

Analysis of mine water from four decommissioned pits in south-western Ghana – implications for remediation programmes for mine closure

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Abstract

Research into water quality status of accumulated water in decommissioned pits is a grey area in Ghana and could be of significant benefit in the effectiveness of remediation of pits after mining. Water sampled from four decommissioned pits in Amansie West District were analysed for their water quality status. Seasonal variations of physico-chemical parameters for determining water quality were reported as well as their average values. In general, the ion concentrations varied from season to season but were within World Health Organization (WHO) maximum permissible limits (MPL) with the exception of boron. Similar observation was made for heavy metals/trace elements analysed, with the exception of As and Fe. Seasonal and average concentrations of As were higher than the WHO MPL. Similarly, the mid-season concentration of Fe recorded from a water sample collected from one pit was higher than WHO limits. Turbidity levels were significantly higher in two pits. The studies revealed that some parameters for water quality determination were above WHO acceptable limits for potable water, an indication that the effect of mining on water quality from water bodies investigated persisted after mine closure. Hence remediation programmes should be broadened to include effective reclamation of mine water accumulated in pits during mine closure.

Keywords: Amansie West; Decommissioned; Mine water; Pits; Remediation; South-western Ghana

1. Introduction

Even though various forms of gold mining exist, all forms could essentially be grouped into two, namely, underground and surface mining (Schueler *et al.*, 2011). Surface mining, which is also known as open cast mining, results in the creation of large pits due to the gradual extraction of rock

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boulder containing the ore from the surface to several metres deep. This form of gold mining is the most widely practised in Ghana, both by the large-scale miners and small-scale artisanal miners. In most instances, mining companies stop mining midstream of the mining life and such pits are left without any proper reclamation. Examples are the Konongo Mines and the Bonte Mines all along the Ashanti Belt in Ghana. The Ghanaian Environmental Protection Agency, in their effort to fight the menace that abandoned mines leave in their trail, came up with the Reclamation Bond Policy, where mining companies deposit at the bank an amount equivalent to the cost of reclamation of disturbed lands during mining. Mining companies reclaim this money, as they progressively rehabilitate disturbed sites during their operations. After the mine life, the complete reclamation is carried out and the mining company is issued with a Certificate of Closure.

One of the greatest worries of countries, environmental institutions and particularly communities where mining thrives is the degradation of natural resources after mine life. The impact of mining on water bodies assumes a central role and in most cases, is used as the barometer for measuring the sensitivity of mining companies during the operational period of the mine. Paradoxically however, the regeneration of land (vegetative cover) becomes the focus rather than water bodies, and how well the vegetation is regenerated has become the yardstick of assessment during the restoration process of disturbed natural resources by a mining company. In effect, land instead of water, assumes a more important role in the reclamation process. Many authors have underscored how abandoned or decommissioned mines have left in their trail, the deterioration of water bodies due to acid mine drainage from tailings, waste rock dumps and pits (Holmström *et al.*, 2001; Carlsson *et al.*, 2003; Widerlund *et al.*, 2004; Clausen *et al.*, 2011; Jia *et al.*, 2013). In effect, it has been noted that the after-effects of mining, particularly on water quality have been found to persist long after mine closure (Blowes & Jambor, 1990; Blowes *et al.*, 1994; Ljungberg & Öhlander, 2001; Luza, 2006; Valipour, 2012a, 2012b; Edraki *et al.*, 2014; Mahdizadeh Khasraghi, *et al.*, 2015; Nordstrom *et al.*, 2015; Valipour *et al.*, 2015; Yannopoulos *et al.*, 2015).

In many instances, after decommissioning of a mine, there is lack of comprehensive studies of the effects of mining or remedial measures taken to prevent surficial weathering of mine tailings (Bhattacharya *et al.*, 2006). The study of natural attenuation (NA) processes after decommissioning is of great importance, because NA may offset serious pollution threats of water systems (Graupner *et al.*, 2007).

In post-independent Ghana, a large-scale surface mine at Manso Nkran in the Amansie West District of south-western Ghana was decommissioned and Resolute Amansie Ltd, which operated the mine, became the first gold mining company to be officially issued with a Certificate of Closure after mining. Hence research into the water quality status of decommissioned pits is a grey area in Ghana and could be of significant benefit, regarding the environmental and safety status of accumulated water in decommissioned pits and the effectiveness of the remediation or restored use of pits after mining. It could also provide a useful foundation for policy makers to integrate into the requirements needed for mine closure (Ravengai *et al.*, 2005). This article therefore tries to assess the effectiveness of reclamation from the viewpoint of the status of water quality of abandoned mine pits which oftentimes is neglected.

Four pits were created by the operations of Resolute Amansie Ltd, which essentially practised the open cast (surface mining) method. These pits are named *Nkran pit-RPIT 1 (Nkran 1)*, *Ahubia pit-RPIT 4 (Nkran 2)*, *Abore North pit-RPIT 2 (Abore 1)* and *Abore South pit-RPIT 3 (Abore 2)*. These pits were filled with large volumes of water, when dewatering was halted after the operations of the mine. The pits were later converted into fish ponds as part of the reclamation measures adopted by the company and handed over to the community.

This study examines the mine water from these four decommissioned pits, and the data obtained are used to measure the efficacy of the remediation measures put in place, as well as the environmental and safety of accumulated water in pits to the host community after the mine closure, and tries to bring out some valuable lessons that could be learnt from this and which could guide or streamline policies regarding future mine closures. This study is unique since the pits analysed and reported in this manuscript have not been studied for the presence of heavy and trace metals, physico-chemical parameters or nutrients after decommissioning. In addition, we have reported the seasonal (dry, mid- and wet season) variation of the parameters that influences water quality since the intensity of artisanal mining in Ghana varies from season to season.

2. Study area

Geographically, the Amansie West District is located within longitude (6.05°, 6.35°) west and latitude (1.40°, 2.05°) north, approximately 40 km WNW of Obuasi (Government of Ghana (GOG), 2006). It spans an area of about 1,230 square kilometres and it is one of the largest districts in the Ashanti Region of Ghana. Map of the district is shown in Figure 1. The area features rolling hills with topographic relief in the range 50–100 m rising considerably in the rugged hills where elevation is 530–560 m (GOG, 2006). The topography can therefore be considered as undulating with an elevation of 210 m above sea level.

The area experiences semi-equatorial climatic conditions with a double maxima rainfall regime (Dickson & Benneh, 1977) with the major rainy season occurring between March and July while the minor rainy season occurs between September and November. The mean annual rainfall ranges between 855 mm and 1,500 mm. Temperatures are uniformly high all year round with mean annual temperature around 25.5 °C with relative humidity peaking between 75% and 80% in the wet season. The generally forested area has been reduced to open forest and wooded savannah due to inappropriate farming and mining activities, leaving isolated primary forest at the Oda River, Apamprama, Gyeni and Jimira forest reserves in the District (Dickson & Benneh, 1977; Water Resources Research Institute (WRI), 1989). Prominent streams that drain the area include the Offin, Ayensu, Kenanko, Asuoyaa, Ampofowaa, Akuasiso, Apoama, Dwiri and Adubia rivers most of which have been heavily impacted by illegal mining activities. In addition, most water bodies are under stress due to the excessive demand for water from both artisanal and formalized mining in the area. Apart from agriculture, fishing and logging which forms 59.2% of the total labour force, mining and quarrying feature prominently in the income-generating activities of the people in the area, employing 16.5% of the total labour force (Ghana Statistical Service (GSS), 2014).

Geology and gold mineralization, according to Griffis *et al.* (2002), is typical of the West African greenstone belts, comprising Birimian metasediments intruded by granitoids. The Nkran Hill falls within the general portion of the meta-volcanic units and some intermediate granitoids of possible belt affiliation as well as some late-stage felsic intrusives. The highland area north of the town of Manso Nkwanta is notable because of the presence of fairly coarse clastic metasediments also with a strong radiometric potassium signature (Kesse, 1985). Gold mineralization appears to occur mainly in the veins but some also occurs in the adjacent host rocks. The gold mineralization is free milling although there is strong association with both pyrite and arsenopyrite, which occur in the veins and particularly in the host rocks adjacent to the veins (Kesse, 1985; Coakley, 1996).



