.194	4.860	0.001	0.050
Hg	0.001	0.001	0.000	0.000	-	-	0.001	0.001
Cr	0.003	0.002	0.003	0.000	1.913	3.764	0.001	0.009
Ni	0.002	0.001	0.001	0.000	0.884	-1.750	0.001	0.004
PO4	0.582	0.590	0.083	0.007	0.152	1.067	0.470	0.700

From the above, concentrations of SO4, NO3, NO2, Cd, Cu, Pb, Hg, Cr, Ni, and PO4 at Subriso East Monitoring shallow borehole before remediation ranged between 0.00 to 2.00 mg/l, 0.00 to 1.570 mg/l, 0.00 to 0.050 mg/l, 0.00 to 0.020 mg/l, 0.00 to 0.020 mg/l, 0.00 to 0.010 mg/l, 0.00 to 0.001 mg/l, 0.00 to 0.010 mg/l, 0.00 to 0.020 mg/l and 0.00 to 0.460 mg/l separately. After remediation, concentrations ranged from 2.00 to 19 mg/l, 2.050 to 5.530 mg/l, 0.005 to 0.150 mg/l, 0.001 to 0.001 mg/l, 0.001 to 0.007 mg/l, 0.001 to 0.050 mg/l, 0.001 to 0.001 mg/l, 0.001 to 0.009 mg/l, 0.001 to 0.004 mg/l and 0.470 to 0.700 mg/l respectively. Comparatively, medial concentration of Cd, Cu, Cr and Ni in water samples collected after remediation were far lower than those sampled before the remediation. SO4, NO3, NO2, Pb, Hg and PO4 showed mean concentration of high values after the remediation process than before. The pH values at the Subriso East Monitoring shallow borehole before remediation ranges from 6.5 to 7.8 with mean of 6.1 while after remediation the pH ranges from 7.3 to 7.7 with mean of 7.4.

Table 4: Summary statistics for the deep monitoring borehole (10 m) before and after remediation are presented in Table 4.

Measured physicochemical parameters of water samples from a deep borehole (10 meters deep) before and after Remediation

Before (2011/2012)								
Parameter	Mean	Median	SD	Variance	Skewness	Kurtosis	Minimum	Maximum
pH	7.254	7.120	0.523	0.274	0.312	-3.047	6.760	7.830
EC	465.800	452.000	27.243	742.200	0.813	-1.752	444.000	504.000
Temp	26.320	26.400	0.249	0.062	-1.671	2.815	25.900	26.500
TSS	15.200	15.000	1.789	3.200	-0.052	-2.324	13.000	17.000
TDS	232.800	226.00	13.535	183.200	0.844	-1.579	222.000	252.000
SO_4	1.080	0.900	0.526	0.277	1.988	4.128	0.700	2.000

NO_3	0.334	0.210	0.367	0.135	2.065	4.376	0.110	0.980
NO_2	0.050	0.050	0.000	0.000	-	-	0.050	0.050
Cd	0.002	0.002	0.000	0.000	-2.236	5.000	0.001	0.002
Pb	0.009	0.010	0.002	0.000	-2.236	5.000	0.005	0.010
Hg	0.001	0.001	0.000	0.000	-	-	0.001	0.001
Cr	0.009	0.010	0.002	0.000	-2.236	5.000	0.005	0.010
Ni	0.017	0.020	0.007	0.000	-2.236	5.000	0.005	0.020
PO4	0.900	0.910	0.281	0.079	-0.317	-1.228	0.520	1.220
After 2016/2017								
Parameter	Mean	Median	SD	Variance	Skewness	Kurtosis	Minimum	Maximum
pH	7.575	7.525	0.1465	0.021	1.267	0.935	7.450	7.830
EC	732.166	689.500	102.458	10497.770	0.829	-1.565	640.000	880.000
Temp	25.966	26.100	0.592	0.351	-0.538	-1.642	25.100	26.500
TSS	3.333	3.500	2.944	8.667	-0.065	-3.133	0.000	6.000
TDS	366.000	344.500	51.330	2634.8	0.825	-1.577	320.000	440.000
SO4	2.066	0.900	2.461	6.055	2.272	5.229	0.800	7.000
NO3	9.751	6.360	12.473	155.571	2.067	4.612	0.006	34.300
NO2	2.923	0.085	6.024	36.293	2.349	5.575	0.05	15.100
Cd	0.001	0.001	0.000	0.000	-	-	0.001	0.001
Pb	0.000	0.000	0.0001	0.000	2.449	6.000	0.001	0.001
Hg	0.000	0.000	0.000	0.000	-	-	0.000	0.000
Cr	0.003	0.001	0.003	0.000	0.997	-1.702	0.001	0.009
Ni	0.002	0.002	0.001	0.000	0.857	-0.300	0.001	0.005
PO4	3.365	3.030	1.906	3.635	0.471	-1.752	1.680	6.150

