

The Combined Impact of Mine Drainage in the Ankobra River Basin, SW Ghana

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Received: 13 February 2008 / Accepted: 8 November 2008 / Published online: 6 January 2009
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Abstract This study assessed the combined effects of seven large-scale gold mines, one manganese mine, and scattered artisanal gold mining sites on the quality of water in the Ankobra Basin in a geologically complex terrain. Water samples from streams, boreholes, hand dug wells, and mine spoil were analysed. Scatter plots of trends among measured parameters were used to assess drainage quality and differential impacts. Drainage quality exhibits wide seasonal and spatial variations; the geology strongly influences the water chemistry. Areas with low pH (<5.5), and high sulphate ions and trace ions are suggestive of acid mine drainage while sites with high pH (>7.5), HCO_3^- , subdued SO_4^{2-} , and high trace ions are suggestive of sites where acid neutralization is effective. High metal sources are largely confined to mining operations in the Birimian formation with ores containing more than 2% sulphides. However, restricted high metal regimes are observed in drainage in the Tarkwaian formation associated with scattered sulphide-bearing dolerite dykes in the operational areas of the Tarkwa and Damang mines. Earlier studies disputed sulphides in the Tarkwaian formation until recently, when acid-generating dykes were discovered in operating pits. The most degraded waters emanate from the Prestea and Iduapriem mines, and to a lesser extent, the Nsuta mine

sites, all mining Birimian rocks. The Tarkwa mine showed minimal metal loading. Zn, Cu, Ni, As, SO_4 , pH, and specific conductance are essential and adequate parameters in determining if acid drainage is taking place at these sites, and are recommended for routine mine environmental monitoring.

Keywords Ankobra River · Drainage · Ghana · Mine · Water

Introduction

When properly integrated with geological and geochemical data, water quality can be used to assess the degree of metal mobilization and the possible extent of drainage degradation in an area impacted by metal mining (Plumlee 1999). Such an approach is very useful for environmental assessment and land use decisions, but has rarely been applied in the developing world. In Ghana, drainage water and sediment geochemical studies have often been carried out as part of routine reconnaissance prospecting work by mining and exploration companies aimed at delineating areas of heightened interest for potential mineralisation. Such information could provide useful baseline information for environmental studies, but is not usually publicly available. In this study, surface and ground water data was used to assess the metal pollution and the general geological and mine drainage impacts on the surface and ground water in the Ankobra Basin.

The Ankobra is the main river in the Basin, flowing southerly and receiving water from a network of tributaries, many of which flow WSW from the northeastern part of the area. Collectively, the Ankobra and its tributaries receive variously impacted water from one large-scale manganese

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mine at Nsuta and seven large-scale gold mines: Prestea Gold Resources, Sankofa Gold Ltd, both at Prestea; Bogoso Gold Ltd at Bogoso; Goldfields (Tarkwa) Ltd, AngloGold Ashanti (Iduapriem) Mine Ltd, and the defunct Teberbie, all at Tarkwa, and Goldfields (Damang) Ltd, at Damang, as well as drainage from several scattered small-scale, often illegal mine sites.

The sampling programme included streams draining areas of mining activity as well as streams that do not directly carry drainage from mining operations (as controls). After all, as observed by Yager et al. (2000), the water quality in a mined watershed depends not only on the mining-related activities but also on the non-mining related geochemical loading sources. These data also provided the basis for an assessment of the background or baseline concentration of selected physical and chemical parameters in the study area. It is assumed here that mean concentrations of water quality parameters obtained from surface and ground water apparently not directly impacted by mining represent a fair estimation of the natural background concentration of these parameters in the area (Nordstrom and Alpers 1999; Yager et al. 2000).

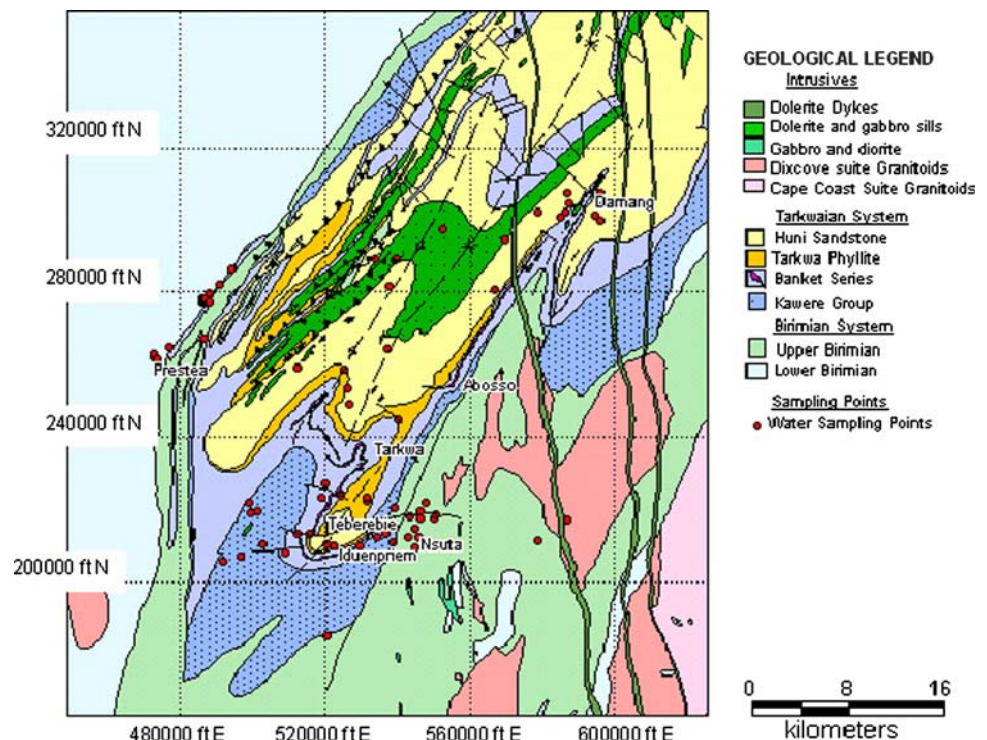
Geological and Topographical Setting

Rocks of the Birimian and Tarkwaian Group, which are supracrustal rocks of the West African Craton, underlie the area (Fig. 1). The Birimian rocks, around 2.2–2.3 billion years (Ga) in age, comprise thick sequences of

metamorphosed sediments and volcanics. The Tarkwaian, 2.1 Ga in age (Melisi et al. 1989; Taylor et al. 1988), consists of much smaller and scattered metamorphosed and unmetamorphosed shallow water sediments (Wright et al. 1985). The volcanic rocks consist of basaltic flows, andesitic to dacitic pyroclastic rocks and lavas, volcanogenic turbidites, and manganese chert that have been metamorphosed to greenschist facies. The sediments comprise fragmental felsic rocks, and flysch-type turbidites, variously metamorphosed to amphibolite facies (Sylvester and Attah 1992). The Tarkwaian rocks are considered a detritus of Birimian rocks that were uplifted and eroded into the centre of the basin to form clastic sedimentary rocks of sandstones, quartzites, conglomerates, and phyllites. These rocks have both been intruded by a variety of early to late kinematic granitoids, aged between 1.6 and 1.9 Ga (Eisenlohr and Hirdes 1992).

The area has been mined continuously by modern mining methods since 1880 and by artisanal miners since 1850 (Kesse 1985). However, many of these mines closed in the late 1950s and current mining operations in the area, largely surface pits, represent rejuvenation of these earlier mines. Prestea Gold Resources, an underground operation, Sankofa Gold Limited, which is re-mining old tailings of the underground mine and the Bogoso mine, a surface operation, are located within the Prestea gold belt in the fringes of deeply inclined Birimian sediments and lavas, which have been overfolded with formation of overthrust faults and shear zones and intruded by porphyritic granites

Fig. 1 Location map of study area showing sampling sites



and basic sills and dykes. The ore bodies are lenses of quartz or sulphide-bearing tuff-argillite; quartz-veined gold occur mainly in carbonaceous phyllites while the mineralisation in the disseminated sulphides is associated with the metavolcanics (Adaddey 1983). Base metal sulphides and sulphosalts, including arsenopyrite, pyrite, sphalerite, sphalerite, pyrrhotite, and tetrahedrites, dominate ore mineralogy (Table 1) (Akabzaa 2004; Hammond and Tabaka 1998; Mumin et al. 1994). The Prestea mine is an underground operation with the ore processed by roasting and conventional cyanidation using carbon in pulp (CIL). Ore here generally has a sulphide content greater than 2%. A summary of the geochemical characteristics, mining, and processing characteristics of the large scale mines in the area is presented in Table 1.