Fig. 1. District map of Amansie West. Source: GSS-Geographic Information System.

3. Sampling and analysis

After preliminary investigation of the study area and perusing all sites where active mining activities took place, the four decommissioned pits were selected, mainly due to the fact that the area formed the

largest site where active mining activities occurred and also large volumes of water were found in each pit. The investment made as part of the restoration effort by the mining company operating in the area was also factored into the selection of the site.

The composition of both surface and groundwater is dependent on hydrology, geology mineralogy), meteorology (climatic), topography, and nature of aquifer, all of which define the recharge regime and the nature of the catchment area. Natural processes such as rate of evaporation, transpiration, percolation of rain water, flooding, selective uptake by vegetation, oxidation/reduction, cation exchange, dissolution of minerals, precipitation and leaching of minerals, dissolution and mixing of water are all regulated by climate which is also defined by the seasons. In addition, anthropogenic activities particularly farming and mining are also regulated by the seasons. Hence water sampling was carried out in three different sampling regimes to reflect the dry, wet and moderate (in-between dry and wet, referred to as mid season) season characteristics of the climatological conditions in Ghana. This will help in assessing the effect of seasons on water quality. Since the study is about decommissioned pits, a sample was taken from each of the four pits at the three different seasons. The samples were taken in January, May and July representing the dry, mid- and wet seasons, respectively.

The four pits investigated are shown in [Figure 2](#).

Guided by the standard sampling procedure as outlined (United Nations Educational, Scientific and Cultural Organization (UNESCO)/World Health Organization (WHO)/United Nations Environment Programme (UNEP), 1992; Bartram & Ballance, 1996; American Public Health Association (APHA)/American Water Works Association (AWWA)/Water Environment Federation (WEF), 1999; Appelo & Postma, 2005), there was strict adherence to standard sampling procedure throughout the sampling, storage and transport of samples. Floaters were used to aid samplers to get to the required depth. Samples were drawn from these sources with the help of a bailer which at each point was rinsed several times before sampling.

All samples were collected into sterilized high density polyethylene bottles (100 ml for heavy metals and 250 ml for major ions), throughout the sampling period. At each sampling site, a total of 3 samples was collected: one for major ions, one for heavy metals and one as a spare. The base rather than the neck of sampling bottles was held to avoid the introduction of possible contamination from samplers. Samples were filtered using a Sartorius filtering apparatus and a 0.45 µm cellulose acetate filter membrane after which samples for heavy metal analysis were acidified with reagent grade nitric acid. In order to avoid mix-up of samples, the coded name for each sample was written on the bottle just before sampling commenced at each sampling site with asterisks on samples acidified for heavy/trace elements analysis.

Thirty-five physico-chemical parameters of water quality significance were analysed for complete water quality determination. All major ions were analysed at the laboratories of the Water Research Institute of the Centre for Scientific and Industrial Research in Ghana whereas all heavy/trace elements analyses were conducted at the Geological Survey of Denmark and Greenland, Denmark. Parameters such as pH, temperature, electrical conductivity (EC) and alkalinity were analysed *in situ* in the field. In all analysis, strict quality assurance and quality control measures were adopted to ensure the integrity of results.

3.1. pH and EC

On site or *in situ* analysis for pH, temperature and EC were conducted using a WTW-Multiline P4 Universal Meter which was calibrated periodically to ensure accuracy of readings.

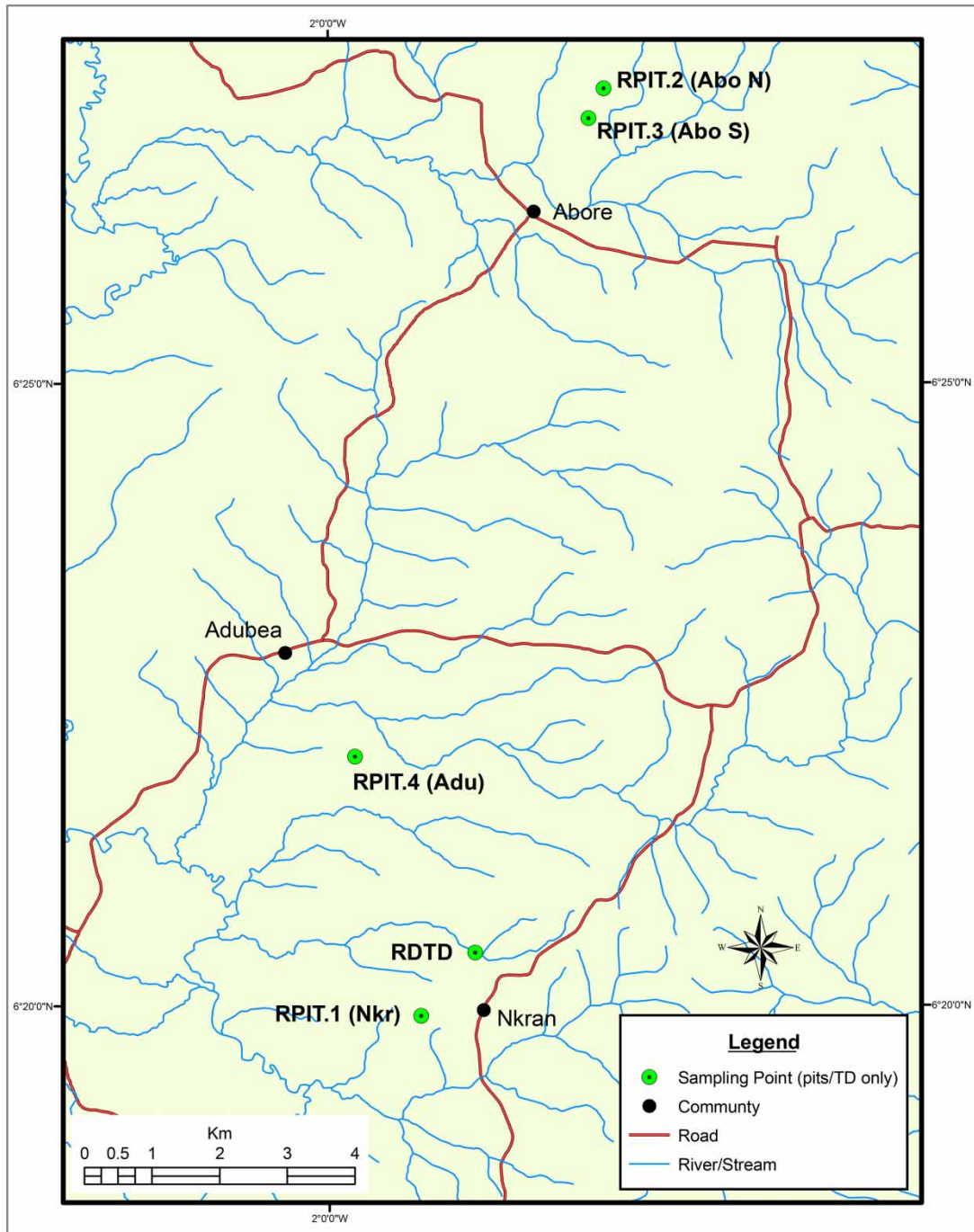


Fig. 2. Topographic map of a section of Resolute Amansie Ltd (RAL) concession, showing pits (RPIT) and decommissioned tailings dam (RDTD). Names given to the pits by the mining company are provided in brackets (). For easy identification, the four pits in this figure have been named as follows in this paper: Nkran 1 for RPIT 1 (Nkr), Abore 1 for RPIT 2 (AboN), Abore 2 for RPIT 3 (AboS) and Nkran 2 for RPIT 4 (Adu).