The above results shows concentration of SO4, NO3, NO2, Cd, Pb, Hg, Cr, Ni, and PO4 before remediation varying from 0.700 to 2.00 mg/l, 0.110 to 0.980 mg/l, 0.050 to 0.050 mg/l, 0.001to 0.002 mg/l, 0.005 to 0.010 mg/l, 0.001 to 0.001 mg/l, 0.005 to 0.010 mg/l, 0.005 to 0.020 mg/l and 0.520 to 1.220 mg/l respectively. After remediation, the concentrations ranged from 0.8 to 7.0 mg/l, 0.006 to 34.30 mg/l, 0.050 to 15.10 mg/l, 0.001 to 0.001 mg/l, 0.001 to 0.001 mg/l, 0.00 to 0.00 mg/l, 0.001 to 0.009 mg/l, 0.001 to 0.005 mg/l and 1.680 to 6.150 mg/l respectively. Relatively, average concentrations of Cd, Pb, Hg, Cr and Ni in sampled water collected after remediation were lower than before the remediation. SO4, NO3, NO2, and PO4 showed mean concentration of high values after the remediation processes. PH values of deep monitoring borehole before remediation ranged from 6.8 to 7.8 with mean of 7.25 while after remediation ranged from 7.5 to 7.8 with mean of 7.6.

Pearson Correlation Analysis for the Subriso Upstream After Remediation

Pearson correlation coefficients for the Subriso upstream site after remediation are presented in Table 5.

Table 5: Correlation Matrix for the Subriso Upstream after the Remediation

	pH	SO_4	NO_3	NO_2	Cd	Cu	Pb	Hg	Cr	Ni	PO_4
pH	1										
SO_4	0.4	1									
NO_3	0.13	-0.3	1								
NO_2	0.13	-0.43	0.87	1							
Cd	-0.45	-0.42	-0.28	-0.26	1						
Cu	-0.35	-0.32	-0.44	-0.4	0.87	1					
Pb	-0.46	-0.44	-0.32	-0.3	0.98	0.94	1				
Hg	0.29	0.65	-0.39	-0.31	-0.33	0.05	-0.24	1			
Cr	-0.38	-0.38	-0.3	-0.28	0.99	0.87	0.98	-0.29	1		
Ni	-0.33	-0.3	-0.31	-0.32	0.98	0.84	0.95	-0.32	0.99	1	
PO_4	-0.27	0.62	-0.34	-0.34	-0.2	-0.25	-0.25	0.48	-0.2	-0.21	1

