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Impact of mining on groundwater quality in SW Ashanti, Ghana: a preliminary study

C. Kofi Bempah[1, 2*], H-J. Voigt[2] and A. Ewusi[3]

1. Faculty of Environmental Sciences and Process Engineering, Chair of Environmental Geology, Brandenburgische Technische Universität, Cottbus, Germany
2. Nuclear Chemistry and Environmental Research Center, National Nuclear Research Institute, Ghana Atomic Energy Commission, Legon, Accra, Ghana
3. Geological Engineering Department, University of Mines and Technology, Tarkwa-Ghana

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**Corresponding author: crentbempah@hotmail.com (C. Kofi Bempah).*

Abstract
The focus of this research work is on the determination of the impact of mining on the groundwater quality in the historical mining region of SW Ashanti region in Ghana. This work describes the characteristics of the groundwater chemistry and pollution of the aquifer in the gold-ore bearing formation, which is highly weathered and fractured. The fractures control the permeability and depth of the groundwater within the studied area. The concentrations of the major ions and trace elements (As, Fe, Cu, Mn and Zn) present are determined in 63 groundwater wells at dry and wet seasons. The results obtained showed that the concentrations of some ions and elements were below the World Health Organization (WHO) guideline values for drinking water. However, concentrations of the As and Fe ions were very high above the guideline values. The wells with high As and Fe concentration levels might be located at an apparent rock fractured zone that extends to a nearby mine. Such fractured zones allow groundwater to move more rapidly away from a mine, creating more severe mine-drainage pollution in their paths. The results obtained from this study suggested a possible risk to the population of the studied area, given the toxicities of the As and Fe ions, and the fact that for many people living in the studied area, groundwater is a main source of their water supply.

Keywords: *Gold deposits, Mining, Groundwater, trace elements, SW Ashanti.*

1. Introduction

The most significant impact of mining activities is its effects on the water quality and availability of water resources within the mining area. The degree of impact depends upon many factors, in particular, the mining type and method, and the operation size. Mining activities in the past have generated uncontrolled waste and tailings deposits, and today, they are a major source of acid mine drainage [1]. Mining activity mainly disturbs and changes the topography of land, which ultimately affects the hydro-geologic conditions [2]. The potential source of groundwater pollution from mines is the seeping or leaching of mine drainage water from the waste rock piles or unlined tailings dams into the aquifer [3]. This becomes a great concern where the groundwater feeds surface streams or lakes or where the groundwater is being used as a source of drinking water, as being experienced in the SW part of Ashanti region in Ghana. Moreover, underground mining of the ore body in the Obuasi mine generally lowers the groundwater table, resulting in the inflow of groundwater and rainwater into mining excavations. When this water comes into contact with a virgin rock mass containing pyrites in presence of atmospheric air, acid mine water is formed, thereby, affecting the groundwater quality [4].

Ghana is the Africa's second-largest gold-producing country after South Africa. Until the introduction of the bio-oxidation (BIOX) technology of extracting gold, in most mining areas, particularly Ashanti region (Obuasi) and western region (Tarkwa), processing of the ore for gold involved crushing and grinding it into fine powders, followed by dissolution and precipitation of the free gold [5]. During the ore preparation by roasting, sulfur dioxide and arsenic trioxide were released into the terrestrial and atmospheric environments. In addition, arsenic-rich tailings, heaped and kept in dams, were left at the mercy of the rain with subsequent leaching into the nearby rivers, streams, and aquifers [6]. For example, from 1947 until 1992, effluents were discharged without precaution, thereby, resulting in the degeneration of the environment [7]. Exploitation of hitherto low-grade ore as a result of the Ashanti mine expansion program (AMEP) caused increased mining activities, and hence, increased chemical contamination at the Obuasi mine and its satellite areas [8]. AMEP was part of the several responses of the Ghanaian Mining Industry Policy Initiative to promote investment in the sector. Unfortunately, these initiatives were rather weak on the provision of guidelines for the management of the associated negative environmental impacts [9].

There has also been a considerable increase in the number of domestic and international companies to explore gold reserves during the last three decades. Many civic centers including hospitals, clinics, homes, and football facilities have already been established on the geological formations containing gold bodies, but the adverse effects of exploring gold mines in the SW part of the Ashanti region in Ghana have not been well-explored, and their influence on groundwater is fairly limited [10].

This is the first study carried out in the SW part of the Ashanti region in Ghana with a population of 618,828 using the 2010 National Housing and Population Census [11] and comprising of three districts and two municipal assemblies including the Amansie west District, Amansie central district, Adansi north district, Obuasi municipality, and Bekwai municipality. These districts and municipalities are located at the Ashanti region in Ghana (Figure 1), being about 64 km south of Kumasi (the regional capital), and 300 km NW of Accra (the capital of Ghana) [12]. The studied area houses the administrative headquarters of the biggest gold-mining industry (AngloGold Ashanti-Obuasi Mine) in the West Africa's sub-region.

The gold deposits within the area are a gold-quartz vein and sulfide-disseminated type in the Birimian group, a Lower Proterozoic greenstone formation. The deposit has many common geological and mineralogical features to the worldwide meso-thermal gold deposits, and, therefore, has been referred to as the meso-thermal type [13]. The common minerals in the gold-bearing quartz veins are arsenopyrite, sphalerite, galena, chalcopyrite, gold, ferroan calcite, and sericite. The minor minerals include pyrite, stibnite, pyrrhotite, alabandite, bornite, tetrahedrite, tourmaline, and hydrothermal graphite [14].

The objective of this study was to investigate the potential environmental effects of mining on groundwater quality, and to describe the characteristic of the groundwater chemistry and likely pollution of the aquifer in the ore deposit of the SW part of the Ashanti region in Ghana.

2. Geological setting

The geology of the studied site (Figure 2) consists of the Proterozoic rocks of the Birimian meta-sedimentary. The main constituents of the meta-sediments are argillites, carbonaceous shales, wackes, and chemical sediments. The meta-volcanics consist mainly of basic to intermediate volcanic rocks [15]. The Birimian meta-sediments are unconformably overlain by sediments of the Tarkwaian rocks. Quartz veins in this deposit are concentrated in the shear zones, but sometimes occur as stockworks in the meta-sediments and meta-volcanics. Sizes commonly range from 0.2 to 5 m in width, sometimes reaching 25 m [13].

Four main generations of quartz veins have been identified in the deposit including the massive smoky blue gray quartz veins, ribboned milky white quartz veins, quartz-calcite veins (containing about 20 % of calcite), and completely barren quartz veins [14]. Wall rock alterations, mainly carbonate alteration (magnesian ankerite) and sericitization, are very common along with sulfidation in the immediate vicinity of the quartz veins [13].

3. Ore deposit

Two main ore types mined from this deposit are gold-bearing quartz veins, and gold-sulfide disseminations in the meta-sediments and meta-volcanics in the neighborhood of the shear zones. A granite body to the SW of the studied area is also mined for gold in a surface pit, where gold and sulfide minerals are disseminated in a manner similar to the occurrence in the meta-sediments and meta-volcanics [13].