3.2. Alkalinity

The digital titration method was used to measure alkalinity values on the field using the HACH Digital Titrator Model 16900-01. A 100 ml sample was measured using a measuring cylinder and transferred into a 250 ml Erlenmeyer flask after which one ‘pillow’ of powdered Bromocresol Green-Methyl Red indicator was added to it. The green coloured sampled was titrated with 1.6 N sulphuric acid in a titrant cartridge by turning the counter knob of the digital counter and swirling the sample as titration went on until an end point indicated by a pinkish colour was reached. The value on the digital counter was observed and recorded. Alkalinity was calculated by multiplying the digits that appeared on the digital counter by a digit multiplier from the manual taking into account the volume of sample used.

3.3. Total hardness

Total hardness, which is the sum of the calcium and magnesium concentrations, was determined by pipetting a 50 ml sample into a conical flask and buffering it to a pH of 10.0 ± 0.1 . A few crystals of Eriochrome Black T were added as an indicator and the solution titrated with standard 0.01M EDTA until the last trace of purple colour disappeared.

The total hardness was subsequently calculated using the following equation:

$$\text{Total Hardness} = \frac{\text{ml EDTA} \times B \times 1,000}{\text{ml of sample}}$$

where B = mg of CaCO_3 equivalent to 1.00 ml EDTA titrant. That is

$$\frac{\text{mg CaCO}_3}{\text{ml EDTA}}$$

3.4. Silicon

A 50 ml sample was quickly transferred into a conical flask with 1.0 ml HCl and 2.0 ml ammonium molybdate reagent. Mixing was ensured by inverting it about six times and leaving it to stand for 5 to 10 minutes after which 2 ml oxalic acid solution was added and mixed thoroughly. Colour was read within 2 to 15 minutes at 410 nm. Silicon concentration was determined directly from the calibration curve.

3.5. Ions (nutrients)

A Dionex 120 Ion Chromatograph (Dionex Corporation, USA) was used to determine the selected anions and cations, i.e. fluoride, chloride, nitrate, phosphate, sulphate, sodium, ammonium, potassium, calcium and magnesium. Standard solutions of elements under investigation were prepared from aliquot solutions into various concentrations (in ppm) using the simple dilution formula ($M_1V_1 = M_2V_2$). The instrument was standardized using standard solution. Samples were then injected into the instrument for the determination of elements. Concentration peaks of various elements were automatically processed by the computer and results printed out. Dispersion of the various elements in a sample was done by

the eluent in two different columns for anions and cations, respectively. The anion eluent was a solution of 3.5 mM Na₂CO₃ and 1.0 mM NaHCO₃ whilst the eluent for cations was 1.23 ml of H₂SO₄. During the preparation of eluent, trapped air was degassed in an ultrasonic bath.

3.6. Total dissolved solids

The gravimetric method was employed for the analysis of total dissolved solids (TDS). A 100 ml sample was measured and transferred into a prepared disc. The measured sample was filtered through a glass fibre filter using a vacuum pump apparatus for about 3 minutes. The filter was washed with 10 ml of deionized and filtered water. The total filtrate was transferred to a weighed evaporating disc and evaporated to dryness on a water bath. The disc was then placed in an oven for at least 1 hour at 180 °C, cooled in a desiccator and weighed to a constant weight. The drying and cooling cycle was repeated until a constant reading or a difference of <0.5 mg was obtained.

Total dissolved solids was then calculated as follows:

$$\text{Total Dissolved Solids (mg/L)} = \frac{(A - B)}{C} \times 10^6$$

where A = weight of dried residue and dish, g

B = weight of dish, g

C = volume of sample, ml

3.7. Chemical oxygen demand

The closed tube reflux method was used to measure the amount of chemical oxygen demand (COD) in samples collected. A 5 ml sample was placed in a culture tube. A total of 3 ml of K₂CrO₄ was added to the solution followed by 7 ml of H₂SO₄ reagent (that is silver sulphate in sulphuric acid). The sample was tightly capped and shaken to mix completely and the tubes were placed in a COD digester preheated to 150 °C and refluxed for 2 hours. Samples were removed to cool to room temperature, 1 or 2 drops of ferroin indicator were added and titrated against Standard Ferrous Ammonium Sulphate (FAS) until a blue-green to reddish brown end point was reached.

The above process was repeated for a blank containing the reagents and a volume of deionized water equal to that of the sample.

COD was then calculated as follows;

$$\text{COD as MgO}_2/\text{LCOD as MgO}_2/\text{L} = \frac{(A - B) \times M \times 8,000}{\text{ml sample}}$$

where A = ml FAS used for blank

B = ml FAS used for sample

M = molarity of FAS

8,000 = milliequivalent weight of oxygen × 1,000 ml/L

3.8. Heavy/trace elements analysis

Trace elements and heavy metals in water samples were analysed by inductively coupled plasma mass spectrometry on a PerkinElmer Elan 6100DRC at the Geological Survey of Denmark and Greenland. The instrument was controlled by Elan software version 2.3.2, which was also used for calibration, data collection and quantification. For quantitative analysis, solutions based on the Merck VI multi-element standard were used. The following elements were determined: Ag, Al, As, Be, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Ti and Zn.

4. Results

The values obtained from the evaluation of some of the physico-chemical parameters for water quality determination from water sampled in three different seasons (wet, mid- and dry seasons) are presented in Table 1. The data from water samples analysed from Nkran 1, Nkran 2, Abore 1 and Abore 2 were different from season to season. For the same pit, the pH values recorded at the three different seasons were similar. The pH values recorded for each of the four pits at the three different seasons were within the World Health Organization (WHO) acceptable limit of pH 6.5–8.5. The TDS values obtained from the water samples analysed from Nkran 1 were similar for each of the three seasons that is 246 mg/L, 253 mg/L and 257 mg/L for the wet, mid- and dry seasons, respectively. However, the TDS values obtained from Nkran 2, Abore 1 and Abore 2 were significantly different for the three seasons. As an example, the TDS values recorded for Nkran 2 were 102 mg/L, 197 mg/L and 104 mg/L for the wet, mid- and dry seasons, respectively. The seasons with the highest TDS also

Table 1. Physico-chemical parameters for water quality determination in three different seasons.

Seasons	pH	EC (μScm^{-1})	Temp ($^{\circ}\text{C}$)	TDS (mg/L)	Turbidity (NTU)	Total hardness (mg/L)	Alkalinity (mEq/L)
Nkran 1							
Wet	8.24	466.00	32.40	246.00	5.66	170.00	100.00
Mid	7.98	474.00	28.70	253.00	1.94	190.00	112.00
Dry	7.75	494.00	29.30	257.00	2.00	175.00	97.00
Avg.	7.99 ± 0.1	478 ± 8.3	30.13 ± 1.2	252 ± 3.2	3.2 ± 1.2	178.33 ± 6.0	103 ± 4.6
Nkran 2							
Wet	7.83	194.00	31.10	102.00	40.30	64.00	84.00
Mid	7.85	200.00	29.90	197.00	52.00	87.00	80.00
Dry	7.82	202.00	29.70	104.00	1.00	75.00	75.00
Avg.	7.83 ± 0	198.67 ± 2.4	30.23 ± 0.4	134.33 ± 31.3	31.10 ± 15.4	75.33 ± 6.6	79.67 ± 2.6
Abore 1							
Wet	7.65	109.00	32.00	61.00	2.96	30.00	48.00
Mid	7.32	160.00	30.30	87.00	2.12	70.00	80.00
Dry	7.27	126.00	30.20	67.00	5.00	40.00	60.00
Avg.	7.41 ± 0.1	131.67 ± 15	30.83 ± 0.58	71.67 ± 7.9	3.36 ± 0.9	46.67 ± 12	62.67 ± 9.3
Abore 2							
Wet	7.10	113.00	30.00	58.00	3.01	30.00	50.00
Mid	7.15	150.00	30.20	84.00	69.20	75.00	72.00
Dry	7.10	146.00	30.40	80.00	2.00	50.00	61.00
Avg.	7.12 ± 0	136.33 ± 11.7	30.2 ± 0.12	74.00 ± 8.1	24.74 ± 22.2	51.67 ± 13	61.00 ± 6

recorded the highest EC values with the exception of the water samples analysed from Nkran 2 pit. It should be mentioned that all the TDS values recorded for each of the four pits at the three different seasons were within the WHO acceptable limits of 600 mg/L. Turbidity values of water samples recorded from Nkran 1 during the wet season, Nkran 2, during the wet and mid seasons and Abore 2 during the mid season were all above the WHO acceptable limit of 5 NTU, with Abore 2 recording the highest value of 69.20 NTU at the mid-season.