Pearson correlation analysis performed studied possible inter-relationships existing between SO4, NO3, NO2, Cd, Cu, Pb, Hg, Cr, Ni, PO4 and pH from upstream sites at $p \leq 0.05$ and $p \leq 0.01$ for both upstream and downstream. Emphasis was made on values greater or equal to ± 0.5 ($\geq \pm 0.5$) for both. At upstream site, NO3/NO2 (0.87), Cu/Cr (0.87), Cu/Ni (0.84) and Cd/ Cu (0.87) displayed high positive correlations while SO4/Hg (0.65), and SO4/PO4 (0.62 showed moderate positive correlations. Therefore, associations showed each pair of the metals (Cu/Cr), Cd/Cu, and /Cu/Ni) had probability of common origin. Cd/Cr (0.99) and (Cr/Ni) gave high correlations followed by Cd/Ni (0.98), Cd/Pb (0 .98), Pb/Cr (0.98), Pb/Ni (0.95) and Cu/Pb (0.94). Low positive and negative correlation were exhibited by pH/SO4 (0.40), Hg/PO4 (0 .48), pH/Cd (-0.45), pH/Pb (-0.46), Ph/Cu (-0.35), Ph/Cr(-0.38), SO4/NO2 (-0.43), Ph/Ni (-0.33), SO4/Cd (-0.42), SO4/Cr (-0.38), NO3/Cu (-0.44), SO4/Pb(-0.44), NO2/Cu (-0.40), NO2/Pb (-0.30), SO4/Cu (-0.32), NO2/Hg (-0.31), NO2/Ni (0.33),Hg/Ni (-0.32) and NO2/PO4 (-0.34). Negative correlation exhibited indicated that SO4, NO3, NO2, Cd, Cu, Pb, Hg, Cr, Ni, PO4 and pH traces are from different sources throughout the correlation.

Pearson correlation coefficients for the Subriso East shallow monitoring borehole after remediation are presented in Table 6.

Table 6: Correlation Matrix for the Subriso East Shallow Monitoring Borehole after the Remediation

	pH	SO_4	NO_3	NO_2	Cu	Pb	Cr	Ni	PO_4
pH	1								
SO_4	-0.18	1							
NO_3	-0.19	0.88	1						
NO_2	0	0.16	0.57	1					
Cu	0.41	0.03	0.16	0.58	1				
Pb	-0.65	-0.29	-0.51	-0.57	-0.33	1			
Cr	0.81	-0.53	-0.66	-0.48	-0.03	-0.19	1		
Ni	-0.14	-0.58	-0.86	-0.84	-0.4	0.81	0.42	1	
PO_4	-0.45	0.91	0.95	0.42	0.05	-0.21	-0.82	-0.68	1

For east monitoring deep borehole site, pH/Pb (0.85), and Cr/Ni (0.75) posited high positive correlation while Ni/PO4 (-0.83) displayed negative high correlations. Moderate negative correlations were for Cr/PO4 (-0.65) and pH/Ni (-0.65). Negative correlation exhibited by Cr/PO4 (-0.65) and pH/Ni (-0.65) indicates various elements from different sources. SO4/Pb (0.98), NO3/NO2 (0.95) and pH/SO4 (0.92) gave high positive correlations. Low positive and negative correlation were for pH/NO2 (0.41), NO2/PO4 (0.35), SO4/PO4 (0.31), Pb/Cr (-0.31), Pb/Ni (-0.40), NO2/Ni (-0.46), NO2/Cr (-0.36), SO4/Ni (-0.49), SO4/Cr (-0.39) and pH/Cr (-0.37). SO4 > Pb > NO2 metals are negligible.

Hierarchical Cluster Analysis

Dendrograms constructed for the Subriso upstream (surface water at depth 0m), East Monitoring shallow borehole (at depth 5m) and East Monitoring deep borehole (at depth 10 m) are presented in Fig. 2, 3 and 4.