The Ghana Manganese Company operates an open pit manganese mine at Nsuta. The manganese deposits consist of manganese oxides, carbonates, and a transitional oxidation product, locally called 'carbox', hosted in fine-grained chemical metasediments. The oxides are considered supergene alteration of the manganese proto-ore,

comprising rhodochrosite-rich carbonates and manganese-rich carbonaceous meta-sediments (Kleinschrot et al. 1994). Ore mineralogy is dominated by kutnahorite and rhodochrosite.

The general topography of the study area mirrors the geology and consists of low-lying plains with prominent hills and ridges usually less than 200 m in height with abrupt changes in the nature of the country at the boundaries between the Birimian and Tarkwaian rock units. The Tarkwaian beds, dominated by quartzite, show markedly variable resistance to erosion and therefore exhibit topography of extremely regular strike ridges and valleys, which reflect its structure of folds and faults well. The Birimian, on the other hand, has much less regular topography due to the fact that it has fewer resistant beds and more complex folds and fault structures. In the central part of the study area, prominent parallel ridges and intervening valleys reflect the fold structures in the Banket Series and the Tarkwa phyllite of Tarkwaian rocks. They exhibit generally moderate relief, which varies between 30 and 335 m above sea level, and slope to the south.

Table 1 Summary of geochemical characteristics and mining and processing technologies of large-scale mines in the study area

Mine	Ore mineralogy	Gangue minerals	ABA, NAG static tests results	Mining/processing method
Teberebie mine	Quartz, hematite, magnetite			Open cast/cyanide heap leaching
Iduapriem mine	Quartz, hematite, magnetite, pyrrhotite, arsenopyrite, chalcopyrite,	Quartz, Fe–Ti oxides, rutile, albite, tourmaline, chlorite	Acid generating potential with NAG pH < 5, NP < 1, sulphides <2% of ore	Open cast/CIL and heap leach
Bogosso mine	Pyrrhotite, arsenopyrite, gersdorffite, sphalerite, tennalite, bournonite, chalcopyrite, boulangerite, galena	Pyrite, calcite, dolomite, ankerite, quartz, feldspars, micas, chlorite,	Acid generating potential with NP < 1, NPR of 5:1, and NAG pH < 5; sulphide >2% of ore	Open cast/CIL
Tarkwa mine	Quartz, hematite, magnetite	Quartz, Fe–Ti oxides, rutile, albite, tourmaline, chlorite	No acid generating potential except for basic intrusives; NNP > 20 CaCO ₃ /ton, NAG pH > 5, NP > 1	Open cast/heap leach
Prestea mine	Pyrrhotite, arsenopyrite, gersdorffite, sphalerite, tennalite, bournonite, chalcopyrite, boulangerite, galena	Pyrite, calcite, dolomite, ankerite, quartz, feldspars, micas, chlorite	Acid generating potential with NAG pH < 5, and NPR of 5:1, sulphide >2% of ore	Underground/roasting/cyanidation/CIL
Damang mine	Quartz, hematite, magnetite, pyrite, arsenopyrite, chalcopyrite	Quartz, Fe–Ti oxides, rutile, albite, tourmaline, chlorite, calcite, dolomite	Non acid generating except dolerite intrusives; NNP > 20CaCO ₃ /ton, NAG pH > 5, NP > 1, sulphides < 1%	Open cast/CIL and heap leach
Nsuta	Rhodochrosite, kutnahorite	Calcite, siderite, dolomite, pyrite, sphalerite, chalcopyrite, ullmannite	Acid generating potential with NAG pH > 5, sulphides <1%	Open cast/washing of oxides and carbonate ore for shipment

Sources: Akabzaa 2004; Hamound and Tabaka 1998; Mumin et al. 1994; Nyame et al. 2002; Smith 2001

Faulting and jointing, dips, and scarp slopes of these beds determine the transverse valleys and gaps in ridges. The Huni sandstones and the Kawere conglomerates define low-lying swamps in this area. Repeated strike faulting, particularly in the Tarkwa phyllite, has produced elongated depressions. However, some of these pronounced depressions in the area have resulted from the weathering of acidic and basic sills intruding the Tarkwaian (Smith 2001).

Materials and Methods

Sampling and Sampling Procedures

A variety of media were sampled for the assessment of drainage quality: water from streams, boreholes and hand dug wells; leachate from mine waste dumps, tailings impoundments, spent heap leach stacks, and abandoned mine pit lakes. Sampling was undertaken in the dry and wet seasons. A total of 161 water samples, 72 for the dry season, (November 2001–February 2002), with a mean rainfall of 1,450 mm and 89 for the wet season (March to September 2002), with a mean rainfall of 2,600 mm. Sample distribution was as follows: six from boreholes, four from hand dug wells, and 151 samples from streams and mine pits lakes and related drainage. Sample locations are shown in Fig. 1.

In each case, two aliquots were taken: samples for anion, calcium, magnesium, and silica analyses were filtered but not acidified; and a second sample for dissolved minor or trace element analyses was preserved with pure nitric acid (HNO_3) to a pH less than 2 (Appelo and Postman 1999; Barcelona et al. 1985).

Sample Analysis

Temperature, pH, and electrical conductivity were measured in the field with a WTW-Multiline Universal Meter. Alkalinity was also measured in the field by Grant titration using a Hatch digital titrator Model 16900 with 0.16 N H_2SO_4 . All other analyses were performed at the Water Research Institute (WRI) of the Council for Scientific and Industrial Research (CSIR), except for select samples, which were analysed at the SGS Commercial Laboratory in Tema and the Ecological Laboratory (Ecolab) at the University of Ghana for quality assurance and control purposes.

Quality control and quality assurance (QC/QA) protocols were based on APHA et al. (1998), Ficklin and Mosier (1999), and Eppinger et al. (1999). All sample bottles and corks were thoroughly cleaned before setting off for the field. During sample collection, the containers were flushed

at least thrice using the water to be sampled. Bottles were well labelled and sample site duplicates and laboratory-spiked blanks were included for quality assurance and control. The WTW-Multiline Universal Meter and the Hatch digital titrator were frequently calibrated with standards after a few measurements. Some of the duplicates, reagent blanks, and field blanks were analyzed at the SGS Commercial Laboratory and Ecolab. These results were compared with analyses from CSIR to ensure inter-laboratory quality assurance, as recommended by Ficklin and Mosier (1999).

The dry season samples were analysed using Philips PU 9200 Atomic Absorption Spectrophotometer (AAS) with a detection limit of 0.01 mg/L for the measured parameters. Mercury was determined by cold vapour Atomic Fluorescence Spectrometry with a detection limit of 0.001 mg/L. Wet season samples, except arsenic (with ARL 341 hydride-generator), were, however, analysed using a Unicam 969 Atomic Absorption Spectrophotometer that was then available. The Unicam 969 has a detection limit of 0.001 mg/L for the ions measured.

Results and Discussion

Results of water quality analyses are presented in Table 2. Drainage water quality demonstrated wide variability, reflecting both seasonal fluctuations and strong spatial variation showing the strong influence of the varied and complex geology on the water chemistry.

Statistical Treatment of Data and Scatter Plots

Correlation between parameters for both dry and wet season measurements for the entire drainage area was computed (Table 3). However, in recognition of the influence of local geological factors on elements associations, correlation between parameters was also computed for individual mine sites. All computations were done using Spearman rank correlation coefficients, a method appropriate for data that is not normally distributed (Rollinson 1993). Ficklin plots, which are scatter plots depicting relations among various parameters and pH constitute a convenient way of graphically displaying these relationships (Ficklin and Mosier 1999) and are presented in Figs. 2 and 3 for dry and wet set data, respectively. The descriptive statistics and the bivariate scatter plots of trends among measured parameters have being combined with Piper trilinear plots (Piper 1944) to assess water types (Fig. 4.) and drainage quality. Differential impacts have been clearly depicted with surface plots of concentrations of trace and major ions, pH values, alkalinity and electrical conductivity.