In the quartz veins, gold is mainly concentrated in the earlier formed smoky blue gray quartz veins and the milky white quartz veins. Minor amounts occur in the quartz-calcite veins. Large gold grains visible to the unaided eye are observed in the quartz veins, although most grains are microscopic. Other common minerals available in the gold-bearing quartz veins include arsenopyrite, sphalerite, galena, chalcopyrite, ferroan calcite, and sericite. Minor minerals include pyrite, stibnite, pyrrhotite, alabandite, bornite, tetrahedrite, tourmaline, and hydrothermal graphite [13].

In the meta-sediments and meta-volcanics, gold is usually microscopic, and is closely associated with sulfide minerals, chiefly arsenopyrite. Silicification is locally important, and has generated siticified phyllites and tuffaceous sediments, which, in places, host significant amounts of disseminated gold-sulfide ore. The bulk of the ore of the mine consists of the gold-sulfide disseminated ore in the meta-sediments and meta-volcanics [13].

4. Hydrology and hydro-geology

The studied area is a humid tropical climate that has an annual average precipitation of 1450 mm, of which 70 % is subjected to evapo-transpiration, according to mean annual balances. Surface run-off is very high since 40% of the annual precipitation can occur in 1–2 days. Therefore, the main mechanism for the contaminant mobilization from primary sources is the run-off and mechanical dispersion caused by the wind. The groundwater pollution and loss of soil fertility as well as surface water contamination are the main symptoms of the environmental degradation brought about by uncontrolled disposal of mining waste in this area [7].

The tailings present in the studied area have been spilled over the ancient crystalline rocks, incorporating mainly metamorphosed sediments and granite. The most important gold-bearing areas occur within the non-granitoid Birimian rocks, which is of significant economic value.

Groundwater flow is mostly restricted to the joints and fractures within the crystalline rock formations. Borehole yields are, therefore, often limited. In some areas, a thick layer of weathered friable material (‘regolith’) overlies the crystalline basement, and provides the potential for the increased groundwater storage. This weathered layer can be in excess of 100 m thick in places, though it is typically in the thickness range of 1-70 m [16]. Groundwater supplies may be higher in the minor sedimentary deposits of the coastal basins.

Main aquifer recharge is mostly the infiltration of rainfall, irrigation return, losses due to filtration from the rivers and streams that drain the area, and the contribution of smaller collateral aquifers. The main outflows of the system are through pumping for domestic, industrial, and irrigation purposes. The chemical analysis of groundwater samples shows significant amounts of trace elements (Hg, As, Ba, Fe, Mn, Mo, Pb, Zn, etc.) in soils and groundwater within the studied area as a result of the mining and illegal artisanal mining activities [7]. Metal attenuation is very significant during the transportation of metals through the non-saturated zone of the aquifer, and probably accounts for the low concentrations of several other dissolved contaminants in the groundwater.

5. Research methods

Sixty three sampling sites were visited during the entire study period. Sampling was designed to cover a period of 12 months, covering the dry and wet periods in 2012 and 2013. The samples were collected at monthly intervals, beginning from August and November 2012 to February 2013 for the dry season, and from the September to October 2012 and March to July 2013 samples for the rainy season. Care was taken to collect subsequent samples from same locations in both seasons. Overall, 63 wells including shallow wells, boreholes, and hand-dug wells were sampled. The samples were collected wearing polyethylene gloves, and employing the sampling protocol methods as described by Knödel *et al.* [17]. 1-Liter, high density polyethylene sample bottles were rinsed with the groundwater samples before being filled completely, and were preserved airtight in order to avoid evaporation.

A flow-through cell and a calibrated hand held YSI® Multi-Parameter Water Quality Meter (Model YSI 6 l0-DM/600XL) connected to a peristaltic pump (low-flow pump) was used to purge wells at a flow rate of 500 mL/min. This instrument contained probes that simultaneously measured the indicator parameters including pH, conductivity, dissolved oxygen, oxygen reduction potential (ORP), and temperature, except turbidity, which was measured separately by a calibrated Hach 2100Q Portable turbidimeter. The indicator parameters were measured at 15 minutes intervals throughout the purge period. When the parameters stabilized to consistent readings, and without interrupting flow from the well, the tubing was immediately disconnected from the flow through cell to fill the 1-L high density polyethylene sample bottles with the groundwater

samples. At each designated sample collection interval, the pump rates were reduced to between 100 and 300 mL/min to prevent turbulence as the groundwater was directed into the sample containers.
The sample bottles were filled to capacity (i.e. minimal headspace) to minimize air exposure. Unfiltered samples were collected for total (dissolved + particulate) As, while filtered groundwater samples were collected for the analysis of major anions and cations, trace elements, and nitrates. The samples were immediately acidified to a pH of < 2 using nitric acid for the total As and trace elements. Nitric acid preserves the sample by lowering the sample pH to 2, which prevents the precipitation of iron, and prevents the oxidation of Fe^{2+} ions present in solution that might cause some arsenic to be sorbed, as described by Holm *et al*. [18]. The indicator parameters were again measured using a fresh groundwater sample. . Teflon-lined caps were applied to ensure a tight seal. For each monitoring well locations, groundwater samples were collected using the low flow on the same day to reduce day-to-day variation in the concentration of the site contaminants that may exist at each sampling location. The groundwater samples collected for the analysis of the major ions were tested within 24 hours. Analyses of the trace elements were completed within a week after collection. The groundwater samples were analyzed for trace elements by flame atomic absorption spectroscopy, while the anions and cations were determined simultaneously in groundwater samples using Metrohm 761 Compact IC and Dionex 4500i IC system, respectively, in the Nuclear and Environmental Research Laboratory at Ghana Atomic Energy Commission.
For quality control, replicate samples were processed with each analytical batch. Standard reference materials were employed to determine accuracy [19]. The reported results represent an average of three measurements. The reproducibility of the groundwater analyses in the given concentration range s was around 10%. Accordingly, the analyzed trace element concentrations are displayed in Table 1 through Table 4. The WHO drinking water quality standards [20] were, therefore, used as the basis for comparison in the analysis of the impact of mining on the groundwater quality.
The information regarding the permeability of the Proterozoic rocks in the Birimian meta-sedimentary ore-bearing zone was obtained from the AngloGold Ashanti mine to ascertain the surface observation within the studied area.

Figure 1. Map of studied area and its boundaries.