Fig. 2 Dendrogram Explaining Hierarchical Cluster Analysis of pH and

Metal Concentration in Water for Subriso Upstream (0m) after Remediation

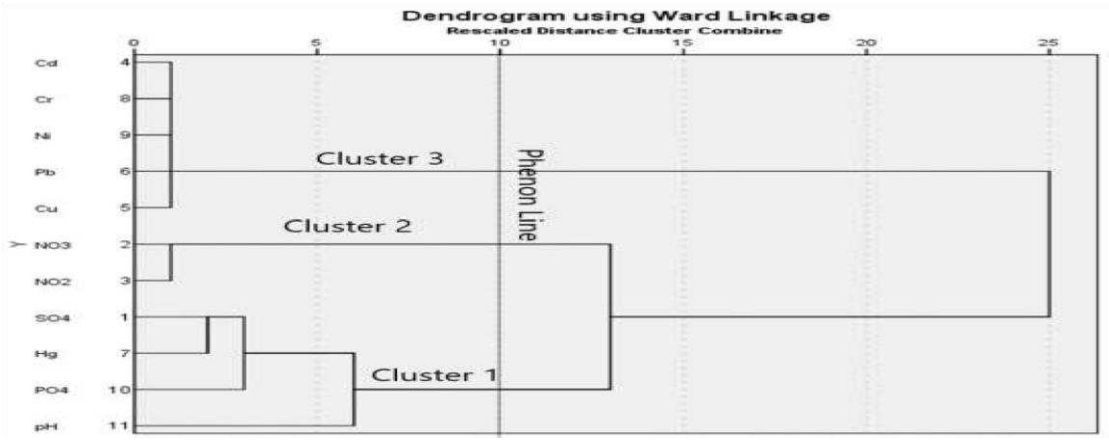

Fig. 2 Dendrogram Explaining Hierarchical Cluster Analysis of pH and

Metal Concentration in Water for Shallow Borehole (5m) after Remediation

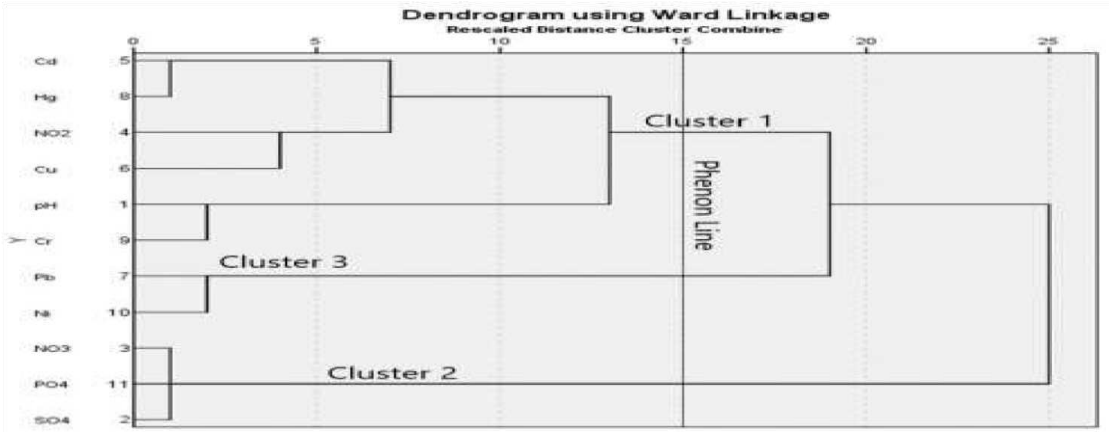

Fig. 3 Dendrogram of Hierarchical Cluster Analysis of pH and Metal Concentration in Water for Deep Borehole (10m) after Remediation