Table 2 Summary of measured parameters for dry and wet seasons; all are in mg/L, except for Hg (ppb)

	Dry season				Wet season			
	Meann	SD	Min.	Max.	Mean	SD	Min.	Max.
pH	6.3	0.9	3.1	8.6	8.6	0.9	3.4	9.8
Temp (°C)	26.7	2.1	24.2	32.6	32.6	1.8	23.3	30.5
Cond. (μS/cm)	231	296	33	1264	1264	643	33	4320
Alkalinity	46	36	0	162	162	216	0	1552
HCO ₃ [−]	56	44	0	198	131	264	0	1893
SO ₄	54	82	5	407	6	47	1	254
Ca	15	16	0	0	198	18	0	112
Cl	18	19	2	2	72	20	0	124
Mg	14	23	0	131	120	1020	0	4534
Na	–	–	–	–	407	94	3	825
K	–	–	–	–	180	4	0	17
PO ₄	–	–	–	–	645	0	0	1
NO ₃	–	–	–	–	15	1	0	6
SiO ₂	–	–	–	–	103	6	0	26
Zn	0.656	1.095	0.030	6.250	6.250	0.275	0.001	1.444
Cu	0.121	0.710	0.009	5.840	1.090	2.858	0.001	25.570
Mn	0.848	1.856	0.030	15.000	21.380	4.273	0.029	26.270
Ni	–	–	–	–	8.000	1.239	0.001	10.980
Fe	5.677	16.344	0.030	103.000	1.817	8.172	0.174	59.170
Pb	0.209	0.220	0.029	1.090	0.001	0.067	0.001	0.493
Cd	–	–	–	–	0.001	0.001	0.001	0.008
As	0.558	2.732	0.001	21.380	0.056	3.589	0.001	28.950
Hg	1.276	1.125	0.700	8.000	–	–	–	–

Cond. conductivity (μS), and pH, SD standard deviation

Table 3 Correlation among measured parameters for both wet and dry seasons

	pH	Cond.	Alk	Ca	Mg	SO ₄	Zn	Cu	Mn	Ni	Fe	Pb	As
pH		−0.061	0.621	−0.038	0.347	−0.402	−0.300	−0.019	0.091	–	0.075	−0.040	−0.059
Cond.	0.510		0.502	0.714	0.642	0.523	0.368	0.027	0.404	–	0.149	0.041	−0.038
Alk	0.528	0.805		0.461	0.741	−0.057	−0.027	0.006	0.338	–	0.100	−0.012	−0.017
Ca	−0.199	0.135	−0.104		0.434	0.466	0.215	−0.003	0.173	–	0.009	−0.055	−0.052
Mg	0.312	0.480	0.196	−0.183		0.189	0.361	0.004	0.544	–	0.306	0.144	−0.035
SO ₄	−0.045	0.147	−0.042	0.680	−0.154		0.319	0.023	0.206	–	0.125	0.021	−0.069
Zn	0.133	0.267	0.340	−0.103	0.168	−0.122		−0.012	0.625	–	0.440	0.475	0.003
Cu	0.347	0.716	0.752	−0.096	−0.024	−0.001	0.071		0.096	–	0.010	0.525	−0.029
Mn	−0.095	−0.079	−0.112	−0.125	0.024	−0.129	0.396	−0.017		–	0.554	0.454	0.040
Ni	0.324	0.691	0.725	−0.107	0.009	−0.027	0.074	0.980	0.004	–	–	–	–
Fe	0.129	0.231	0.457	−0.066	0.122	−0.043	0.507	0.063	−0.019	0.050		0.445	−0.037
Pb	0.220	0.329	0.538	−0.072	0.171	−0.008	0.697	0.138	0.077	0.123	0.893		0.110
As	0.450	0.781	0.904	−0.105	0.080	−0.041	0.276	0.902	−0.043	0.885	0.355	0.441	