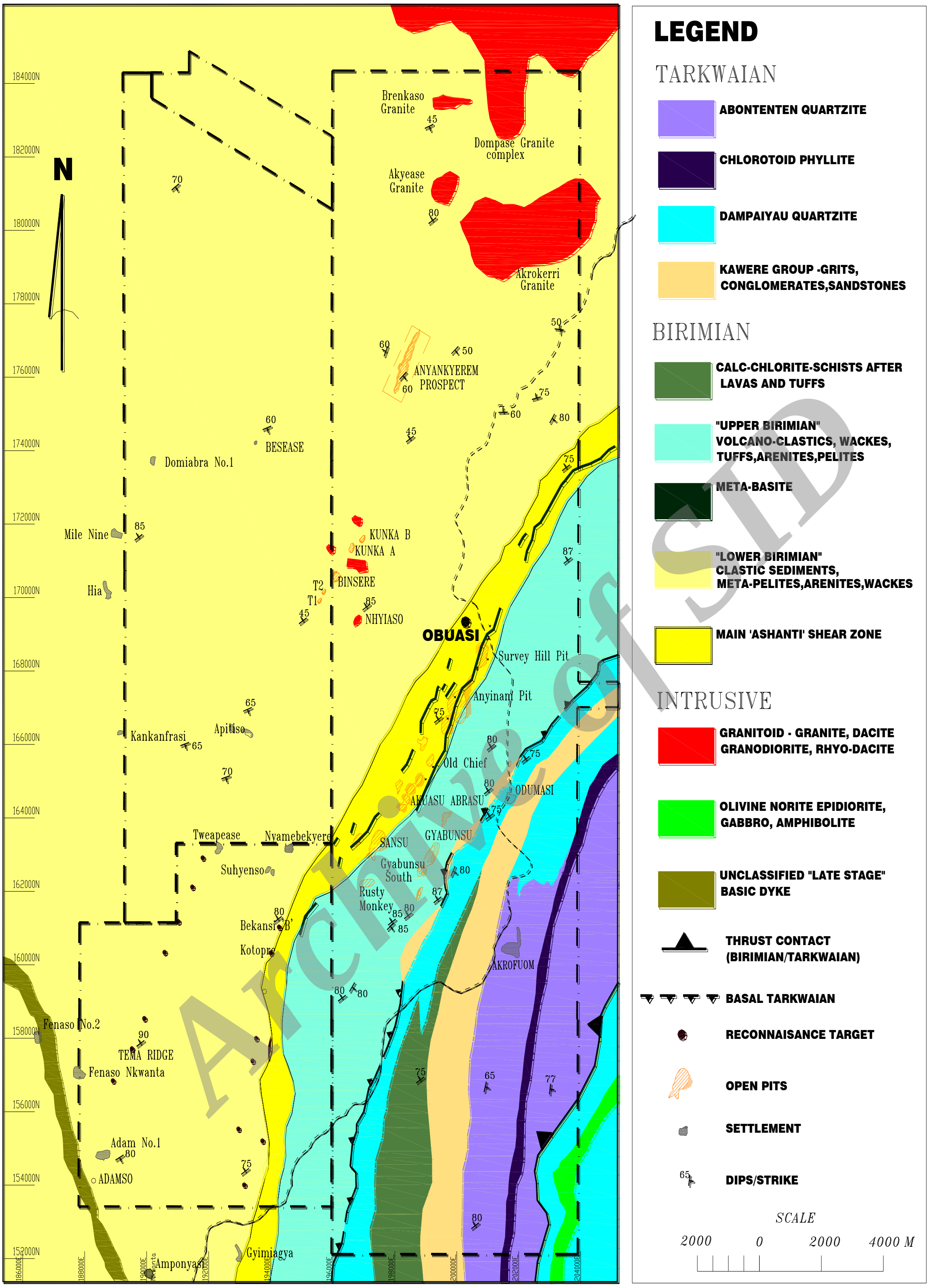

Figure 2. Geological map of studied area.

Table 1. Summary of main physico-chemical parameters, and major cation and anion concentrations of the surveyed groundwater samples during dry season in SW part of Ashanti region in Ghana. Concentrations are in mg/L, except as noted.