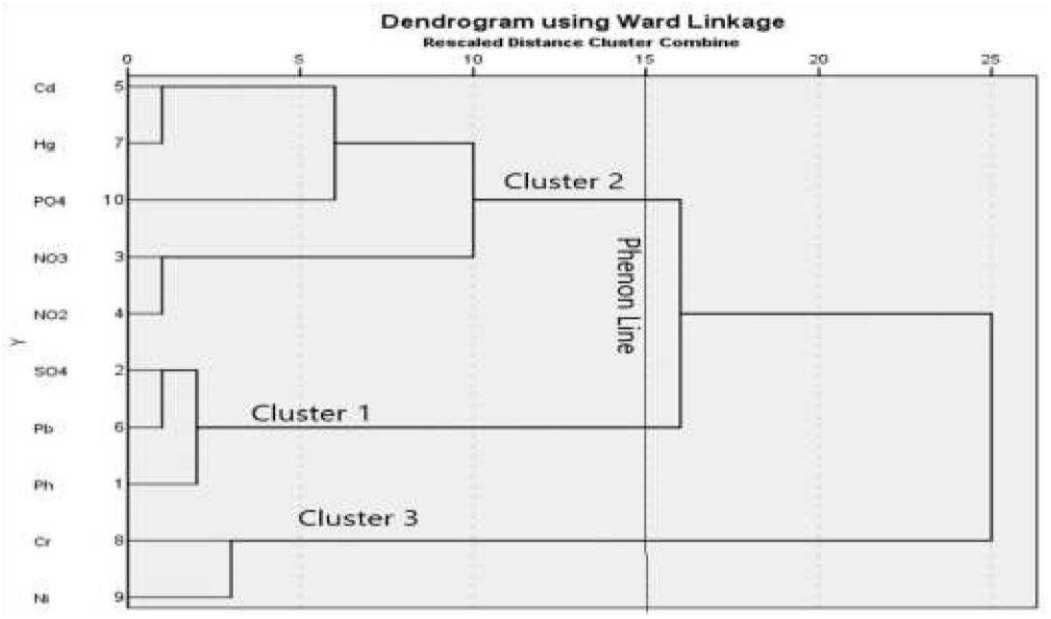

Fig. 4 Dendrogram (Ward linkage; squared Euclidean distance) showing hierarchical cluster analysis of pH and selecting chemical variables in water for the shallow monitoring borehole (5 m) after remediation.

Based on the phenonline, the upstream site (depth of 0 m), SO_4, Hg, PO_4 and pH were the first cluster, followed by NO_3 and NO_2 and Cd, Cu, Cr, Ni and Pb the third. For shallow borehole site, pH, NO_3, Cd, Cu, Hg and Cr were first clusters. SO_4, NO_3, and PO_4, second and Ni and Pb were third clusters. For deep borehole site, the first cluster contained pH, SO_4, and Pb followed by NO_3, NO_2, Cd, Hg and PO_4 as second and Cr and Ni as third.

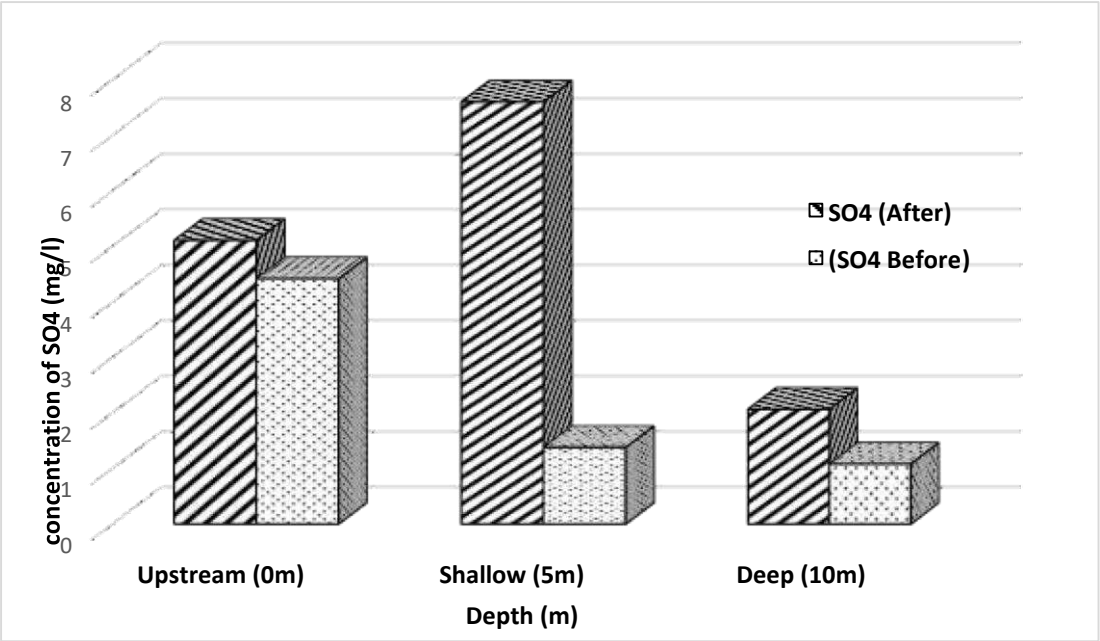

Fig. 5 Distribution of Sulphate (SO_4) in Water Samples with to Depth

After remediation, sulphate concentration within upstream revealed 5.110 mg/l, for shallow borehole 7.60 mg/l and deep borehole was 2.066 mg/l.