Dry season statistics in bold face

Cond. conductivity, Alk alkalinity

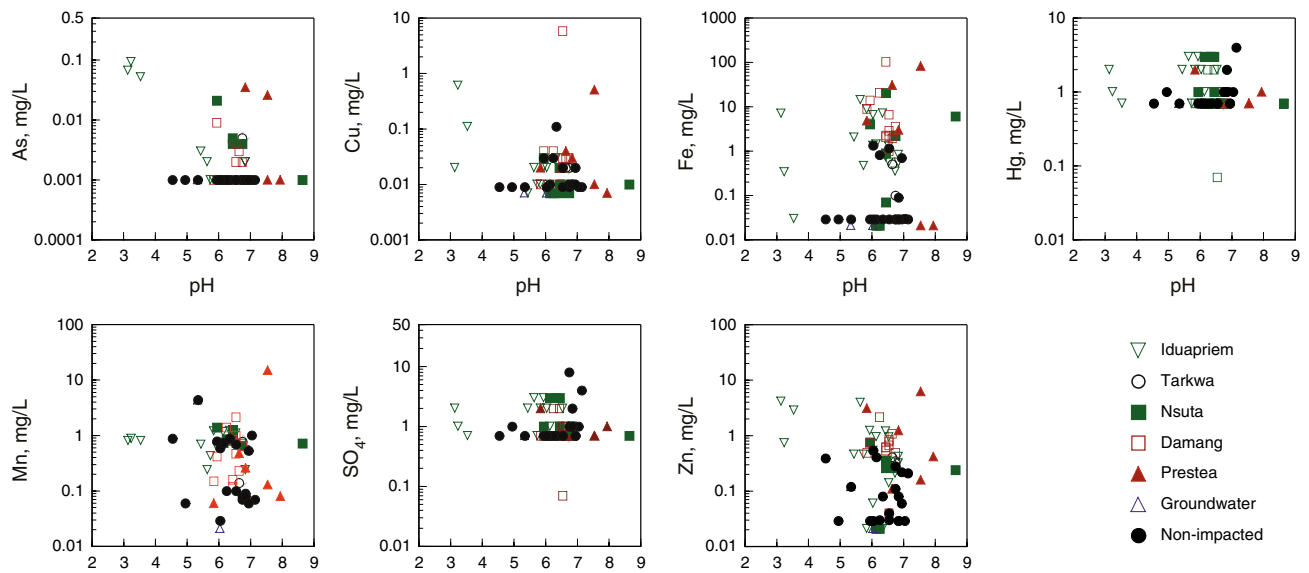


Fig. 2 Scatter plots of pH versus measured ions for dry season samples

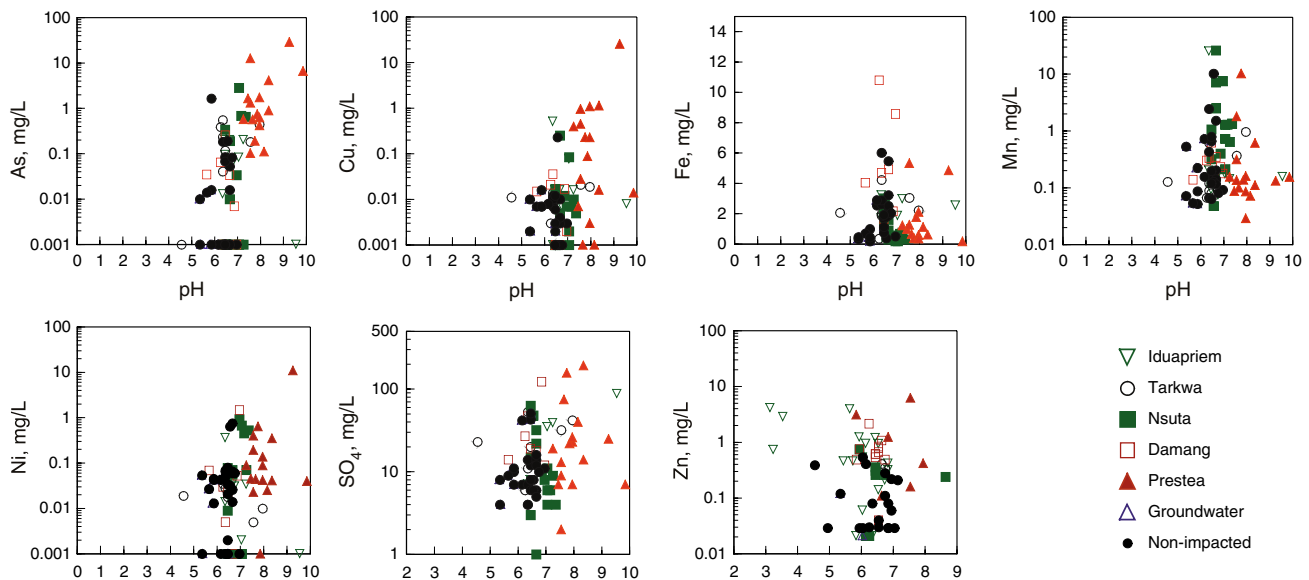


Fig. 3 Scatter plots of pH versus measured ions for wet season

Seasonal Variation in Water Quality Data

It was not always possible to sample at exactly the same location for both seasons due to the fact that certain streams that were accessible in the dry season became inaccessible during the wet season due to flooding, while some streams that were accessible during the wet season dried up during the dry season. Moreover, some specific parameters could not be measured during both seasons as a result of bottlenecks at the laboratory and financial constraints. Nevertheless, considerable differences exist between wet and dry season parameters that are likely the result of seasonal variation.

Zinc concentrations in the surface water samples were much higher in the dry than wet season, but are generally persistent in the entire drainage basin and throughout varied pH regimes. This persistence of zinc values, even in near-neutral pH regimes, is not abnormal. Herr and Grey (1995) and Foote et al. (1986) independently observed that Zn sulphides, particularly sphalerite, exhibit high solubility in acid waters, and because zinc is not readily sorbed onto particulates, once dissolved, zinc can persist over a wide range of pH.

On the other hand, wet season values for manganese, copper, nickel, and arsenic were higher than the corresponding dry season values. Such fluctuations in seasonal

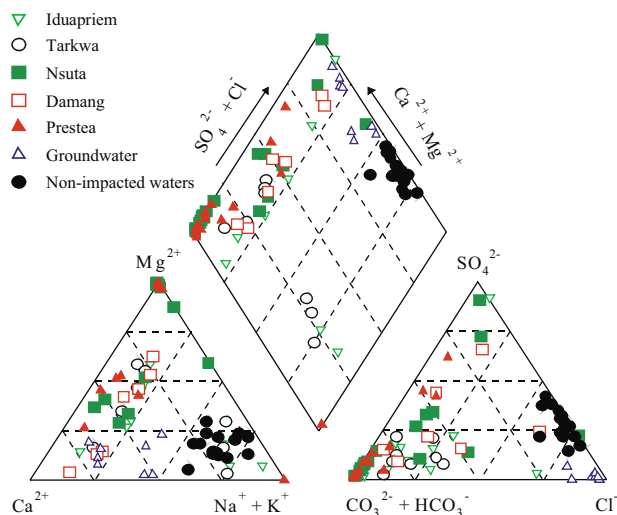


Fig. 4 Trilinear Piper-plots of water types in the study area

measurements are not unique. Ferguson and Errington (1998) pointed out that the accumulation of contaminants in a given environment is proportional to the length of time between weathering cycles. As the length of the cycle increases, oxidation products will tend to accumulate in the environment. A high magnitude weathering event will flush accumulated contaminants out of the environment. This relationship is strongly reflected in the increase in dissolved major ions load expressed by high conductivity values in the wet season compared to the dry season.

The negative correlation between pH and ions observed for the dry season was not observed in the wet season. Generally, pH values for the wet season are more poorly correlated with measured ions, and where such correlations exist, it is positive (Table 3). The highest measured values of most ions were associated with the highest recorded pH regimes in the wet seasons (8.0–9.8). However, elevated concentrations of various measured ions were more persistent over a wider range of pH regimes in the wet season than the dry season. Generally, circum-neutral pH values were associated with lower ions concentrations in both seasonal measurements.

The persistence of major and trace ion concentrations, particularly Zn, As, Mn, Fe, and to a lesser extent Cu, throughout the range of recorded pH regimes for both wet and dry seasons in the area underscores the observation by Miller (1998) that low pH conditions do not necessarily need to be established for many environmentally important elements to be released from mine overburden at concentrations that may adversely impact drainage quality. On the whole, most ions show very little correlation with pH for both seasons.

The highest concentrations of SO_4^{2-} and Cl^- , Zn, and As were recorded within the pH range of 3.0–3.5.

However, SO_4^{2-} , Ca, conductivity, and total hardness exhibited two peaks: at a pH range of 3.0–3.51, and from 7.5 to 8.6 in the dry season and 7.5 to 9.4 in the wet season. Arsenic, Cu, Ni, and Pb concentrations were significantly correlated with bicarbonate values in the wet season, but rarely correlated with the dry season measurements. The most probable explanation for this disparity is that during the wet season, more water is available to dissolve both carbonate- and sulphide-bearing strata, which are the sources of these metals and the bicarbonate.

The low pH regimes are also dominated by relatively high values of Fe, Mg, Ca, SO_4 , Zn, and As, and the near absence of alkalinity and bicarbonate, and is suggestive of concomitant oxidation of sulphides (ARD) and buffering activity through dissolution of carbonates (Evangelou 1995). However, the rate of sulphide oxidation should be more pronounced and faster than the buffering effect of carbonates, resulting in the dominance of these sulphide oxidation products (Evangelou 1995). The significant levels of Fe, Mg, Zn, Ca, and As in this regime probably point to dissolution of rocks with these components. Similarly, the preponderance of high alkalinity and bicarbonate values in samples with high pH values attest to faster and more pronounced dissolution of carbonate rocks in more than sufficient quantities to buffer any possible sulphide oxidation (Akabzaa 2004).

The oxidation of sulphides could account for the significant sulphate and arsenic values. Carbonate dissolution is probably also responsible for the augmented Ca and Mg. Iron and Zn concentrations are probably the result of both sulphide oxidation and dissolution of iron-bearing carbonates and aluminosilicates. The concentrations of individual elements in the drainage waters, in part, reflect the abundance of these elements in the deposits drained by the waters.

Mineralogical composition of rock samples within the catchments of these waters indicate that sphalerite, arsenopyrite, arsenian pyrite, and pyrite are common sulphide constituents, while ankerite, rhodochrosite, siderite, and to lesser extent, dolomite, magnesite, and calcite are common constituents of carbonate-bearing strata that could have been the source of these ions (Akabzaa 2004). Weathering of sulphide minerals in the area therefore accounts for the augmented levels of the various metal ions in the waters.

Non-Mine Impacted Drainage

Summary of descriptive statistics of parameters measured in non-mine impacted drainage waters in the area are presented in Table 4. The water-sampling programme also included streams upstream of the mining areas that form part of the mosaic of streams constituting the Ankobra

Table 4 Descriptive statistics of non-impacted waters (background values); all are in mg/L, except for conductivity (Cond.) (in $\mu\text{S}/\text{cm}$), and pH