Studied area	Location	Depth (m)	*T* (^{0}C)	pH	EC (µS/cm)	Eh (mV)	DO	HCO_3	F	CL	SO_4	PO_4	Na	K	Mg	Ca	NO_3	DOC	TDS
Detection limit							**0.1**	**5**	**0.01**	**0.15**	**0.1**	**0.1**					**0.1**	**0.1**	**5**
Adansi North District	Meduma	53	27.2	7.78	109	422	0.9	58.71	0.01	2.09	1.36	0.16	19.04	3.86	4.26	6.12	0.8	1.81	73.9
	Abedwum	6	31.4	6.56	62	412	1.6	113.96	0.03	4.43	3.23	0.28	6.04	0.15	0.71	7.03	1.03	4.05	42.1
	Wioso	18	29.8	7.47	97	467	2.0	83.42	0.13	4.96	1.72	0.36	11.18	2.73	1.65	3.62	<0.1	2.07	65.8
	Patakro Dunkwa	36	28.3	7.21	303	252	1.6	212.10	0.41	7.34	1.92	0.19	21.12	4.02	8.63	42.07	<0.1	0.93	205.6
	Nkwanta	25.5	29.2	6.58	43	463	2.6	78.03	0.03	3.20	1.21	0.13	19.87	0.87	2.88	1.16	1.05	0.34	29.2
	Kokotease	35	27.4	7.78	71	402	3.8	82.34	0.03	4.32	1.34	0.18	17.12	0.32	3.02	3.35	1.7	1.86	48.2
	Kofikurom	38	26.2	6.55	109	414	1.9	36.63	0.04	3.45	0.23	0.24	11.14	0.24	12.34	6.57	1.25	3.56	73.9
Amansie West District	Odahu	60	25.9	8.14	159	257	0.5	93.67	0.17	6.3	1.82	0.10	18.97	0.04	8.25	5.21	0.42	0.77	107.9
	Agroyesum Hsp	52	27.7	6.12	391	242	<0.1	269.42	0.20	3.20	1.33	0.20	30.35	0.24	11.13	58.9	<0.1	0.36	265.3
	Apanapron	80	25.3	7.39	282	274	<0.1	163.40	0.18	7.40	1.07	0.31	13.9	0.32	4.01	38.99	1.03	3.70	191.4
	Ankam	38	31.5	6.54	157	241	1.2	98.83	0.31	6.12	5.09	0.17	14.3	0.05	5.02	16.33	1.33	1.02	106.5
	Mim 1	57	27.3	6.85	226	317	1.1	91.48	0.21	2.45	0.12	0.21	14.38	0.46	6.17	23.34	0.33	0.85	153.4
	Abodom	46	26.2	8.05	128	412	1.4	70.20	0.08	6.45	1.63	0.11	10.43	0.34	1.09	4.46	1.04	1.01	86.9
	Mim 2	49	27.6	6.94	201	402	1.0	68.32	0.19	7.87	0.16	0.13	17.45	0.37	6.33	11.17	1.47	3.95	136.4
	Antoakurom 1	70	25.7	8.42	293	233	0.5	182.42	0.09	17.07	1.30	0.19	14.47	0.91	5.15	38.09	0.42	0.30	198.8
	Manso Akropon	43	29.2	6.57	189	405	<0.1	52.0	0.17	7.45	0.87	0.14	17.23	0.01	3.19	7.49	1.08	1.45	128.3
	Antoakurom 2	32	25.3	7.34	132	252	1.9	79.43	0.04	12.15	1.43	0.11	19.42	0.36	4.17	4.02	1.86	1.37	89.6
	Nsiana	49	29.8	6.58	148	433	0.8	40.65	0.07	9.03	0.21	0.13	14.2	1.45	3.89	7.09	1.7	1.27	100.4
	Yawkurom	49	27.2	8.44	202	237	<0.1	132.91	0.19	7.89	0.27	0.27	10.45	0.43	7.18	21.85	0.26	1.36	137.1
	Manso Atwere	19	28.4	6.53	112	392	0.5	97.30	0.07	4.00	3.04	0.19	14.2	0.63	5.30	7.20	<0.1	2.73	76.0
	Odumase	43	29.2	6.18	402	282	1.3	48.0	0.09	5.30	0.72	0.11	15.4	0.67	13.04	41.3	<0.1	3.02	272.8
Amansie Central District	Mile 9	46	28.4	7.61	168	352	1.2	92.37	0.18	7.43	1.16	0.30	22.33	0.54	1.91	16.03	0.36	2.06	114.0
	Mile 14	64.5	26.9	8.47	221	239	0.4	221.33	0.04	8.98	0.23	0.37	14.26	0.32	24.9	24.12	0.23	1.32	149.9
	Boni	66	28.3	6.58	326	436	0.7	38.04	0.07	6.32	1.04	0.12	23.26	1.75	22.09	26.89	1.03	1.3	221.2
	Hunatado	54	26.9	7.86	122	459	2.3	21.13	0.05	3.90	0.23	0.15	19.17	1.36	3.43	4.98	1.32	1.05	82.8
	Poano	61	29.5	8.23	207	263	<0.1	126.18	0.09	3.56	1.43	0.21	9.18	0.43	14.32	15.9	0.62	0.82	140.5
	Ntinako	52	26.9	7.71	197	326	1.3	68.16	0.09	21.53	1.65	0.21	21.43	0.28	3.55	8.24	<0.1	0.33	133.7
	Kofitanokrom	8	31.2	6.64	143	412	1.7	109.18	0.05	5.46	1.23	0.11	24.29	1.48	0.93	6.73	0.77	1.95	97.0
	Patase	34	28.8	8.46	142	348	2.8	26.18	0.13	11.34	0.82	0.10	25.4	3.23	2.34	14.43	1.24	1.02	96.4
	Apitiso	43.5	25.7	8.36	304	397	1.1	103.42	0.07	23.25	1.03	0.21	23.54	0.32	16.34	26.21	<0.1	3.67	206.3
	Fiankoma	65	29.4	6.85	113	292	<0.1	42.43	0.08	4.43	0.53	0.14	22.70	0.24	9.39	6.34	<0.1	1.07	76.7
	Dangase	4	31.6	6.59	42	313	1.1	111.13	0.02	3.06	2.02	0.32	11.09	0.34	0.38	0.33	1.38	2.45	28.5
	Odumto	15	29.9	8.14	70	411	1.5	92.30	0.05	7.00	1.13	0.30	7.20	0.52	0.93	0.33	1.43	1.06	47.7
	Sabe	22	29.0	8.33	295	219	<0.1	183.65	0.39	9.35	0.11	0.31	16.47	1.25	20.98	21.48	0.14	1.06	200.2
	Mile 18	8	30.0	6.84	142	293	1.8	127.30	0.06	5.09	2.43	0.13	13.4	0.41	4.03	4.73	1.08	2.39	96.4
	Mamfo	28	28.5	8.18	302	341	<0.1	192.65	0.23	4.84	1.52	0.14	14.7	0.32	2.23	3.98	0.64	0.23	204.9
	Dekyewa	24	29.4	6.62	134	267	0.5	91.43	0.05	7.28	2.52	0.21	13.8	0.68	3.13	1.75	1.90	1.95	90.9

Table 1. (Continued).