From Table 2, it can be seen that the nitrate and chloride ions were significantly higher for water samples obtained from the pits at mid-season with the exception of Abore 2, where nitrate and chloride values from the wet season were higher than the dry and mid-seasons. As an example, the chloride concentrations recorded for the mid-season were 14.90, 14.90, 5.0 and 9.90 mg/L for Nkran 1, Nkran 2, Abore 1 and Abore 2, respectively. It should however be noted that the chloride and nitrate ions recorded for the four pits at each of the three seasons were within WHO acceptable limits of 200–300 mg/L and 50 mg/L, respectively. Similar observations were made for the fluoride ions from each of the four pits at the three different seasons. The fluoride ion concentrations recorded were within the WHO maximum permissible limit (MPL) of 1.5 mg/L. The Mg and Mg Hard concentrations were generally higher at the mid-season (for example Mg Hard concentrations for Nkran 1, were 63.75, 69.75 and 34.75 mg/L, for the wet, mid- and dry seasons) than the wet and dry seasons with the exception of the water samples analysed from the Nkran 2 pit. The Ca Hard and HCO₃ concentrations varied from pit to pit and from season to season as well.

The sulphate and sodium ion concentrations recorded for the different pits at the three different seasons were within the WHO MPL and they varied from pit to pit and from season to season (Table 3). No

Table 2. Ions (nutrient) concentration for the three different seasons.

Seasons	HCO ₃	Ca Hard	Mg Hard	Mg	F	NO ₃	Cl
	(mg/L)						
Nkran 1							
Wet	122.00	106.25	63.75	15.49	1.32	0.25	9.90
Mid	136.64	120.25	69.75	16.95	0.10	1.40	14.90
Dry	118.34	140.25	34.75	8.44	1.02	0.00	9.90
Avg.	125.66 ± 5.6	122.25 ± 9.9	56.08 ± 10.8	13.63 ± 2.6	0.81 ± 0.4	0.55 ± 0.4	11.57 ± 1.7
Nkran 2							
Wet	102.48	32.00	32.00	7.78	1.09	0.15	9.90
Mid	97.60	60.00	27.00	6.56	1.04	1.95	14.90
Dry	91.50	40.00	35.00	8.51	0.96	0.21	7.90
Avg.	97.19 ± 3.2	44.00 ± 8.3	31.33 ± 2.3	7.61 ± 0.6	1.03 ± 0	0.77 ± 0.6	10.90 ± 2.1
Abore 1							
Wet	58.56	16.00	14.00	3.40	1.20	0.31	7.90
Mid	97.60	27.50	42.50	10.33	0.34	0.00	5.00
Dry	73.20	30.00	10.00	2.43	0.89	0.00	6.00
Avg.	76.45 ± 11.4	24.50 ± 4.3	22.17 ± 10.2	5.39 ± 2.5	0.81 ± 0.3	0.11 ± 0.1	6.30 ± 0.9
Abore 2							
Wet	61.00	16.00	14.00	3.40	1.29	1.33	7.90
Mid	87.84	35.00	40.00	9.72	1.11	5.00	9.90
Dry	74.42	30.00	20.00	4.86	0.83	0.39	4.00
Avg.	74.42 ± 7.7	27.00 ± 5.7	24.67 ± 7.9	5.99 ± 7.9	1.08 ± 0.1	2.24 ± 1.4	7.27 ± 1.7

Table 3. Physico-chemical parameters for water quality determination in three different seasons.

Seasons	SO ₄	Si	Na	NH ₄	Ca	K	COD
	(mg/L)						
Nkran 1							
Wet	121.00	18.50	26.50	0.80	42.50	3.10	57.00
Mid	109.98	15.21	39.50	1.17	48.10	2.90	10.00
Dry	158.00	16.00	26.10	0.58	56.10	2.60	19.20
Avg.	129.66 ± 14.5	16.57 ± 1	30.70 ± 4.4	0.85 ± 0.2	48.90 ± 3.9	2.87 ± 0.1	28.73 ± 14.4
Nkran 2							
Wet	4.87	18.80	18.70	0.07	12.80	2.50	42.40
Mid	36.87	1.53	16.60	0.69	24.00	2.00	35.20
Dry	10.30	20.60	14.90	0.12	16.00	1.90	38.40
Avg.	17.35 ± 9.9	13.64 ± 6.1	16.73 ± 1.1	0.29 ± 0.2	17.60 ± 3.3	2.13 ± 0.2	38.67 ± 2.1
Abore 1							
Wet	5.76	10.70	14.20	0.20	6.40	2.00	32.60
Mid	10.98	3.44	16.10	0.00	11.00	0.90	44.80
Dry	10.90	14.00	12.60	0.00	12.00	1.90	54.40
Avg.	9.21 ± 1.7	9.38 ± 3.1	14.30 ± 1	0.07 ± 0.1	9.80 ± 1.7	1.60 ± 0.4	43.93 ± 6.3
Abore 2							
Wet	1.00	14.40	10.90	0.10	6.40	3.80	26.10
Mid	11.76	0.83	13.60	1.29	14.00	3.40	12.80
Dry	24.80	11.40	11.60	0.77	12.00	3.60	16.00
Avg.	12.52 ± 6.9	8.88 ± 4.1	12.03 ± 0.8	0.72 ± 0.3	10.80 ± 2.3	3.60 ± 0.1	18.30 ± 4.0

observable trend was noticed as far as the season by season variation is concerned. A similar observation was made for Si, Na and Ca ion concentrations. However, the K ion concentrations were generally higher at the wet season than the mid- and dry seasons. It was also observed that the COD values for Nkran 1 and Nkran 2 pits were higher in the wet season than the other two seasons. However, the highest COD values in the Abore 1 and Abore 2 pits were recorded in the dry season. With WHO MPL of 35 mg/L, the ammonium cation concentrations recorded at the three different seasons were within the MPL.

It can be seen from Table 4 that the Fe concentration varied from pit to pit and from season to season. The maximum Fe concentration of 0.61 mg/L was recorded in the mid-season and it was obtained from Nkran 1 pit. This value is above the WHO MPL of 0.3 mg/L. The Cr ions were absent from each of the pits analysed and for all the seasons. The Al concentrations recorded were within the WHO MPL of 0.1–0.2 mg/L. It should however be noted that the Al concentration recorded for the Nkran 1 pit in the mid-season was 0.9 mg/L. The Ti and Mn values recorded were almost negligible. It should be noted that the B concentration of 0.19 mg/L recorded for Nkran 1 pit in the dry season is above the WHO MPL. The S concentration was significantly higher for the water sample obtained from the Nkran 1 pit and at the wet season. It should be noted that the Nkran 1 pit did not record any S ions in the dry and mid-seasons.

Negligible concentrations of the heavy metals: Co, Ni, Cu, Zn, Ag, Cd, Hg, Pb and Sb were recorded from each of the pits at the three different seasons (Tables 5 and 6). All the recorded values were within the WHO MPL. However, the As concentrations recorded at the three different seasons for each of the pits examined were above the WHO MPL of 0.01 mg/L. For example, the As concentration for Nkran 1 pit was 0.26, 0.31 and 0.37 mg/L for the wet, mid- and dry seasons, respectively.