Statistic	Location	pH	Cond.	Alk	HCO_3^-	Ca	SO_4	Mg	Mn	Fe	Cu	Zn	Pb	As
Mean	Iduapriem	5.98	149.7	40.7	49.7	8.6	26.7	5.0	0.644	0.329	0.031	0.220	0.156	0.001
Min.		4.46	42.1	17.5	21.4	3.2	5.1	1.0	0.100	0.029	0.009	0.029	0.040	0.001
Max.		6.89	250.0	95.0	116.0	14.4	61.5	10.7	0.880	1.340	0.110	0.540	0.360	0.001
Mean	Tarkwa	6.82	70.2	35.3	43.1	5.9	8.4	14.2	0.073	0.029	0.009	0.200	0.036	0.001
Min.		6.69	47.7	18.0	22.0	4.8	6.4	12.6	0.070	0.029	0.009	0.110	0.029	0.001
Max.		7.08	103.0	64.0	78.1	7.2	10.2	16.0	0.080	0.029	0.010	0.280	0.050	0.001
Mean	Nsuta	6.76	178.0	52.5	64.1	17.6	41.9	7.5	0.850	0.595	0.015	0.030	0.085	0.001
Min.		6.53	176.0	50.0	61.0	17.6	38.3	3.9	0.690	0.030	0.009	0.029	0.029	0.001
Max.		6.98	180.0	55.0	67.1	17.6	45.6	11.2	1.010	1.160	0.020	0.030	0.140	0.001
Mean	Damang	6.16	213.5	45.3	55.3	28.3	40.5	8.9	0.077	0.049	0.010	0.046	0.046	0.001
Min.		4.93	32.7	8.0	9.8	4.0	10.9	3.4	0.060	0.029	0.009	0.029	0.029	0.001
Max.		6.80	512.0	110.0	134.0	72.1	90.2	18.9	0.090	0.090	0.010	0.080	0.080	0.001
Mean	Average	6.36	136.8	40.4	49.3	11.7	48.2	7.0	0.383	0.249	0.019	0.146	0.097	0.001
Min.		4.46	32.7	8.0	90.8	1.6	5.1	0.5	0.060	0.029	0.009	0.029	0.029	0.001
Max.		7.08	512.0	110.0	134.0	72.1	179.1	18.9	1.010	1.340	0.110	0.540	0.360	0.001

drainage basins but do not directly carry drainage from mining operations. Non- mine impacted drainage here therefore, refers to samples from these streams that do not drain or receive drainage from areas influenced directly by mining operations. This drainage is mainly upstream and peripheral to mining areas. After all, as observed by Yager et al. (2000), the water quality in a mined watershed will depend not only on the mining-related activities but also on the non-mining related geochemical loading sources. The influence of local geology on selected parameters can be seen in the peaks in concentration of Fe, Mn, Cl, and specific conductivity in waters draining Birimian rocks, dominated by the concentration of these parameters at the Nsuta, Iduapriem and to lesser extent, Prestea mine sites. These rocks are dominated by the so-called greenstones, comprising of basaltic flows, andesitic to dacitic pyroclastic rocks, and manganiferous chert, iron-bearing carbonate alterations, and chlorite schist (Sylvester and Attah 1992).

Water draining rocks of the Tarkwa and Damang area exhibit very subdued concentrations of trace ions but record relatively high levels of magnesium. The rocks here are dominated by quartzite. However, on the whole, the concentrations of the parameters do not vary greatly among the sites (Table 5). The non-mine impacted measurements also provides sound basis for an assessment of the background or baseline concentration of selected physical and chemical parameters in the study area. It is presumed here that mean concentrations of water quality parameters obtained from surface and ground water not directly impacted by mining represent a fair estimation of the natural background concentration of these parameters in the area (Norstrom and Alpers 1999; Yager et al. 2000).

Mine-Impacted Drainage

Summary of selected descriptive statistics of measured parameters from various mine-impacted drainage are presented in Table 4. Individual point sources of metal ion loading, anomalous pH, and elevated conductivity and alkalinity values is discernable. Spatial discrimination of the data from mine-impacted areas show that the Prestea mine site has had more impact on the immediate drainage area than any of the areas under study. This is followed by the mines at Iduapriem and Teberibie, Nsuta, Damang, and Tarkwa in that order. The Tarkwa mine area exhibits very low metal loading, modest specific conductivity and alkalinity values, and near-neutral pH (Tables 5, 6).

The geology and geochemistry of the ore-bearing rocks and, to some extent, the ore processing method employed by these mines, have considerable control on the quality of drainage water. The Prestea, Iduapriem, and parts of Teberibie are located within meta-volcanic and meta-sedimentary sequences with sulphide and altered carbonate mineralisation. At Prestea, the ore has traditionally been processed by roasting, with reported release of substantial sulphide oxidation products, including arsenic, into the atmosphere (Amonoo-Neizer 1980).

The Prestea had the highest concentration of trace ions and sulphate in drainage water. Peak values were observed in streams taking drainage from old tailings dumps at Bondai near Prestea, with pH values near 4. However, in other areas, the pH of the drainage was alkaline, though water degradation was evident, as indicated by elevated sulphate, Mn, Fe, Zn, Cu, and As concentrations. The high alkalinity values of drainage in some areas demonstrated the dominance of acid-buffering carbonates.

Table 5 Concentrations of mine drainage-impacted physico-chemical parameters for dry season with EPA (Ghana) and WHO maximum allowable guide values; all are in mg/L, except for Hg (ppb) and pH

Mine site	pH	HCO ₃ ⁻	SO ₄	Mn	Fe	Cu	Zn	Pb	As	Hg
Iduapriem										
Mean	5.7	40	72	0.77	3.23	0.05	1.04	0.18	0.01	1.53
SD	1.2	29	128	0.31	3.97	0.14	1.29	0.15	0.03	0.84
Min.	3.1	0	8	0.24	0.03	0.01	0.02	0.02	0.00	0.70
Max.	6.8	104	407	1.23	14.31	0.61	4.16	0.64	0.09	3.00
Tarkwa										
Mean	6.7	29	14	0.46	0.31	0.02	0.38	0.28	0.00	0.70
SD	0.0	10	5	0.45	0.29	0.00	0.04	0.02	0.00	0.00
Min.	6.6	22	10	0.14	0.10	0.02	0.35	0.26	0.001	0.70
Max.	6.7	37	17	0.78	0.51	0.02	0.41	0.29	0.01	0.70
Nsuta										
Mean	6.6	69	24	0.96	4.23	0.01	0.28	0.29	0.01	1.35
SD	0.8	20	12	0.29	6.94	0.01	0.23	0.26	0.01	1.03
Min.	5.9	37	6	0.66	0.02	0.01	0.02	0.06	0.00	0.70
Max.	8.6	104	45	1.40	20.52	0.03	0.75	0.86	0.02	3.00
Damang										
Mean	6.4	38	35	0.69	14.10	0.51	0.76	0.38	0.00	0.94
SD	0.3	13	29	0.60	28.62	1.68	0.51	0.30	0.00	0.55
Min.	5.8	17	7	0.12	1.00	0.01	0.04	0.08	0.00	0.07
Max.	6.7	56	101	2.14	103.00	5.84	2.16	1.09	0.01	2.00
Prestea										
Mean	7.0	93	84	2.67	20.16	0.10	1.88	0.29	0.286	0.97
SD	0.8	83	114	6.05	32.62	0.20	2.42	0.33	0.67	0.52
Min.	5.8	15	10	0.06	0.02	0.01	0.11	0.03	0.00	0.70
Max.	7.9	198	262	15.01	82.33	0.51	6.25	0.94	1.65	2.00
EPA (GH)				0.10	5.00	2.5	5.00	0.1	0.5	0.1
WHO				0.50	3.00	2.00	3.00	0.01	0.01	0.01

Acid–base accounting (ABA) tests conducted on some rock samples from the area showed significant sulphide–sulphur content; these would be acid generating if exposed to air and water. Other samples had high neutralization potential values and contained carbonates, such as dolomite, ankerite, and siderite (Akabzaa 2004). Acid waters produced near these rocks are quickly buffered by dolomite and ankerite $[\text{Ca}(\text{Mg}, \text{Fe}^{2+}, \text{Mn})(\text{CO}_3)_2]$. The dissolution of such minerals releases divalent metals (Ca^{2+} , Fe^{2+} , Mg^{2+} , and Mn^{2+}) and bicarbonate (HCO_3^-) ions to solution (Balistreri et al. 2002). In fact, there was a strong correlation among Fe^{2+} , Mg^{2+} , Mn^{2+} , and HCO_3^- in water from the area, supporting this scenario.

Although the Iduapriem mine site appears less impacted than Prestea, the single most impacted point source was identified here. A buried dyke of stripped mine overburden with considerable sulphide mineralogy sends acid drainage to one of the streams draining the area. Two small streams carrying leachate from this source join the Bediebawuo stream further downstream. Relatively low pH (3.5–4.5) values, accompanied by very high metal concentrations and low alkalinity values, were recorded at sampling points

along these two streams. A strong negative correlation between pH and trace and major ions and the strong positive correlation among trace and major ions in the Iduapriem area suggest that these ions are likely derived locally from water–rock interactions (Fig. 2). The waste site is currently been managed as potentially acid forming by the mine owners.