Studied area	Location	Depth (m)	*T* (^{0}C)	pH	EC (µS/cm)	Eh (mV)	DO	HCO_3	F	CL	SO_4	PO_4	Na	K	Mg	Ca	NO_3	DOC	TDS
Detection limit							**0.1**	**5**	**0.01**	**0.15**	**0.1**	**0.1**					**0.1**	**0.1**	**5**
Amansie Central District	Afoako	42	27.3	7.45	56	458	3.7	26.13	0.07	3.21	1.73	0.15	8.17	4.38	0.92	3.34	<0.1	0.23	38.0
	Aketekyiso	3	29.7	7.27	59	319	1.1	108.14	0.05	7.09	3.38	0.15	9.04	0.49	0.33	0.38	1.20	3.27	40.0
	Tweapease	43	25.3	8.42	163	313	0.8	93.43	0.21	5.90	0.75	0.11	17.4	0.26	4.12	10.35	0.16	0.27	110.6
	Abuakwa	48	25.9	6.02	202	273	0.3	123.42	0.04	7.43	1.29	0.31	13.54	0.34	3.09	26.32	0.78	1.08	137.1
Obuasi Municipal Assembly	Nhyiaso	18	28.9	6.52	98	401	1.6	109.12	0.07	8.42	2.19	0.13	13.40	0.32	2.71	3.04	<0.1	2.09	66.5
	Akrofuom	32	31.3	7.73	638	233	1.1	63.16	0.15	41.09	2.03	0.28	24.17	1.18	4.04	8.23	1.47	2.04	432.9
	Sanso	42	29.8	6.52	167	452	3.1	116.13	0.06	5.48	5.61	0.14	27.74	0.49	7.13	10.34	0.93	1.07	113.3
	Brahabebome	19	31.6	7.32	98	474	1.3	52.18	0.03	1.97	3.85	0.27	9.07	1.23	0.66	14.39	0.11	1.71	66.5
	Diewieso	25	29.8	6.53	321	527	2.1	98.12	0.13	28.94	2.38	0.28	27.19	3.18	4.62	3.91	<0.1	2.89	217.8
	Nyamso North	48	27.4	7.54	112	384	0.6	54.36	0.28	4.92	1.04	0.13	11.14	0.15	4.82	3.73	0.67	1.05	76.0
	Nyamso South	32	25.8	7.05	67	352	<0.1	85.32	0.03	3.86	1.38	0.30	9.23	0.24	3.46	2.01	1.47	1.38	45.5
	Konka New Town	30	28.9	6.52	102	212	1.1	72.43	0.05	8.36	1.17	0.17	16.30	0.18	1.93	0.43	1.62	2.45	691.2
	Apitikokoo	40	31.4	6.63	111	254	1.3	17.11	0.03	6.93	0.13	0.13	11.12	2.91	4.12	1.83	0.80	1.92	75.3
	Kokotenten	34	30.5	8.46	274	494	3.6	162.42	0.19	2.18	4.12	0.12	19.30	2.31	5.14	27.09	1.08	0.33	185.9
	Nyamekyere	43	27.0	6.52	67	283	1.2	31.30	0.05	7.04	0.52	0.20	7.60	0.13	1.02	2.01	1.30	2.48	45.5
	Obuasi BH 3	100	25.2	8.31	984	651	0.5	217.42	0.13	16.89	9.55	0.11	31.50	2.43	41.06	82.56	1.71	2.39	442.4
	Mensakurom	9	26.2	6.92	98	413	1.5	13.0	0.05	4.60	5.86	0.10	7.30	0.83	0.69	0.93	0.32	0.73	66.5
	Obuasi BH 2	70	25.9	6.15	654	662	2.6	143.64	0.13	11.14	8.14	0.13	33.15	1.01	45.21	61.46	1.03	2.02	443.8
	Obuasi BH 1	70	26.0	8.19	652	586	2.1	122.43	0.39	10.53	8.97	0.12	28.67	0.98	85.12	82.32	0.80	2.55	667.7
	Wamase	4	33.3	8.12	96	371	1.7	132.71	0.07	4.70	6.82	0.23	23.25	0.24	0.09	7.25	<0.1	1.82	65.1
Bekwai Municipal Assembly	Old Edubiase	43	29.7	7.01	132	419	2.1	72.13	0.14	3.13	1.14	0.11	22.31	1.07	3.01	7.98	0.33	2.05	89.6
	Dwondoso	5.5	32.6	6.73	42	243	1.6	83.15	0.04	3.20	6.17	0.23	18.39	0.76	0.14	7.23	<0.1	1.74	28.5
	Aminase	4	33.9	6.65	88	299	3.0	125.19	0.09	5.87	7.01	0.31	26.44	0.86	0.32	4.45	0.62	0.41	59.71
	Amoamo	1.5	34.6	8.19	278	341	<0.1	31.40	0.19	29.42	1.82	0.28	13.19	0.19	2.45	19.02	0.31	0.82	188.6
	Ankase	48	27.2	6.84	152	413	0.9	14.14	0.12	4.28	0.13	0.30	12.13	2.71	11.09	8.79	0.43	1.97	103.1
	Bogyawe	58	26.8	6.14	164	215	1.2	113.18	0.31	2.54	1.32	0.23	21.43	3.43	9.34	10.16	0.93	0.86	111.2
Statistical Data	**Minimum**		**25.2**	**6.02**	**42.0**	**212.0**	**<0.1**	**13.0**	**0.01**	**1.97**	**0.11**	**0.10**	**6.04**	**0.01**	**0.09**	**0.33**	**<0.1**	**0.23**	**28.5**
	Maximum		**34.6**	**8.47**	**984.0**	**662.0**	**3.8**	**269.42**	**0.41**	**41.09**	**9.55**	**0.37**	**33.15**	**4.38**	**85.12**	**82.56**	**1.9**	**4.05**	**691.2**
	Mean		**28.54**	**7.22**	**200.3**	**359.06**	**1.53**	**96.53**	**0.13**	**8.01**	**2.18**	**0.20**	**17.06**	**1.02**	**7.86**	**15.04**	**0.74**	**1.64**	**145.9**
	Median		**28.40**	**7.21**	**148.0**	**352.0**	**1.20**	**92.3**	**0.08**	**6.12**	**1.32**	**0.19**	**16.30**	**0.49**	**4.03**	**7.25**	**0.78**	**1.38**	**103.1**
	Standard deviation		**2.27**	**0.75**	**168.84**	**103.72**	**0.86**	**55.32**	**0.09**	**7.15**	**1.36**	**0.08**	**6.59**	**0.09**	**5.06**	**12.03**	**0.59**	**0.98**	**133.9**
	WHO (2004)	-	-	-	**1500**	-	**5**	**384**	**1.5**	**600**	**400**	-	**200**	-	**150**	**200**	**45**	-	**500**

Table 2. Summary of main physico-chemical parameters, and major cation and anion concentrations of the surveyed groundwater samples during the wet (rainy) season in SW part of Ashanti region of Ghana. Concentrations are in mg/L, except as noted.