Comparison of pH and Heavy Metals to WHO Drinking Water Standards

Comparison of pH and Heavy Metals to WHO Drinking Water Standards": "Averages of the measured variables compared with WHO standards are presented in Table 7.

Table 7: Averages of Measured Variables compared with WHO Standards

Variable	Upstream	Shallow Borehole	Deep Borehole	WHO Standards
pH	7.449	7.446	7.575	6.5-8.5
SO_4, mg/L	5.110	7.600	2.066	250
NO3, mg/L	1.565	3.588	9.751	10
NO_2, mg/L	1.142	0.074	2.923	1
Cd, mg/L	0.000	0.001	0.001	0.003
Cu, mg/L	0.007	0.002	N/A	1
Pb, mg/L	0.003	0.013	0	0.01
Hg, mg/L	0.000	0.001	0	0.001
Cr, mg/L	0.003	0.003	0.003	0.05
Ni, mg/L	0.006	0.002	0.002	0.1
PO_4, mg/L	0.052	0.582	3.365	0.03

Conclusion

The study results posited that pH of all water samples (monitoring bores and upstream water body) analyzed fell within drinking water standards. Chemical constituents such as SO_4, NO_3, Cd, Cu, Pb, Hg, Cr, and Ni in the upstream were safe for drinking water except NO_2 and PO_4. Shallow borehole and all metal concentrations analyzed fell within WHO drinking water standards except PO_4 which was out of range. Analyses for deep borehole sites fell within drinking water standards except Cu which was not analyzed and PO_4 which was outside the range rendering the water unsafe for drinking and domestic purposes. Sulphate concentrations also decreased from deep boreholes (10 m) to surface (0m) and shallow boreholes (5m). Hence, concentrations of the sulphate in the water increased after the remediation; therefore, the AMD remediation was unsuccessful.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript."

Ethics Approval and Consent to Participate

This study involved environmental sampling of surface water and groundwater only and did not involve human participants, human data, or animal subjects. As such, formal human research ethics approval and informed consent procedures were not required. Permission to access the site and collect water samples was obtained from the relevant site managers/authorities and all sampling and laboratory analyses were conducted in accordance with applicable institutional procedures and relevant environmental and laboratory safety guidelines.

Consent to publish

Consent to publish is not applicable as this study does not involve identifiable personal data.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available because they include monitoring data obtained from/for an operating mine site and may be subject to data-sharing restrictions or confidentiality requirements. However, the data is available from the corresponding author on reasonable request

Reference

Abu Rukah, Y. and Al-Kofahi, O. (2001), "The assessment of the effect of landfill leachate on ground water quality - A Case Study at El-Akader landfill Site – North Jordan", Arid Environments, Vol. 49, 2001, pp. 615 – 630

Adelekan, B. A and Abegunde, K. D. (2011), "Heavy Metals Contamination of Soil and Groundwater at Automobile Mechanic Villages in Ibadan Nigeria", International Journal of the Physical Sciences, Vol. 12 No. 7, July 23, 2020

Akabzaa, T. and Darimani, A. (2001), "Impact of mining sector investment in Ghana: A Study of the Tarkwa mining region", draft Report for SARPRI. pp. 1-64.

Agency for Toxic Substances and Disease Registry (ATSDR). 1989. Toxicological profile for n-Nitrosodimethylamine. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

Bitala, M. F. (2008), "Evaluation of Heavy Metals Pollution in Soil and Plants Accrued from Gold Mining Activities in Geita, Tanzania", A Dissertation Submitted in partial fulfillment of the requirements for the Degree of Master of Integrated Environmental Management of the University of Dar es Salaam: pp. 6-50.

Carroll C, Merton L & Burger P 2000, 'Impact of vegetative cover and slope on runoff, erosion, and water quality for field plots on a range of soil and spoil materials on central Queensland coal mines', Australian Journal of Soil Research 38(2), CSIRO Publishing, Collingwood, Victoria.