At Nsuta, the manganese ore consists of manganese carbonates and oxides with subordinate sulphides as accessory minerals in the enclosing country rocks. The processing of the ore entails washing the excavated oxide or carbonate to remove manganese impurities; the resulting waste slurry, containing Mn and associated Fe, is usually discharged into the drainage system. Not surprisingly, the Nsuta area records the highest Mn concentrations.

Black slurry of manganese oxide is very common in streams draining the area. The level of degradation increases towards the centre of active mining and processing activities. However, the concentrations of other measured metal ions are generally lower here than at Prestea and Iduapriem. Although cadmium concentrations were generally below detection in the entire study area,

Table 6 Concentrations of mine drainage-impacted physico-chemical parameters for wet season with EPA (Ghana) and WHO maximum allowable guide values; all are in mg/L, except for pH

Mine site	pH	SO ₄	Zn	Cu	Mn	Ni	Fe	As
Iduapriem								
Mean	6.9	22.93	0.11	0.07	2.95	0.06	2.51	0.10
SD	1.0	27.48	0.25	0.17	8.43	0.11	0.57	0.09
Min.	6.3	4.94	0.00	0.00	0.08	0.00	1.72	0.00
Max.	9.5	87.67	0.78	0.51	25.42	0.36	3.23	0.20
Tarkwa								
Mean	6.4	23.73	0.01	0.01	0.31	0.03	2.12	0.25
SD	1.0	17.39	0.01	0.01	0.33	0.02	1.16	0.20
Min.	4.5	4.03	0.00	0.00	0.07	0.01	0.36	0.00
Max.	7.9	52.82	0.02	0.02	0.97	0.06	4.23	0.56
Nsuta								
Mean	6.8	16.07	0.04	0.03	3.40	0.19	0.90	0.32
SD	0.3	18.10	0.11	0.07	6.76	0.30	0.83	0.74
Min.	6.4	0.65	0.00	0.00	0.05	0.00	0.19	0.00
Max.	7.3	62.72	0.42	0.25	26.27	0.93	3.01	2.83
Damang								
Mean	6.4	37.20	0.01	0.01	0.31	0.24	5.27	0.06
SD	0.4	39.45	0.01	0.01	0.16	0.55	3.32	0.09
Min.	5.6	12.21	0.00	0.00	0.14	0.00	1.64	0.00
Max.	6.9	122.52	0.02	0.04	0.62	1.48	10.80	0.26
Prestea								
Mean	8.0	40.05	0.33	1.89	0.90	0.82	7.55	3.83
SD	0.7	55.93	0.52	6.33	2.53	2.71	16.88	7.46
Min.	7.2	1.98	0.00	0.00	0.03	0.00	0.17	0.10
Max.	9.8	193.02	1.44	25.57	10.26	10.98	59.17	28.95
Groundwater								
Mean	5.8	21.88	0.03	0.01	0.39	0.02	1.01	0.01
SD	0.4	19.81	0.02	0.00	0.32	0.02	0.94	0.01
Min.	5.3	4.13	0.00	0.00	0.05	0.00	0.18	0.00
Max.	6.4	51.24	0.06	0.02	0.79	0.05	2.89	0.02
Non-impacted								
Mean	6.3	13.00	0.06	0.01	0.75	0.08	1.87	0.09
SD	0.4	12.43	0.23	0.04	2.01	0.18	1.46	0.32
Min.	5.3	3.93	0.00	0.00	0.05	0.00	0.18	0.00
Max.	6.9	51.24	1.20	0.23	10.26	0.76	6.02	1.66
EPA (GH)			5.00	2.50	0.10	0.01	5.00	0.5
WHO			3.00	2.00	0.50	0.50	3.00	0.01

detectable concentrations were observed in the Nsuta area with a maximum of 8 µg/L in drainage waters from the manganese mine. Foote et al. (1986) has intimated that Cd in leachates may normally be controlled by sphalerite, because in sphalerite, a small part of the Zn is often isomorphously substituted by Cd. An energy dispersive spectra (EDS) probe of some sphalerite grains in samples from Nsuta indicated that Cd was present but generally at

very low concentrations, not exceeding 0.02 atomic weight percent.

The Tarkwa and Damang mines are located within the paleosedimentary Tarkwaian sequences. The ore at Damang is dominated by conglomerates, with subordinate mineralized basic intrusives. The conglomerates are largely quartz and devoid of sulphides and carbonates; however, the mineralized intrusives have considerable sulphides. In contrast, mineralisation in the Tarkwa mine is confined to only the conglomeritic horizons.

Water Types

Hydrochemical facies of spatially distinct waters were determined using Aquachem 3.7 computer source code to generate trilinear Piper plots (Piper 1944; University of Waterloo 1999). These graphical methods, apart from being very useful in evaluating the relative dominance of the major ions in these waters, also enables one to discern evolutionary pathways and possible mixing of waters (Freeze and Cherry 1979; Petals and Diamantis 1999). Samples of ground water, non-impacted water, and impacted surface water were analyzed from the Prestea, Nsuta, Tarkwa, and Iduapriem mine drainage sites. However, a ground water sample could come from either an impacted or non-impacted area.

The data form distinct linear clusters on the Piper plots, showing a wide variation in water types ranging from calcium–magnesium–bicarbonate waters to sulphate, sodium, and chloride-rich varieties of magnesium waters (Fig. 4; Table 7). This has enabled the discrimination of separate clusters and some individual water sources.

Stream waters exhibit the highest variability, ranging from Ca–Mg–HCO₃[−], Mg–Ca–HCO₃–Cl, Mg–Cl–HCO₃, Mg–Ca–SO₄, Mn–Mg–HCO₃, Na–Mg–HCO₃–SO₄, K–Mg–Ca–Cl, Mg–Ca–Mn–HCO₃–Cl, and Na–HCO₃–Cl. Such multiple cation and anion water types may be the product of mixing of waters from mine pit lakes, other mine spoil, and pristine waters. Henderson (1982) observed that mixing of poorly buffered waters with weakly acidic storm run-off characterised by low dissolved solids could result in water with these trends.

There is close clustering of non-impacted water and ground water, which are Ca + Mg + Cl and Ca + Mg + Na⁺ C[−] rich, respectively. Earlier studies have shown that ground water in the area, with some exceptions, is not as greatly affected by mine seepage as surface water (Kuma and Younger 2000). However, in some areas, surface and ground water are closely related due to localized recharge to regolith and bedrock aquifers and infiltration of surface water underground through localized fractures (Kuma and Younger 2000). Kortatsi (2004) has argued that where the aquifers are in hydraulic continuity with the