Studied area	Location	Depth (m)	*T* (^{0}C)	pH	EC (µS/cm)	Eh (mV)	DO	HCO_3	F	CL	SO_4	PO_4	Na	K	Mg	Ca	NO_3	DOC	TDS
Detection limit							**0.1**	**5**	**0.01**	**0.15**	**0.1**	**0.1**					**0.1**	**0.1**	**5**
Adansi North District	Meduma	53	26.0	5.43	132	473	1.2	61.22	<0.01	3.43	1.48	0.19	22.45	4.32	5.43	9.19	0.7	2.63	88.50
	Abedwum	6	25.7	6.76	73	412	2.2	127.40	<0.01	7.18	3.56	0.34	8.22	2.33	2.33	11.23	1.42	3.23	43.66
	Wioso	18	23.4	5.53	105	472	2.4	100.75	0.10	6.12	1.88	0.27	13.25	3.54	4.36	5.32	0.82	2.36	78.45
	Patakro Dunkwa	36	26.0	7.55	338	268	1.9	235.58	0.34	7.56	2.20	0.17	19.32	6.12	11.34	44.25	0.55	1.08	215.73
	Nkwanta	25.5	25.5	4.23	73	472	3.2	98.37	0.42	8.33	1.34	0.19	22.31	1.54	4.35	5.32	1.15	0.78	46.70
	Kokotease	35	25.7	5.90	56	398	3.5	113.32	<0.01	41.17	1.46	0.23	19.43	2.43	5.38	7.33	1.62	2.53	53.85
	Kofikurom	38	24.3	5.05	112	423	2.7	77.32	0.02	5.17	0.98	0.16	15.32	1.32	14.87	6.32	1.05	4.73	98.35
Amansie West District	Odahu	60	26.8	5.33	185	267	0.8	125.50	0.13	2.05	2.05	0.15	21.22	3.45	11.87	9.34	0.43	1.43	135.40
	Agroyesum Hsp	52	25.7	6.25	432	258	0.6	320.45	0.17	30.62	1.45	0.28	38.56	2.35	15.33	65.11	0.86	0.78	288.56
	Apanapron	80	25.0	6.56	305	285	0.4	187.40	0.15	5.15	1.13	0.43	19.35	3.42	6.37	44.23	0.65	4.26	223.40
	Ankam	38	26.3	5.67	138	273	1.5	110.23	0.26	4.32	5.22	0.15	11.46	3.22	7.55	21.23	1.42	1.84	125.67
	Mim 1	57	25.2	6.04	233	298	1.7	100.25	0.27	8.86	1.33	0.12	17.36	3.45	9.63	28.43	0.55	1.64	183.80
	Abodom	46	26.7	6.17	153	422	1.9	110.36	0.06	7.21	1.83	0.18	21.26	1.22	3.22	8.33	1.04	1.78	123.20
	Mim 2	49	23.7	6.15	241	382	1.3	75.48	0.10	2.57	0.46	0.19	19.46	2.33	9.67	15.23	1.47	4.38	158.20
	Antoakurom 1	70	26.1	6.55	345	248	0.5	220.34	0.03	7.83	1.42	0.21	25.33	3.13	7.22	44.22	0.42	0.87	235.37
	Manso Akropon	43	26.7	5.23	222	442	0.7	77.84	0.15	19.15	1.22	0.13	21.34	3.22	5.87	8.30	1.23	1.95	156.89
	Antoakurom 2	32	24.2	5.88	337	268	2.2	98.46	<0.01	4.92	1.56	0.16	22.43	0.22	9.66	7.13	1.96	1.67	112.40
	Nsiana	49	23.6	5.84	128	452	1.3	67.54	0.03	13.20	0.25	0.19	17.54	2.33	5.87	9.32	1.22	1.85	152.95
	Yawkurom	49	24.9	6.58	278	252	0.2	784.56	0.12	11.24	0.33	0.23	22.34	0.56	9.15	25.63	0.58	1.74	154.38
	Manso Atwere	19	25.9	6.75	98	412	0.6	134.57	0.03	6.25	3.67	0.15	19.35	0.99	8.46	11.30	0.45	3.63	95.75
	Odumase	43	24.7	5.58	398	305	1.5	86.54	0.07	3.78	0.98	0.17	17.98	1.23	17.33	45.32	0.84	3.53	294.76
Amansie Central District	Mile 9	46	24.5	5.85	174	352	1.7	113.23	0.12	3.67	1.33	0.30	26.32	0.57	2.33	21.37	0.56	2.83	145.30
	Mile 14	64.5	24.6	6.56	288	248	0.5	265.43	<0.01	6.21	0.27	0.39	22.65	0.76	27.87	29.45	0.93	1.74	158.48
	Boni	66	23.7	5.75	353	457	1.2	76.83	0.03	32.43	1.14	0.17	27.58	0.67	28.45	31.58	1.78	1.38	222.50
	Hunatado	54	25.1	4.94	155	472	2.6	65.48	0.02	5.24	0.68	0.19	21.87	1.66	7.36	8.47	1.65	1.85	120.32
	Poano	61	24.7	5.46	225	283	0.7	158.49	0.07	3.72	1.47	0.24	12.48	0.94	16.33	19.46	0.90	1.34	145.30
	Ntinako	52	25.7	5.84	320	337	1.5	100.38	0.05	4.43	1.95	0.22	28.93	0.65	7.45	11.48	0.66	0.87	165.42
	Kofitanokrom	8	26.8	5.72	187	425	2.3	135.85	0.03	7.72	1.35	0.14	31.65	1.22	3.44	9.76	0.83	2.53	110.35
	Patase	34	25.3	5.51	164	358	3.1	87.39	0.10	6.30	1.28	0.18	33.68	3.66	5.35	17.85	1.54	1.78	113.84
	Apitiso	43.5	24.9	5.58	335	412	1.3	145.30	0.04	7.87	1.23	0.22	29.57	0.38	17.88	31.67	0.88	3.93	233.45
	Fiankoma	65	24.4	5.32	156	320	0.7	87.49	0.03	8.75	0.74	0.11	30.34	0.73	13.76	9.45	0.64	1.65	95.87
	Dangase	4	24.9	3.88	89	324	2.3	129.35	<0.01	44.64	2.43	0.37	17.48	0.66	3.26	5.37	1.67	2.96	43.56
	Odumto	15	24.4	5.40	112	438	2.6	112.65	0.03	6.05	1.05	0.34	11.36	1.23	2.55	4.16	1.62	1.58	72.12
	Sabe	22	23.6	6.55	387	229	0.8	268.50	0.24	2.87	0.15	0.39	16.94	1.76	26.46	27.45	0.55	1.26	223.74
	Mile 18	8	26.7	5.48	125	382	2.5	174.39	0.03	32.55	2.33	0.12	17.49	0.33	6.33	8.49	1.54	2.85	120.43
	Mamfo	28	25.6	6.28	333	363	1.1	220.45	0.17	5.85	1.64	0.17	65.35	0.47	5.38	5.55	0.75	0.76	258.47
	Dekyewa	24	25.5	5.73	148	282	0.9	127.73	0.02	4.20	2.34	0.22	19.47	0.92	8.32	1.64	1.98	2.33	103.52

Table 2. (Continued).