Cooper, E. L. and Wagner C. C. (1973), "The effect of acid mine drainage of fish populations In: Fish and Food Organisms in Acid Mine Water Pennsylvania", Environmental Protection Agency Report, No. EPA-R3-73-032, 114 pp..

Depledge, M. H. (1987), "Enhanced copper toxicity resulting from environmental stress factor synergies", Comp. Biochem. Physiol. 87C: pp. 15-19.54

DOEPKER, P.E. (1993) Implementing the product realization process in the design sequence, Paper number 93-WA/MET-10 (New York, ASME).

Duffus, J. (2002). Heavy Metals—A Meaningless Term. Pure Applied Chemistry, 74, 793-807.

D. Dupler, “Heavy Metal Poisoning,” In: J. L. Longe, Ed., Gale Encyclopedia of

Alternative Medicine, Gale Group, Farmington Hills, 2001, pp. 2054-2057.

E. Steinnes, H. Krog, (1977), “Determination of mercury, arsenic and selenium fall-out from an industrial complex studied by means of lichen transplants. Oikos 28, 160-164(1977).

EPA (SA) (2009) Water quality: [http://www.epa.sa.gov.au/water_glossary.html]

(Accessed 2016 February 10)

Essortment. (2002). Children of Working Mothers. Essortment.

Farmington Hills, MI: Gale Group. Ferner DJ (2001). Toxicity, heavy metals. eMed. J. 2(5): 1.

Friberg, L., Piscator, M., Nordberg, G. F and Kjellstrom, T. (1974). Cadmium in environment. 2nd. Ed. CRC Press, Boca Raton, FL.

Gover, R.A. (1991) Toxic effects of metals. In Amdur, M.O., Doull, J., and Klaassen, C.D., eds, Casarett and Doull's Toxicology: The Basic Science of Poisons, 4th edition, pp. 623–80. New York: Pergamon Press.

Goyer, R. (1991). Toxic effects of metals. In: Amdur, M.O., J.D. Doull and C.D.

Klassen, Eds. Casarett and Doull's Toxicology. 4th ed. Pergamon Press, New York. Pp.623-680.

521 Hoekman, T. (2008).Heavy metal toxicology.[www.ucs.mun.ca/~thoekman],

522 (Accessed 2016 February 13)

523 55 Järup, L. (2003). Hazards of Heavy Metal Contamination. British Medical Bulletin;
524 68:167-179

525 Jennings, S.R., Neuman, D.R. and Blicker, p.s., 2008. "Acid Mine Drainage and

526 Effects on fish health and ecology: A Review". Reclamation Research Group

527 Publication, Bozeman, MT. pp1-29

528 Kegley, S. E., Hill, B. R., Orme, S. and Choi, A. H. (2009). Copper. PAN Pesticide

529 Database, Pesticide Action Network, North America (San Francisco, CA),
530 [http:www.pesticideinfo.org], (Accessed March 2011).

531 Kortatsi, B.K., 2004. Hydrochemistry of Groundwater in the Mining Area of Tarkwa–
532 Prestea. Ghana, PhD thesis. University of Ghana, Legon-Accra, Ghana.

533 Larocque ACL, Rasmussen PE (1998), An overview of trace metals in the environment:
534 mobilization to remediation. EnvironGeology 33:85–91

535 Marcovecchio, J.E., S.E. Botte and R.H. Freije, 2007.Heavy Metals, Major Metals,

536 Trace Elements. In: Handbook of Water Analysis. L.M. Nollet, (Ed.).2ndEdn. London:
537 CRC Press, pp.: 275-311.

538 MDH (Minnesota Department of Health),(2006). Copper in drinking water, health
539 effects and how to reduce exposure.