Table 7 Water types from study site

Location	Sample Id	Source	Watertype
Damnag	BH001	Borehole	Ca–Na–Cl–HCO ₃
	BH02	Borehole	Mg–Ca–HCO ₃ –Cl
	WWS026	Stream	Ca–HCO ₃
	WWS027	Stream	Mg–Ca–HCO ₃
	WWS028	Stream	Mg–Ca–HCO ₃ –Cl
	WWS029	Stream	Ca–HCO ₃ –Cl–SO ₄
	WWS030	Stream	Ca–HCO ₃
	WWS031	Stream	Mg–Ca–Fe–HCO ₃
	WWS033	Stream	Mg–Ca–HCO ₃
	WWS034	Stream	Mg–Ca–SO ₄
	WWS32	Stream	Mg–Ca–SO ₄ –HCO ₃
	WWS025	Stream	Mg–Cl–SO ₄
	HDW02	Hand dug well	Mg–Ca–HCO ₃
Nsuta	BH03	Borehole	Mg–Cl–HCO ₃
	BH04	Borehole	Mg–Ca–HCO ₃ –Cl
	BH05	Borehole	Mg–HCO ₃
	WWS017	Stream	Ca–Mg–SO ₄ –Cl
	WWS018	Stream	Mg–Ca–HCO ₃ –Cl
	WWS020	Stream	Ca–HCO ₃ –Cl
	WWS023	Stream	Ca–Mg–HCO ₃ –SO ₄
	WWS067	Mine Pit Lake	Mg
	WWS068	Mine Pit Lake	Mg
Huniso	HDW01	Hand dug well	Na–Ca–Mg–Cl
Iduapriem	WSS01	Stream	Mn–Mg–HCO ₃
	WWS003	Stream	Ca–Mg–Na–HCO ₃ –Cl
	WWS004	Stream	Na–HCO ₃ –Cl
	WWS006	Stream	Na–HCO ₃
	WWS009	Stream	Na–HCO ₃
	WWS010	Stream	Mg–Cl–HCO ₃
	WWS011	Waste Dump	Ca–SO ₄
	WWS007	Stream	Mg–Ca–HCO ₃ –Cl
Tarkwa	WWS035	Stream	Mg–Ca–HCO ₃
	WWS038	Stream	Na–HCO ₃
	WWS039	Stream	Na–HCO ₃ –Cl
	WWS040	Stream	Ca–HCO ₃ –Cl–SO ₄
	WWS054	Stream	Mg–Ca–HCO ₃ –Cl
Prestea	WWS042	Mine pit lake	Mg–Ca–HCO ₃
	WWS043	Mine pit lake	Ca–Mg–SO ₄ –HCO ₃
	WWS044	Mine pit lake	Ca–Mg–HCO ₃ –SO ₄
	WWS046	Stream	Mg–Ca–HCO ₃
	WWS047	Stream	Mg–Ca–Na–HCO ₃ –SO ₄
	WWS049	Stream	K–Mg–Cl
	WWS050	Stream	K–Mg–Ca–Cl
	WWS041	Mine Pit	Mg–HCO ₃
	WWS051	Stream	Mg–Ca–Mn–HCO ₃ –Cl
	WWS051	Stream	Ca–Mg–HCO ₃ –Cl
	WWS052	Stream	Mg–Ca–HCO ₃ –Cl
	WWS059	Tailings drainage	Mg–HCO ₃

Table 7 continued

Location	Sample Id	Source	Watertype
	WWS060	Mine Pit Lake	Mg
	WWS061	Mine Pit Lake	Mg
	WWS062	Tailings Discharge	Na–HCO ₃
	WWS063	Mine Pit Lake	Mg
	WWS065	Stream	Mg–HCO ₃
	WWS066	Stream	Mg–HCO ₃

streams, ground water recharge could occur by transmission losses through fissured rocks buried under the thin alluvium of the stream channels.

Mine pits and lakes also exhibit some variability in water type, dominated by Mg, Mg–HCO₃, and Mg–Ca–HCO₃–SO₄, Ca–Mg–SO₄, Mg–HCO₃ waters and can be said to reflect bed rock mineralogy (Table 7). Mine pit lakes and tailings discharged from Prestea exhibit the greatest variability while pit lakes in the Nsuta manganese mine site are dominated by Mg. Water dominated by K–Mg–Cl, K–Mg–Ca–Cl, and Mg–K, as exhibited by some samples from Prestea and Nsuta mines, probably reflect incongruent dissolution of micas, calcic plagioclase, and amphiboles in the rocks. Similarly, Ca–Mg–SO₄–HCO₃ dominated water in the Prestea and Nsuta mine sites likely results from the dissolution of dolomite, siderite, and sulphides.

Bicarbonate (HCO₃[−]) dominated water appears to be generally more diffuse in occurrence and is not unique to acid-generating sites or buffering sites.

It is clear that the water that is most affected by acid rock drainage generally has low pH, alkalinity, and HCO₃[−] values, and high sulphate values. Such high sulphate ion concentration in drainage is commonly indicative of sulphide oxidation (Hem 1985; Plumlee et al. 1999). Sulphate and HCO₃[−] ions dominate in defined pH regimes, implying that both sulphide and carbonate dissolution reactions are responsible for these peak sulphate and HCO₃[−] ion concentrations.

Sources of Major and Trace Metals in Drainage

The spatial distribution of zones of high trace and major ion concentrations and the preponderance of some ions in specific places clearly shows that these zones of high trace and major ion concentrations represent either point or diffuse sources of pollutants in the drainage. The spatial distribution of high trace element regimes, in particular, strongly reflect the influence of geology on the water chemistry.

Principal component analysis (PCA) was applied to the data from the entire study area, and data sets from the

Iduapriem, Nsuta, Damang, and Prestea mines sites, respectively, in order to extract principal factors corresponding to the different sources of variation in the water chemistry. The Kaiser criterion (Kaiser 1960) was used to extract principal components from the data and rotated using varimax normalization for each location. The data was reduced to three principal components representing over 70% of the sources of variation in the water chemistry in the different locations, as it was clear that the fourth and fifth components do not constitute significant sources of variance in the hydrochemistry for most sites. The water chemistry appears mainly controlled by weathering and dissolution of carbonates, silicates, and sulphides, with strong incorporation of a variety of trace elements. The strong influence of geology on the hydrochemistry is well illustrated by the PCA results (Table 8). The hydrochemistry of drainage from the Prestea, Nsuta, and Iduapriem mine sites, underlain mainly by metavolcanics and metasediments of the Birimian formation reflects the dissolution of carbonates, silicates, and the simultaneous oxidation of sulphides that constitute the dominant mineralogy at these sites (Akabzaa 2004; Nyame et al. 2002). The influence of dissolution of a variety of manganese carbonates on the hydrochemistry of drainage from the Nsuta manganese mine site is well highlighted by the PCA results. Similarly, the results show that limited oxidation of sulphides and more pronounced buffering activity from the

dissolution of carbonates, constituents of the scattered dolerite dykes in the Tarkwaian formation that underlie the Damang mine site, also contribute to the drainage chemistry.

The distribution of manganese points to both diffuse and point sources. High Mn loading within mines sites in the Birimian formation, and the highest recorded values of 24.40 and 26.27 mg/L for the dry and wet seasons, respectively, are recorded from the Nsuta mine site (Tables 5, 6) where manganese is being exploited from manganese formations within the the Birimian metavolcanics. Similarly, areas marking the contact between Birimian metavolcanic and metasedimentary rocks, which are generally dominated by manganese-bearing horizons (gondite), exhibit high Mn values. These rocks are common throughout areas underlain by Birimian rocks, such as at the Prestea and Iduapriem mine sites, and can be described as diffuse sources. High Mn loading of 25.42 and 10.26 mg/L have been recorded in the Iduapriem and Prestea mine sites (Table 6), respectively. However, the manganese carbonate and oxide ore that are exposed at Nsuta represent point sources of manganese.

The distribution of arsenic, copper, and nickel exhibits similar patterns. Higher values are located in drainage associated with Prestea, Iduapriem, and Nsuta, which are underlain by Birimian rocks. The concentrations of these elements were also high in drainage from the Damang mine