Studied area	Location	Depth (m)	*T* (^{0}C)	pH	EC (µS/cm)	Eh (mV)	DO	HCO_3	F	CL	SO_4	PO_4	Na	K	Mg	Ca	NO_3	DOC	TDS
Detection limit							**0.1**	**5**	**0.01**	**0.15**	**0.1**	**0.1**					**0.1**	**0.1**	**5**
Amansie Central District	Afoako	42	25.6	5.86	87	472	3.2	45.57	0.05	3.75	1.93	0.17	14.38	4.56	2.36	4.33	0.53	0.67	64.73
	Aketekyiso	3	26.8	5.20	95	338	1.4	118.95	0.03	7.68	3.45	0.15	17.49	0.75	3.46	3.85	1.38	3.84	88.60
	Tweapease	43	26.9	5.68	184	354	1.2	125.67	0.18	6.34	0.92	0.14	22.37	0.56	7.43	15.46	0.66	0.68	143.54
	Abuakwa	48	25.5	6.38	252	280	1.7	148.90	0.02	7.98	1.38	0.33	19.45	0.72	7.44	31.36	0.95	1.94	167.28
Obuasi Municipal Assembly	Nhyiaso	18	25.5	5.42	73	426	2.6	118.46	0.05	8.65	2.32	0.17	17.56	0.66	4.35	5.22	0.40	2.38	89.34
	Akrofuom	32	25.3	3.13	674	262	1.8	88.85	0.12	44.56	2.12	0.31	31.37	1.19	7.95	15.34	1.58	2.84	543.27
	Sanso	42	25.3	6.15	242	475	3.6	178.62	0.04	6.09	5.82	0.15	35.48	0.83	13.66	14.33	1.05	1.48	182.34
	Brahabebome	19	23.8	5.85	125	482	1.5	100.25	0.02	4.32	4.30	0.27	11.35	1.67	4.66	18.47	0.56	2.05	68.43
	Diewieso	25	23.5	4.32	290	513	2.2	138.90	0.10	33.34	2.56	0.31	30.37	3.87	7.55	5.63	0.85	3.26	246.32
	Nyamso North	48	25.3	5.54	132	372	1.4	100.45	0.24	6.33	1.35	0.28	13.45	0.59	6.48	7.33	1.22	1.38	110.20
	Nyamso South	32	25.4	5.05	167	313	1.7	128.90	0.05	5.65	1.67	0.30	16.73	0.38	8.64	4.85	1.58	1.85	76.34
	Konka New Town	30	26.2	5.25	137	242	1.5	98.37	0.03	10.23	1.22	0.21	21.36	0.37	5.88	2.34	1.87	2.95	732.45
	Apitikokoo	40	23.4	6.63	142	267	1.9	45.78	0.07	7.44	0.24	0.19	15.38	3.05	5.23	5.33	1.02	2.53	98.72
	Kokotenten	34	25.4	6.46	312	526	3.8	223.76	0.13	4.43	5.24	0.17	22.48	2.70	7.10	33.25	1.54	0.78	205.87
	Nyamekyere	43	26.4	5.72	88	288	1.4	74.68	0.03	9.32	1.33	0.21	13.28	0.63	4.87	5.37	1.53	2.84	75.39
	Obuasi BH 3	100	26.5	6.45	1230	727	0.5	285.40	0.09	21.68	10.5	0.13	38.47	2.98	44.88	95.67	1.82	2.69	512.15
	Mensakurom	9	26.2	4.20	128	554	1.7	63.20	0.04	8.32	6.35	0.11	16.74	1.04	5.46	4.38	0.45	1.26	88.46
	Obuasi BH 2	70	25.7	6.35	886	788	2.7	198.47	0.08	18.43	9.86	0.15	42.15	1.65	56.33	78.54	1.30	2.48	498.80
	Obuasi BH 1	70	25.0	5.19	898	734	2.5	155.90	0.34	20.12	9.13	0.12	33.90	1.44	93.67	96.55	0.95	2.96	720.47
	Wamase	4	26.3	5.12	102	355	2.2	168.30	0.05	6.85	7.56	0.20	31.45	0.73	3.22	11.33	1.22	2.05	87.55
Bekwai Municipal Assembly	Old Edubiase	43	24.7	5.31	98	512	2.5	115.45	0.11	4.05	1.72	0.13	28.75	1.56	6.44	10.26	0.38	2.67	123.46
	Dwondoso	5.5	24.4	5.93	56	284	1.9	120.36	0.02	3.86	6.89	0.25	22.18	1.37	8.33	9.65	1.04	1.88	56.43
	Aminase	4	26.8	5.75	120	332	3.4	186.34	0.07	6.35	7.56	0.34	31.22	1.45	2.37	7.54	0.76	0.75	98.34
	Amoamo	1.5	23.6	5.39	308	364	0.9	87.34	0.12	31.43	2.06	0.31	19.38	1.53	7.59	22.38	0.67	1.10	132.29
	Ankase	48	25.3	6.19	137	445	1.8	56.33	0.08	5.33	0.38	0.32	17.84	3.01	16.20	11.46	0.83	2.05	167.44
	Bogyawe	58	23.0	6.14	232	228	0.6	187.40	0.27	6.78	1.95	0.27	26.73	3.83	13.54	13.47	0.97	1.64	135.85
Statistical Data	**Minimum**		**23.0**	**3.13**	**56.0**	**228.0**	**0.2**	**45.57**	**<0.01**	**2.05**	**0.15**	**0.11**	**8.22**	**0.22**	**2.33**	**1.64**	**0.4**	**0.67**	**43.6**
	Maximum		**26.9**	**7.55**	**1230.0**	**788.0**	**3.8**	**784.56**	**0.42**	**44.64**	**10.5**	**0.43**	**65.35**	**6.12**	**93.67**	**96.55**	**2.0**	**4.73**	**732.5**
	Mean		**25.24**	**5.70**	**240.13**	**382.49**	**1.92**	**141.95**	**0.10**	**10.92**	**2.49**	**0.22**	**22.85**	**1.78**	**11.31**	**19.19**	**1.05**	**2.12**	**173.2**
	Median		**25.30**	**5.73**	**167.0**	**363.0**	**1.70**	**118.46**	**0.07**	**6.7**	**1.56**	**0.19**	**21.26**	**1.37**	**7.43**	**11.23**	**0.95**	**1.88**	**132.2**
	Standard deviation		**1.03**	**0.74**	**207.74**	**119.78**	**0.84**	**102.1**	**0.09**	**10.72**	**2.47**	**0.08**	**9.21**	**1.30**	**6.13**	**14.17**	**0.45**	**0.98**	**143.3**
	WHO (2004)	-	-	-	**1500**	-	**5**	**384**	**1.5**	**600**	**400**	-	**200**	-	**150**	**200**	**45**	-	**500**

Table 3. Concentration levels of As_{total} and other trace elemental characteristics of surveyed groundwaters during dry season in SW part of Ashanti region in Ghana.