The average of some of the concentrations of the elements analysed are presented in the figures below. From Figure 3, it can be seen that the average concentrations of the metals As, Zn and Fe in

Table 4. Trace elements/heavy metals concentrations for the three different seasons.

Seasons	Al	S	B	Ti	Cr	Mn	Fe
	(mg/L)						
Nkran 1							
Wet	0.02	70.80	0.01	0.03	0.00	0.01	0.03
Mid	0.09	0.00	0.00	0.00	0.00	0.01	0.61
Dry	0.00	0.00	0.19	0.05	0.00	0.11	0.02
Avg.	0.04 ± 0	23.60 ± 23.6	0.06 ± 0.1	0.03 ± 0	0.00 ± 0	0.04 ± 0	0.22 ± 0.2
Nkran 2							
Wet	0.01	2.33	0.00	0.01	0.00	0.01	0.00
Mid	0.01	0.00	0.00	0.00	0.00	0.01	0.01
Dry	0.00	0.00	0.04	0.01	0.00	0.00	0.02
Avg.	0.01 ± 0	0.78 ± 0.8	0.01 ± 0	0.01 ± 0	0.00 ± 0	0.01 ± 0	0.01 ± 0
Abore 1							
Wet	0.01	0.00	0.00	0.01	0.00	0.00	0.03
Mid	0.03	0.00	0.00	0.00	0.00	0.07	0.15
Dry	0.00	0.00	0.06	0.01	0.00	0.03	0.09
Avg.	0.01 ± 0	0.00 ± 0	0.02 ± 0	0.01 ± 0	0.00 ± 0	0.03 ± 0	0.09 ± 0
Abore 2							
Wet	0.01	0.00	0.00	0.01	0.00	0.01	0.16
Mid	0.02	0.00	0.00	0.00	0.00	0.58	0.03
Dry	0.00	0.00	0.06	0.01	0.00	0.00	0.00
Avg.	0.01 ± 0	0.00 ± 0	0.02 ± 0	0.01 ± 0	0.00 ± 0	0.20 ± 0.2	0.06 ± 0

the Nkran 1 pit were 0.31 ± 0.0 , 0.01 ± 0.0 and 0.22 ± 0.2 mg/L, respectively. The average As concentrations in all the pits were above the WHO MPL. The average concentration of Zn and Fe in all the pits was between 0 ± 0.0 – 0.02 ± 0.0 and 0.01 ± 0.0 – 0.22 ± 0.2 mg/L, respectively. All these values are within the WHO MPL.

The data from Figure 4 show that the average sulphate and carbonate ion concentrations were higher in the Nkran 1 pit when compared with that of Nkran 2, Abore 1 and Abore 2. However, the average chloride concentrations in all of the four pits were similar. The average sulphate, chloride and carbonate concentrations were within the MPL of WHO.

It is obvious from Figure 5 that a negligible amount of F, NO_3 and S were found in Nkran 2, Abore 1 and Abore 2 pits. However, the concentration of S recorded in the Nkran 1 pit was significantly higher. Though S concentrations of 0 mg/L were recorded for both the dry and mid- seasons, the S concentration recorded in the wet season (70.8 mg/L) was relatively higher. It should however be noted that the average concentrations of F and NO_3 recorded were within the WHO MPL.

The average concentration of Ca Hard in the Nkran 1 pit was significantly higher than that of Nkran 2, Abore 1 and Abore 2 pits (Figure 6). A similar trend was observed for Ca. The Si concentrations recorded from all of the four pits were similar. For all the pits, the concentration of Ca Hard was approximately 60% higher than that of Ca.

Considering the average values of the Mg, Mg Hard and Na recorded (Figure 7), it was observed that Nkran 1 pit had the highest concentrations of all the elements when compared with that of Nkran 2, Abore 1 and Abore 2. The Mg Hard concentrations were approximately 76% higher than those of Mg for all the pits examined. The Na concentrations recorded for all the pits were within the WHO MPL.

Table 5. Trace elements/heavy metals concentrations for the three different seasons.

Seasons	Co	Ni	Cu	Zn	As	Ag	Cd
	(mg/L)						
Nkran 1							
Wet	0.00	0.00	0.00	0.00	0.26	0.00	0.00
Mid	0.00	0.00	0.00	0.00	0.31	0.00	0.00
Dry	0.00	0.01	0.01	0.04	0.37	0.00	0.00
Avg.	0.00 ± 0	0.01 ± 0	0.01 ± 0	0.01 ± 0	0.31 ± 0	0.00 ± 0	0.00 ± 0
Nkran 2							
Wet	0.00	0.00	0.01	0.03	0.01	0.00	0.00
Mid	0.00	0.01	0.00	0.00	0.02	0.00	0.00
Dry	0.00	0.00	0.01	0.02	0.02	0.00	0.00
Avg.	0.00 ± 0	0.00 ± 0	0.01 ± 0	0.02 ± 0	0.02 ± 0	0.00 ± 0	0.00 ± 0
Abore 1							
Wet	0.00	0.00	0.00	0.00	0.08	0.00	0.00
Mid	0.00	0.00	0.00	0.00	0.19	0.00	0.00
Dry	0.00	0.00	0.00	0.06	0.18	0.00	0.00
Avg.	0.00 ± 0	0.00 ± 0	0.00 ± 0	0.02 ± 0	0.15 ± 0	0.00 ± 0	0.00 ± 0
Abore 2							
Wet	0.00	0.00	0.01	0.00	0.14	0.00	0.00
Mid	0.00	0.00	0.00	0.00	0.44	0.00	0.00
Dry	0.00	0.00	0.00	0.01	0.15	0.00	0.00
Avg.	0.00 ± 0	0.00 ± 0	0.00 ± 0	0.00 ± 0	0.24 ± 0.1	0.00 ± 0	0.00 ± 0

Note: The zero values in this table imply that the concentrations of the various metal ions were below the detection limit of the equipment used for the analysis.

As indicated in Figure 8, the average concentration of B, was highest in Nkran 1 pit and lowest in Nkran 2 pit whereas the average concentration of Mn was highest in samples taken from Abore 2 pit and lowest in Nkran 2 pit. Ti however recorded the highest average concentration in samples taken from Nkran 1 and lowest in both Abore 1 and 2 pits. Generally, B and Mn had very low concentrations in samples from Nkran 2 pit. Even though the average B and Mn recorded in all of the four pits were below the WHO permissible limits, the concentration values recorded in some of the seasons were higher than the WHO permissible limit as can be seen in Table 4. For example, the boron concentration in Nkran 1 in the dry season was 0.19 mg/L. Similarly, the Mn concentration recorded in the mid-season in Abore 2 pit was 0.58 mg/L.

5. Discussion

The physico-chemical parameters of water samples investigated in this study varied from pit to pit and from season to season. The hydrochemistry of pit water was noted to stem from the dissolution of minerals from major/parent rocks found in the area, mostly from sulphides, carbonate, quartz and feldspar. Chemicals released from direct mining activities, residues of which were still persistent in the abandoned tailing dam, such as sodium, potassium and copper sulphate also likely contributed immensely to the hydrochemistry of water in the area. Activities of illegal artisanal mining which flourished

Table 6. Heavy metals/trace elements concentrations for the three different seasons.

Seasons	Hg	Pb	Sb
	(mg/L)		
Nkran 1			
Wet	0.00	0.00	0.00
Mid	0.00	0.00	0.00
Dry	0.00	0.00	0.00
Avg.	0.00 ± 0	0.00 ± 0	0.00 ± 0
Nkran 2			
Wet	0.00	0.00	0.00
Mid	0.00	0.00	0.00
Dry	0.00	0.00	0.00
Avg.	0.00 ± 0	0.00 ± 0	0.00 ± 0
Abore 1			
Wet	0.00	0.00	0.00
Mid	0.00	0.00	0.00
Dry	0.00	0.00	0.00
Avg.	0.00 ± 0	0.00 ± 0	0.00 ± 0
Abore 2			
Wet	0.00	0.00	0.00
Mid	0.00	0.00	0.00
Dry	0.00	0.00	0.00
Avg.	0.00 ± 0	0.00 ± 0	0.00 ± 0

Note: The zero values in this table imply that the concentrations of the various metal ions were below the detection limit of the equipment used for the analysis.