540 [http://healthstate.mn.us/dirs/eh/water/com/fs/copper.html], (Accessed

541 March 2011).

542 Mikac, N., Cosovic, B... Ahel, M... Andreis, S. and Tondic.Z. (1997).Assessment of
543 groundwater contamination in the vicinity of municipal solid waste landfill

(Zagreb, Croatia). Wat. Sci. Tech. (this issue). Mining series.Pp. iv-4 (www.ag.gov.au/cca.) 56

Murphy, L. M., Strange, R. W. and Hasnain, S. S. (1997). A critical Assessment of the evidence from XAFS and crystallography for the breakage of the imidazole bridge during catalysis in CuZn Superoxide dismutase. Structure 5, 371–379.

Nyarko BJB, Serfor-Armah Y, Akaho EHK, Adomako D, Osae S (2004) Determination of heavy metal pollution levels in lichens at Obuasi gold mining area in Ghana. J Appl Sci Technol 9(1–2):28–33

Oberthur T, Vetter U, Schmidt Mumm A, Weiser T, Amanor JA, Gyapong WA, Kumi R, Blenkinsop TG (1994) The Ashanti gold mine at Obuasi in Ghana: mineralogical, geochemical, stable isotope and fluid inclusion studies on the metallogenesisof the deposit. Geol Jahrb D100: 31±130

Proceedings of the ASME Winter Annual Meeting, 1993.

Ramasar, V., Madonsela, N. V., Munster, F. and Naicker, I. (2003).Guidelines for the Environmental Assessment of Coastal Mining. An Environmental Assessment (EA) manual to assist Government Agencies, Mining Developers, Non-Governmental Organisations (NGO's) and Community Organisations SEACAM, Maputo

Robert, C. 1999, in IAU Symp. 193, Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies, ed. K. A. van der Hucht, G. Koenigsber-ger, & P. R.

J. Eenens (San Francisco: ASP), in press Sin, S. N., Chua, H., Lo, W. and Ng, L. M. (2001).Assessment of heavy metal cations in sediments Alan, W., (1994).Soils and the Environment. Cambridge University Press, Cambridge, 10, 197-20

Singer, P.C., and W. Stumm 1970, Acid mine drainage the rate determining step.

Science 167:1121-112357

Soghoian,S.(2008).Toxicity,Heavymetals.[http://emedicine.medscape.com/article/814

960-overview], (accessed 2015 September 7).

570 Sterner RW, Chrzanowski TH Elser JJ, George NB (1995) Sources of nitrogen and
571 phosphorus supporting the growth of bacterlo- and phytoplankton in an oligotrophic
572 Canadian shield lake Limnol Oceanogr 40 242-249-249

573 Taylor, P. N, Moorbath, S, Leube, A. and Hirdes, W. (1992). Early Proterozoic crustal
574 evolution in the Birimian of Ghana: Constraints from geochronology and isotope
575 geology. Precambrian Research, Vol. 56, 77-111p.

576 Tetteh, E.N. (2010). Evaluation of land Reclamation practices at AngloGold Ashanti;
577 Iduapriem Mines Ltd, Tarkwa. MSc Thesis. Kwame Nkrumah University of Science
578 and Technology, Kumasi. P 19-44, 78-84

579 U.S. EPA (1994). Test methods for evaluating solid waste, physical/chemical methods
580 (SW0846), 3rd edition U.S. Environmental Protection Agency.

581 Vitosh, M. L., Warncke, D. D. and Lucas, R. E. (1994), "Copper Extension Bulletin;
582 E-486. [http://web1.msue.msu.edu/imp/modf1/05209707.html]: (Accessed 2019 May
583 20).

584 World Rainforest Movement (2008), "World Rainforest movement (WRM). Ghana:

585 Newmont Mining Corp. threatens Ajenjua Bepo Forest and neighboring communities",
586 World Rainforest movement WRM's bulletin No. 135, October 2008
587 http://www.wrm.org.uy/. Accessed 2019 November 10)

588 Young, R. (2005b), "Toxicity profile of Cadmium:
589 http://rais.ornl.gov/tox/profiles/cadmium. shtml], (Accessed 2019 January 21).

590 Young, R. (2005c), "Toxicity profile of Mercury:
591 http://rais.ornl.gov/tox/profiles/mercury. shtml]: Accessed 2019 January 21.

592

593

594