Table 8 Rotation principal component analysis loading for mine-impacted drainage

Components	Entire study area			Iduapriem			Nsuta			Damang			Prestea		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
pH	0.74	0.03	-0.49	0.30	0.86	0.10	-0.29	-0.47	0.65	0.76	-0.09	0.01	0.90	0.01	-0.43
Cond.	0.89	0.02	0.28	0.39	0.83	0.26	-0.18	0.55	0.76	0.52	0.16	0.39	0.99	0.11	-0.05
Alkalinity	0.89	0.02	0.02	0.46	0.71	0.41	-0.81	-0.06	0.15	0.70	0.63	0.15	0.98	0.97	-0.13
HCO ₃	0.89	0.89	0.29	0.46	0.71	0.41	-0.81	-0.06	0.15	0.70	0.63	0.15	0.98	0.10	-0.13
Ca	0.80	-0.17	-0.32	0.83	0.27	-0.12	-0.72	0.34	0.51	0.84	0.02	-0.12	0.93	-0.09	-0.01
Mg	0.69	0.15	0.88	0.44	0.03	0.44	0.25	0.88	0.19	0.01	0.22	-0.61	0.75	0.31	-0.52
Cl	0.16	-0.07	0.12	0.36	0.27	0.82	-0.22	0.04	0.85	0.09	0.53	0.41	0.55	0.83	0.03
SO ₄	0.27	0.58	0.54	0.87	0.03	0.16	0.05	0.81	0.19	-0.04	0.27	0.77	-0.07	0.84	-0.38
Mn	0.22	0.55	0.03	-0.19	-0.06	0.76	0.75	-0.01	-0.50	0.54	0.20	0.33	0.33	0.94	-0.00
Fe	-0.37	0.69	-0.16	0.38	0.82	0.18	0.38	-0.90	0.11	-0.58	-0.10	0.14	-0.44	0.88	0.14
Cu	0.13	0.75	-0.49	0.71	-0.19	0.06	0.79	-0.41	-0.30	0.22	0.78	-0.26	0.11	0.98	0.17
Zn	-0.14	0.31	-0.30	-0.24	0.02	-0.88	0.70	-0.52	0.30	-0.13	-0.57	0.29	0.12	0.46	0.85
Pb	-0.11	0.68	-0.33	-0.09	-0.49	-0.76	0.41	-0.80	-0.25	-0.02	0.84	-0.22	-0.04	0.90	0.13
As	-0.14	0.42	0.47	0.17	0.02	-0.46	0.80	0.08	0.35	-0.10	0.84	0.25	-0.47	0.21	0.86
Hg	-0.27	-0.04	0.47	0.52	-0.72	0.16	-0.06	-0.05	-0.76	-0.38	0.19	-0.50	-0.34	-0.41	0.74
Total variance explained (rotation sum of squared loadings)															
Eigen values	5.9	2.5	2.3	4.9	4.2	3.5	5.2	5.0	3.7	4.1	3.7	2.5	7.7	5.4	2.9
Variance (%)	34.8	14.8	13.4	28.9	24.6	20.8	30.6	29.2	21.6	23.8	21.7	14.5	45.3	31.9	17.0
Cumulative (%)	34.8	49.6	62.9	28.9	53.5	74.4	30.6	59.8	81.5	23.8	45.5	60.	45.3	77.2	94.2

site in the Tarkwaian formation and are likely associated with the sulphide-bearing dolerite dykes intruding the Tarkwaian rocks, which are mineralised. Price and Errington (1998) observed that such high zones of concentration of metals occur even in neutral pH drainage, and often result from localised acid-generating sources.

Sulphate concentrations were highest in streams taking leachate from the Iduapriem mine (8–407 mg/L), followed by drainage within the Prestea mine site (10–262 mg/L) and three other streams draining the Damang mine (7–101 mg/L) (Tables 5, 6). Sulphate can be used as a measure of the rate of sulphide oxidation, though it is also occasionally dominant in areas where significant acid-buffering reactions are taking place, such as in the mine pits at Prestea and Teberibie. In such situations, depending on the reaction kinetics and the preponderance of carbonate material over acid-generating species, high sulphate concentrations may be correlated with moderately alkaline pH and high Ca^{2+} concentrations. Bicarbonate was also observed to be very high in some non-mining environments, likely resulting from decay of organic matter, and cannot be entirely attributed to rock weathering.

Most pH values of the drainage area show no evidence of acid rock drainage. This is possibly due to rapid neutralization by dolomite and ankerite [$\text{Ca}(\text{Mg}, \text{Fe}^{2+}, \text{Mn})(\text{CO}_3)_2$], which are present in relative abundance in the host rocks (Eisenlohr and Hirdes 1992). It could also be due to other factors, such as the rate of sulphide oxidation and carbonate dissolution, residence time of ions in solution, and water–rock interaction. Signs of drainage degradation are provided by the elevated electrical conductivity and concentrations of sulphate and total dissolved solids.

Among the trace or minor ions measured, mercury and lead appear to have no relationship with pH, conductivity, alkalinity, and the other ions. The main sources of lead in the aquatic environment are leaded-gasoline and mining (Hem 1985). However, in surface waters, lead normally exhibits low concentration levels due to its propensity to co-precipitate with manganese (Hem 1985). The generally very low values of lead in the drainage, and its near uniformity in concentration throughout the area, including areas not influenced by mining operations, probably point to leaded-gasoline and other non-mining products as the sources of lead in the drainage. Slightly elevated values are particularly associated with water carrying drainage from towns and mine machinery maintenance yards. Mercury trends in drainage waters clearly pointed to anthropogenic point sources. The highest recorded mercury concentrations in the drainage were coincident with areas of very active artisanal mining activities. Augmented Hg levels were also identified with water draining historic tailings dumps at Prestea and Tarkwa. In these areas, Hg

concentrations are several times above the maximum allowable limits in drinking water established by Ghana's Environmental Protection Agency (EPA) and the World Health Organization (WHO). These observations are not surprising as Hg is the chemical used in gold extraction by traditional small miners and, before the introduction of cyanide leaching technology, Hg amalgamation was the technology of choice for gold extraction in large-scale mines, which were then mining only free milling gold in quartz reefs (Quashie et al. 1981). Analysis of tailings samples from the historic tailings dumps at Bondaye and Tarkwa, where the mines processed gold with mercury, showed augmented levels of mercury in these tailings.

Most mine-impacted stream waters in the Prestea and Nsuta area in particular have Ni, Fe, Cu, As, and Mn values above both Ghana's EPA and WHO drinking water standards. Average concentration of Mn in drainage in the entire area is several times above both sets of allowable guide values. Similarly, As and Fe values in drainage from the Tarkwa mine area are several times above the allowable limits. The average concentration of Ni and Cu in Prestea also exceed these guideline values.

Many of the communities in these areas have few alternative sources of domestic water supply and largely rely on these streams. High concentrations of hazardous elements in these streams therefore have some serious health implications. Communities in this area have high incidence of skin lesions, which are associated with metal toxicity. However, there has not been conclusive medical investigation of the exact causes of the lesions in these mining-impacted communities, although arsenic dermatitis has been reported in some communities near Bogoso (Songsore et al. 1994).

Conclusions

Drainage quality exhibits wide seasonal and spatial variations with a strong influence of geology on the water chemistry. High loading regimes of measured metal and sulphate ions are associated with Birimian rocks where sulphide constitutes more than 2% of ores. Much more subdued regimes of high ion loading were also observed at Damang in the Tarkwaian formation and are likely associated with oxidation of sulphides in scattered dolerite dykes in this mine, disproving the long-held notion that acid drainage was not possible in mines in the Paleo Conglomerative Tarkwaian formation.

Generally, areas characterized by low pH (<5.5) and high sulphate concentrations, along with the above-named trace cations and anions, are suggestive of acid mine drainage. Similarly, sites characterized by high pH (>7.5), with high alkalinity as HCO_3^- and subdued SO_4^{2-} , but

high trace cations and anions, are suggestive of net acid-neutralizing sites.

The fact that high metal loading was associated with both low and high pH regimes reflects the widely acknowledged fact that pH values need not necessarily be low for significant metal leaching to occur. It is therefore recommended that the practice of creating settling ponds for waste water and subsequently releasing the untreated water to the environment should be discouraged. Instead, remediation measures effective in sequestering the metals should be adopted.

The analyses established that Zn, Cu, Ni, As, Co, SO₄, Sb, pH, specific conductance, and alkalinity were essential and adequate parameters in determining if a specific site in the study area were affected by acid-generating and buffering reactions. It is therefore recommended that mines in the area routinely monitor these parameters. The concentrations in non-impacted areas can be considered baseline concentrations of these parameters.

The average concentrations of several metals are well above the allowable EPA and WHO maximum allowable limits for drinking water in most of the sites studied, while additional metals, such as Cu, Ni, and Hg exceed these limits in the Prestea area. Since communities largely depend on these streams for water, the mines and government need to consider the provision of alternative water sources a priority.

Acknowledgments The authors express our profound gratitude to the Danish International Development Assistance, Enhanced Research Capabilities (DANIDA ENRENCA), BROMKAMP, Germany, and the Third World Network for the financial support for this project. We also thank Mr. Richard Graeme, former Managing Director of Goldfield (Gh.) Ltd, who personally provided logistics and facilitated access to the property of Goldfields for the fieldwork.

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