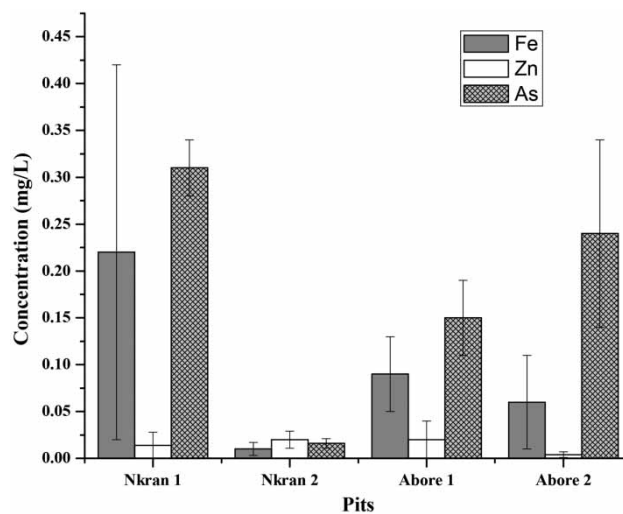


Fig. 3. The average concentrations of Fe, Zn and As ions for water sampled from the four pits investigated.

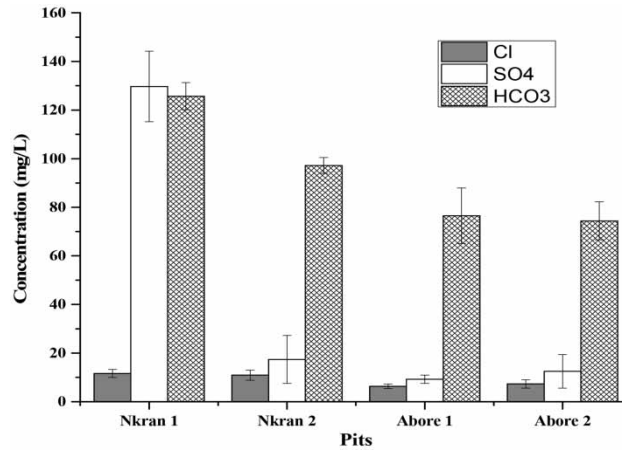


Fig. 4. The average concentrations of Cl, SO₄ and HCO₃ ions for water sampled from the four pits investigated.

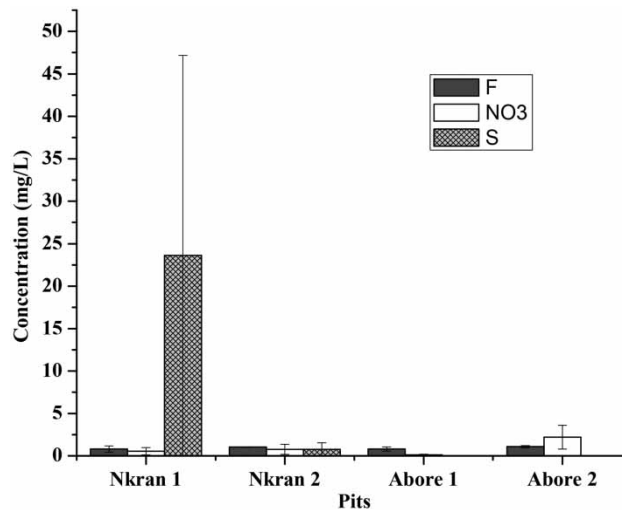


Fig. 5. The average concentrations of F, NO₃ and S ions for water sampled from the four pits investigated.

tremendously just after the mine closure also contributed to the hydrochemistry and trend patterns in the various pits. The recommended land (pit) use which was part of the reclamation process also increased organic nutrients, mainly from feed used to feed fishes in the fishpond, which might also have contributed to the hydrochemistry of water from the four pits studied. Similarly, direct anthropogenic waste both from domestic and agricultural activities seemed to have also played a role in the hydrochemistry of the pit water.

There is a positive correlation between EC and Mg/Na/Ca/SO₄ as shown in Table 7 underscoring the importance of Mg, Na, Ca and SO₄ ions in the overall dissolved solids in solution and subsequent build-up of EC. There is also a strong correlation between Ca and HCO₃, and Ca and Mg, which could be an indication of the high presence of calcite minerals interacting with surface water (Table 8).

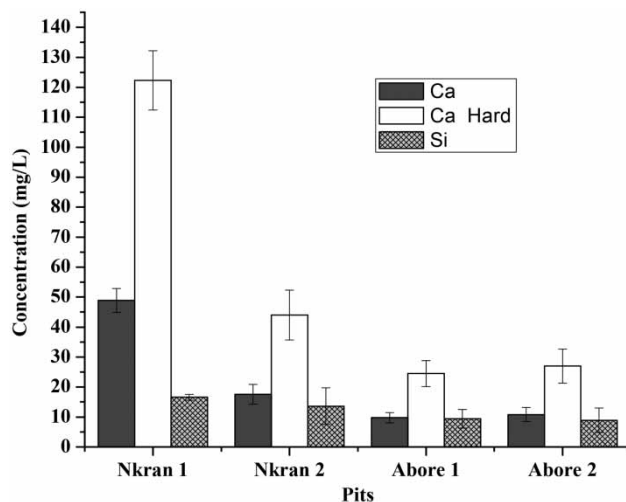


Fig. 6. The average concentrations of Ca, Ca Hard and Si ions for water sampled from the four pits investigated.

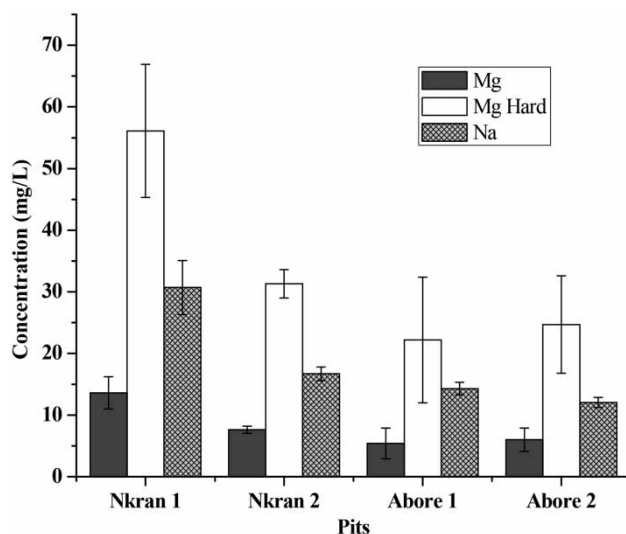


Fig. 7. The average concentrations of Mg, Mg Hard and Na ions for water sampled from the four pits investigated.

Data from water samples analysed from the pit water and graphical presentation from figures show high arsenic contents in almost all pit water sampled. In addition, boron in water from Nkran 1 pit exceeded WHO acceptable limits. Turbidity levels were also higher in Nkran 2 and Abore 2 pits. Most parameters such as conductivity, TDS, bicarbonates, sulphates and calcium were higher in samples from the Nkran 1 pit, though within WHO acceptable limits. Nkran 2 and Abore 2 pits were subjected to intense illegal mining after the mine was officially closed. Turbidity, was also high in samples from Nkran 2 and Abore 2 pits, in most cases higher than WHO permissible levels, again due to the likely impact of intensive artisanal small scale mining operations after the exit of the mining company.

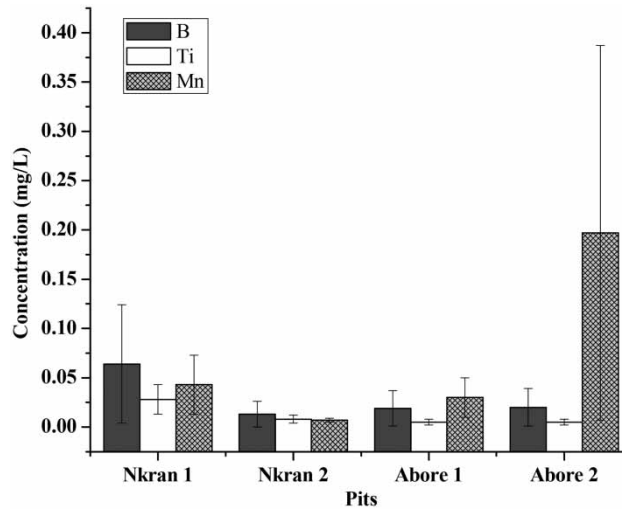


Fig. 8. The average concentrations of B, Ti and Mn ions for water sampled from the four pits investigated.

Table 7. Summary of correlation values between EC and Mg/Na/Ca/SO₄.

EC	Correlation	Significance level
Mg	0.6	0.01
Na	0.6	0.01
Ca	0.55	0.01
SO ₄	0.4	0.05

Table 8. Summary of correlation values between Ca and Mg/HCO₃.*

Ca	Correlation	Significance level
Mg	0.52	0.01
HCO ₃	0.50	0.01

*Correlation values were calculated using SPSS.

Element load, especially in the Nkran 1 pit suggests the occurrence of oxidation of sulphide-bearing rocks exposed during the mining period. This affirms the assertion that rock exposed after the mining period may still be leaching out metals, especially arsenic, long after the closure of the mine (Hudson-Edwards *et al.*, 2003).

Seasonally, rainfall pattern, temperature and wind action are the main natural determinants that affect water quality (Tarras-Wahlberg *et al.*, 2000; Conovitz *et al.*, 2006). However, given the approximately uniform nature of the latter two determinants (temperature and wind action) in Ghana, seasonal changes largely depend on the nature and pattern of rainfall within the year which could greatly influence recharge of both surface and groundwater during the year through direct precipitation, runoffs for surface water and percolation in the case of groundwater recharge. It was realized that most activities, including both illegal mining and farming, were at their peak during the mid-season where rainfall is

moderate and therefore favours a lot of human activities. This is the likely explanation why anthropogenic induced parameters were higher in the mid-season.

Dewatering forms a vital part of underground mining. Once the mining activity stops, groundwater accumulates in the pits. The quality of the accumulated water in the pits is therefore a clear indication of the groundwater quality in the mining community. Once the pits examined had been decommissioned, the community around may have assumed that water accumulated in these pits is safe for use. Considering the physico-chemical parameters for water quality analysed in the study, it can be deduced that the pit water is moderately pristine. However, the incidence of high arsenic in all the pits is worrying. Arsenic, a cancer causing chemical, has a MPL of 0.01 mg/L as stipulated in the WHO drinking water guidelines and standards (Yamamura *et al.*, 2003; WHO, 2011). The average arsenic concentrations recorded in Nkran 1, Nkran 2, Abore 1 and Abore 2 pits were 0.31, 0.02, 0.15 and 0.24 mg/L, respectively with Abore 2 recording as high as 0.44 mg/L arsenic concentration in the mid-season. It is therefore obvious that the water quality of the decommissioned pits with respect to arsenic concentrations is unacceptable. The water in these pits can seep into other water bodies and affect their quality. As discussed earlier, many rural areas not having access to water or due to the proximity of these pits to their homes and/or farms, are likely to rely on this accumulated water (in the pits) as their source of water for drinking, cooking and washing, thereby endangering their lives.

The mining company that operated in the area converted the pits examined in this study into fish ponds as part of the reclamation measures adopted by the company and handed over to the community. However, the indigenes were not interested in fish farming and hence left the ponds to deteriorate. Turning the pits into fish ponds could have negative health consequences on communities that feed on fish from these ponds, due to probable bioaccumulation of the arsenic in the fish tissue. Aside from arsenic, boron concentrations, as well as the water turbidity in some instances, were also above WHO MPL, butressing the fact that water quality in these pits was not totally potable, even after mine closure.

The various measures outlined and implemented by the Ghanaian environmental authorities are laudable and commended, as these measures aim at ensuring that mining companies do not leave sites of their operations unattended to after mine closure. However, the relatively high concentrations of arsenic question the acceptability of the water quality in the pits even after the mining company was given a Certificate of Closure indicating that they have carried out an effective reclamation process. With the knowledge that the water quality in the decommissioned pits could be affected years after mine closure, it is imperative that institutions that safeguard the environment focus on water reclamation in abandoned pits on the same scale as land reclamation. Current structure for reclamation is contained in the Reclamation Security Agreement which stipulates procedures for posting of a Reclamation Bond with the Bank and how to redeem the bonded amount. Schedule 2 of the document sets the criteria for reclamation. Under this schedule, mine water from pits is regarded as effluent (wastewater) and not as natural water. This lapse, in the opinion of the authors, does not allow for critical analysis of mine water accumulated in abandoned pits. There is therefore the need to declassify accumulated water in decommissioned pits from leachate status to natural waters status. Reclamation of water from abandoned pits, should therefore be included in the remediation programme for mine closure to ensure that accumulated water in decommissioned pits meets both local and international standards for potable water after mine closure.

It is likely that the finding that water quality restoration from abandoned pits was not a social issue in the reclamation process has been occurring in other similar regions. Awareness being created by this research therefore suggests other environmental or similar institutions, with the mandate of ensuring

regeneration of disturbed sites, should equally develop benchmarks for ensuring regeneration of pit water during reclamation process.

One major limitation of this study is the authors' inability to conduct sediment analysis of the water in the decommissioned pits. Sediment analysis of water in the decommissioned pits should be conducted in the future. The authors also recommend that bioaccumulation studies should be conducted on the aquatic flora and fauna in the decommissioned pits as well as inhabitants living close to the decommissioned pits.

6. Conclusions

The physico-chemical parameters for water quality analysed for four decommissioned pits (Nkran 1, Nkran 2, Abore 1 and Abore 2) in the Amansie West District show that the quality of water accumulated in the pits, which forms an integral available option as a source of water accessible to the mining community, has to a large extent been affected years after decommissioning. The concentrations of the physico-chemical parameters varied from season to season and from pit to pit. The concentrations of ions (nutrients) analysed were within WHO acceptable limits. For example, the concentrations of Na, Ca, K and NH_4 were 16.73, 17.60, 1.9 and 0.29 mg/L for Nkran 2 pit, respectively. The concentrations of the trace elements/heavy metals (concentrations of B and Mn were 0.19 in Nkran 1 pit and 0.58 mg/L in Abore 1 pit, respectively, while the concentrations of Co, Ni, Cu, Cd, Hg and Pb were almost negligible) were generally also within the WHO acceptable limit. Arsenic was however an exception, as arsenic concentrations recorded from water samples analysed in almost all pits were higher than the WHO acceptable limit. The average arsenic concentrations analysed in Nkran 1, Nkran 2, Abore 1 and Abore 2 pits were 0.31, 0.02, 0.15, 0.24 mg/L, respectively. These values suggest that, though the quality of water from the pits in terms of most of the physico-chemical parameters were acceptable, the high levels of turbidity (69.20 NTU for Abore 2 pit) and arsenic strongly suggest that reclamation after active mining should not focus only on land reclamation but should equally focus on reclamation of accumulated water in abandoned/decommissioned pits.

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References

- APHA/AWWA/WEF (1999). *Standard Methods for the Examination of Water and Waste Water*. American Public Health Association, Washington DC.
- Appelo, C. A. J. & Postma, D. (2005). *Geochemistry, Groundwater and Pollution*, 2nd edn. A. A. Balkema Publishers, Leiden, The Netherlands.

- Bartram, J. & Ballance, R. (1996). *Water Quality Monitoring: A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes*. Published on behalf of UNDP & WHO, Chapman & Hall, London.
- Bhattacharya, A., Routh, J., Jacks, G., Bhattacharya, P. & Mörth, M. (2006). *Environmental assessment of abandoned mine tailings in Adak, Västerbotten district (northern Sweden)*. *Applied Geochemistry* 21(10), 1760–1780.
- Blowes, D. W. & Jambor, J. L. (1990). *The pore-water geochemistry and the mineralogy of the vadose zone of sulfide tailings, Waite Amulet, Quebec, Canada*. *Applied Geochemistry* 5(3), 327–346.
- Blowes, D. W., Frind, E., Johnson, R., Robertson, W., Molson, J. & Ptacek, C. (1994). Acid-neutralization reactions in inactive mine tailings impoundments and their effect on the transport of dissolved metals. In: *Paper Presented at the Proceedings of the International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage*. Volume 1: Mine drainage, United States Department of the Interior, Bureau of Mines Special Publications, SP 06A-94.
- Carlsson, E., Öhlander, B. & Holmström, H. (2003). *Geochemistry of the infiltrating water in the vadose zone of a remediated tailings impoundment, Kristineberg mine, northern Sweden*. *Applied Geochemistry* 18(5), 659–674.
- Clausen, J., Bostick, B. & Korte, N. (2011). *Migration of lead in surface water, pore water, and groundwater with a focus on firing ranges*. *Critical Reviews in Environmental Science and Technology* 41(15), 1397–1448.
- Coakley, G. J. (1996). *The Mineral Industry of Ghana*. US Geological Survey, Minerals Information, Washington, DC.
- Conovitz, P. A., MacDonald, L. H. & McKnight, D. M. (2006). *Spatial and temporal active layer dynamics along three glacial meltwater streams in the McMurdo Dry Valleys, Antarctica*. *Arctic, Antarctic, and Alpine Research* 38(1), 42–53.
- Dickson, K. B. & Benneh, G. (1977). *A New Geography of Ghana*. Longman, London.
- Edraki, M., Baumgartl, T., Manlapig, E., Bradshaw, D., Franks, D. M. & Moran, C. J. (2014). *Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches*. *Journal of Cleaner Production* 84, 411–420.
- GOG (2006). *Ghana Districts – A repository of all Districts in the Republic of Ghana*, A Public-Private Partnership Programme between Ministry of Local Government and Rural Development and Maks Publications & Media Services. Retrieved July 26, 2016, from www.Ghanadistrict.gov.gh/districts.
- Graupner, T., Kassahun, A., Rammlair, D., Meima, J. A., Kock, D., Furche, M., Fiege, A., Schippers, A. & Melcher, F. (2007). *Formation of sequences of cemented layers and hardpans within sulfide-bearing mine tailings (mine district Freiberg, Germany)*. *Applied Geochemistry* 22(11), 2486–2508.
- Griffis, R., Barning, K., Agezo, F. & Akosah, F. (2002). *Gold Deposits of Ghana*. Minerals Commission of Ghana, Accra.
- GSS (2014). *Population and Housing Census. District Analytical Report*, Amansie West District.
- Holmström, H., Salmon, U. J., Carlsson, E., Petrov, P. & Öhlander, B. (2001). *Geochemical investigations of sulfide-bearing tailings at Kristineberg, northern Sweden, a few years after remediation*. *Science of the Total Environment* 273(1), 111–133.
- Hudson-Edwards, K. A., Macklin, M. G., Jamieson, H. E., Brewer, P. A., Coulthard, T. J., Howard, A. J. & Turner, J. N. (2003). *The impact of tailings dam spills and clean-up operations on sediment and water quality in river systems: the Rios Agrio–Guadiamar, Aznalcóllar, Spain*. *Applied Geochemistry* 18(2), 221–239.
- Jia, Y., Stenman, D., Mäkitalo, M., Maurice, C. & Öhlander, B. (2013). *Use of amended tailings as mine waste cover*. *Waste and Biomass Valorization* 4(4), 709–718.
- Kesse, G. O. (1985). *The Mineral and Rock Resources of Ghana*. A. A. Balkema, Rotterdam, The Netherlands.
- Ljungberg, J. & Öhlander, B. (2001). *The geochemical dynamics of oxidising mine tailings at Laver, northern Sweden*. *Journal of Geochemical Exploration* 74(1), 57–72.
- Luza, K. V. (2006). *Tar Creek Oklahoma Superfund Site and its Challenges*. Geological Society of America Abstracts with Programs. Vol. 38, No. 1, p. 32.
- Mahdizadeh Khasraghi, M., Gholami Sefidkouhi, M. A. & Valipour, M. (2015). *Simulation of open- and closed-end border irrigation systems using SIRMOD*. *Archives of Agronomy and Soil Science* 61(7), 929–941.
- Nordstrom, D. K., Blowes, D. W. & Ptacek, C. J. (2015). *Hydrogeochemistry and microbiology of mine drainage: an update*. *Applied Geochemistry* 57, 3–16.
- Ravengai, S., Love, D., Mabvira-Meck, M., Musiwa, K. & Moyce, W. (2005). *Water quality in an abandoned gold mining belt, Beatrice, Sanyati Valley, Zimbabwe*. *Physics and Chemistry of the Earth, Parts A/B/C* 30(11), 826–831.
- Schueler, V., Kuemmerle, T. & Schröder, H. (2011). *Impacts of surface gold mining on land use systems in Western Ghana*. *Ambio* 40(5), 528–539.

- Tarras-Wahlberg, N. H., Flachier, A., Fredriksson, G., Lane, S., Lundberg, B. & Sangfors, O. (2000). Environmental impact of small-scale and artisanal gold mining in southern Ecuador: implications for the setting of environmental standards and for the management of small-scale mining operations. *AMBIO: A Journal of the Human Environment* 29(8), 484–491.
- UNESCO/WHO/UNEP (1992). Water Quality Assessment. A Guide to the Use of Biota, Sediments and Water in Environmental Monitoring. D. Chapman (ed.). Chapman & Hall, London.
- Valipour, M. (2012a). Comparison of surface irrigation simulation models: full hydrodynamic, zero inertia, kinematic wave. *Journal of Agricultural Science* 4(12), 68.
- Valipour, M. (2012b). Sprinkle and trickle irrigation system design using tapered pipes for pressure loss adjusting. *Journal of Agricultural Science* 4(12), 125.
- Valipour, M., Sefidkouhi, M. A. G. & Eslamian, S. (2015). Surface irrigation simulation models: a review. *International Journal of Hydrology Science and Technology* 5(1), 51–70.
- WHO (2011). *Guidelines for Drinking Water*, 4th edn.
- Widerlund, A., Ebenå, G. & Landin, J. (2004). Potential biogeochemical and ecological development of a flooded tailings impoundment at the Kristineberg Zn–Cu mine, northern Sweden. *Science of the Total Environment* 333(1), 249–266.
- WRRRI (1989). *Ashanti Goldfields Corporation (Ghana) Limited Water Resources Survey in the Mines Concession-Final Report*, p. 106.
- Yamamura, S., Bartram, J., Csanady, M., Gorchev, H. G. & Redekopp, A. (2003). *Drinking Water Guidelines and Standards. Arsenic, Water, and Health: The State of the Art (Draft Report)*, WHO, Geneva, Switzerland.
- Yannopoulos, S. I., Lyberatos, G., Theodossiou, N., Li, W., Valipour, M., Tamburrino, A. & Angelakis, A. N. (2015). Evolution of water lifting devices (pumps) over the centuries worldwide. *Water* 7(9), 5031–5060.

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