Studied area	Location	Depth (m)	pH	Fe (mg/L)	Mn (µg/L)	As_{total} (µg/L)	Cu (µg/L)	Zn (µg/L)
DL				**0.01**	**0.1**	**0.1**	**0.1**	**0.1**
Adansi North District	Meduma	53	7.78	<0.01	1.8	5.0	9.0	7.0
	Abedwum	6	6.56	0.08	29.7	<0.1	<0.1	39.0
	Wioso	18	7.47	0.06	14.3	<0.1	44.0	31.0
	Patakro	36	7.21	2.89	175.0	<0.1	<0.1	11.0
	Dunkwa Nkwanta	25.5	6.58	0.35	22.4	<0.1	4.0	12.0
	Kokotease	35	7.78	<0.01	6.8	<0.1	5.0	13.0
	Kofikurom	38	6.55	0.06	32.1	<0.1	9.0	19.0
Amansie West District	Odahu	60	8.14	0.37	103.7	2.0	<0.1	33.0
	Agroyesum Hsp	52	6.12	6.65	319.0	43.0	<0.1	9.0
	Apanapron	80	7.39	1.72	201.0	9.0	<0.1	19.0
	Ankam	38	6.54	0.61	58.7	<0.1	7.0	21.0
	Mim 1	57	6.85	1.03	82.1	<0.1	<0.1	6.0
	Abodom	46	8.05	<0.01	11.9	4.0	17.0	14.0
	Mim 3	49	6.94	0.01	11.7	<0.1	11.0	17.0
	Antoakurom 1	70	8.42	0.73	327.0	48.0	<0.1	9.0
	Manso Akropon	43	6.57	0.42	347.0	<0.1	21.0	42.0
	Antoakurom 2	32	7.34	<0.01	91.3	<0.1	27.0	15.0
	Nsiana	49	6.58	<0.01	27.3	<0.1	13.0	11.0
	Yawkurom	49	8.54	0.13	257.0	56.0	7.0	17.0
	Manso Atwere	19	6.53	0.23	93.2	<0.1	8.0	17.0
	Odumase	43	6.18	1.73	130.0	<0.1	<0.1	172.0
Amansie Central District	Mile 9	46	7.61	0.17	88.2	<0.1	13.0	19.0
	Mile 14	64.5	8.47	0.16	212.0	58.4	8.0	5.0
	Boni	66	6.58	0.03	92.3	<0.1	34.0	31.0
	Hunatado	54	7.86	0.02	41.9	<0.1	11.0	14.0
	Poano	61	8.23	3.72	251.0	5.0	5.0	11.0
	Ntinako	52	7.71	0.01	16.8	4.0	19.0	39.0
	Kofitanokrom	8	6.64	0.02	17.6	<0.1	<0.1	55.0
	Patase	34	8.46	0.04	34.0	1.03	9.0	14.0
	Apitiso	43.5	8.36	0.02	33.6	9.0	17.0	41.0
	Fiankoma	65	6.85	5.12	203.0	<0.1	<0.1	39.0
	Dangase	4	6.59	<0.01	17.3	<0.1	<0.1	13.0
	Odumto	15	8.14	5.63	52.8	<0.1	8.0	23.0
	Sabe	22	8.33	0.24	192.4	72.0	<0.1	253.0
	Mile 18	8	6.84	0.04	211.0	<0.1	<0.1	9.0
	Mamfo	28	8.78	0.72	173.7	22.0	<0.1	38.0
	Dekyewa	24	6.62	11.13	102.3	<0.1	<0.1	1206.0
	Afoako	42	7.45	0.04	11.6	3.0	24.0	21.0
	Aketekyiso	3	7.27	0.42	17.3	<0.1	13.0	35.0
	Tweapease	43	8.52	0.64	71.3	13.0	<0.1	15.0
	Abuakwa	48	6.02	0.73	319.0	5.0	<0.1	9.0
Obuasi Municipal Assembly	Nhyiaso	18	6.52	<0.01	21.9	<0.1	<0.1	13.0
	Akrofuom	32	7.73	0.19	194.6	<0.1	27.0	64.0
	Sanso	42	6.52	6.49	122.0	19.0	<0.1	11.0
	Brahabebome	19	7.32	0.04	7.6	2.0	77.0	508.0
	Diewieso	25	6.53	0.02	273.0	<0.1	48.0	72.0
	Nyamso North	48	7.54	0.38	103.5	<0.1	<0.1	15.0
	Nyamso South	32	7.05	0.16	48.5	<0.1	<0.1	27.0
	Konka New Town	30	6.52	0.01	49.7	<0.1	<0.1	13.0
	Apitikokoo	40	6.63	0.03	49.7	<0.1	35.0	31.0
	Kokotenten	34	8.46	0.93	206.0	13.0	<0.1	7.0
	Nyamekyere	43	6.52	0.50	52.3	<0.1	9.0	28.0
	Obuasi BH 3	100	8.31	12.03	472.0	21.0	<0.1	231.0
	Mensakurom	9	6.92	0.04	21.3	2.0	<0.1	13.0
	Obuasi BH 2	70	6.15	5.13	498.0	7.0	43.0	2301.0
	Obuasi BH 1	70	8.19	9.06	424.0	10.0	9.0	892.0
	Wamase	4	8.12	0.31	50.7	<0.1	11.0	33.0
Bekwai Municipal Assembly	Old Edubiase	43	7.01	<0.01	4.8	<0.1	17.0	14.0
	Dwondoso	5.5	6.73	0.04	7.3	<0.1	<0.1	93.0
	Aminase	4	6.55	0.04	38.9	<0.1	<0.1	33.0
	Amoamo	1.5	8.19	0.17	196.0	2.0	5.0	29.0
	Ankase	48	6.84	0.01	7.2	<0.1	13.0	14.0
	Bogyawe	58	6.18	1.86	116.0	5.2	5.0	9.0
Statistical Data	**Minimum**		**6.02**	**<0.01**	**1.8**	**<0.1**	**<0.1**	**5.0**
	Maximum		**8.47**	**12.3**	**498.0**	**72.0**	**77.0**	**2301**
	Mean		**7.22**	**1.51***	**118.52**	**17.98***	**17.84**	**109.15**
	Median		**7.21**	**0.24**	**71.30**	**8.0**	**12.00**	**19.0**
	SD		**0.75**	**0.84**	**82.12**	**10.26**	**15.58**	**73.48**
	WHO (2004)	**-**	**-**	**0.3**	**500**	**10**	**500**	**5000**

DL=Limit of detection; SD= Standard deviation.

*Values designated by asterisks are higher than the WHO permissible limit of drinking water. Each value is the mean of three samples with three determinations.

Table 4. Concentration levels of As_{total} and other trace elemental characteristics of surveyed groundwaters during wet (rainy) season in SW part of Ashanti Region in Ghana.

Studied Area	Location	Depth (m)	pH	Fe (mg/L)	Mn (µg/L)	As_{total} (µg/L)	Cu (µg/L)	Zn (µg/L)
DL				0.01	0.1	0.1	0.1	0.1
Adansi North District	Meduma	53	5.43	0.05	2.3	3.0	8.0	10.0
	Abedwum	6	6.76	0.15	31.4	<0.1	3.0	27.0
	Wioso	18	5.53	0.13	17.8	<0.1	40.0	36.0
	Patakro	36	7.55	3.02	186.4	<0.1	<0.0	17.0
	Dunkwa Nkwanta	25.5	4.23	0.73	28.4	<0.1	<0.0	28.0
	Kokotease	35	5.90	<0.01	10.5	<0.1	4.0	9.0
	Kofikurom	38	5.05	0.09	36.7	<0.1	11.0	7.0
Amansie West District	Odahu	60	5.33	0.57	132.5	8.6	2.0	42.0
	Agroyesum Hsp	52	6.25	7.05	386.5	48.5	3.0	16.0
	Apanapron	80	6.56	2.32	224.3	16.0	<0.1	21.0
	Ankam	38	5.67	0.33	73.2	<0.1	6.0	29.0
	Mim 1	57	6.04	1.53	100.6	<0.1	3.0	13.0
	Abodom	46	6.17	0.05	24.5	7.0	19.0	19.0
	Mim 3	49	6.15	<0.01	19.7	<0.1	15.0	22.0
	Antoakurom 1	70	6.55	0.95	385.8	53.8	2.0	15.0
	Manso Akropon	43	5.23	<0.01	423.4	<0.1	19.0	48.0
	Antoakurom 2	32	5.88	0.07	176.5	<0.1	23.0	23.0
	Nsiana	49	5.84	<0.01	46.4	<0.1	17.0	14.0
	Yawkurom	49	6.58	0.15	335.4	62.5	9.0	26.0
	Manso Atwere	19	6.75	<0.01	120.8	<0.1	12.0	29.0
	Odumase	43	5.58	2.03	167.4	<0.1	<0.1	225.0
Amansie Central District	Mile 9	46	5.85	0.19	125.5	<0.1	11.0	27.0
	Mile 14	64.5	6.56	0.13	286.43	65.6	14.0	17.0
	Boni	66	5.75	0.07	127.4	<0.1	30.0	35.0
	Hunatado	54	4.94	0.05	87.4	<0.1	8.0	19.0
	Poano	61	5.46	4.02	287.5	9.0	11.0	21.0
	Ntinako	52	5.84	0.07	89.4	7.0	21.0	43.0
	Kofitanokrom	8	5.72	0.07	45.2	<0.1	2.0	62.0
	Patase	34	5.51	0.08	67.8	4.5	13.0	17.0
	Apitiso	43.5	5.58	0.05	84.3	13.0	21.0	48.0
	Fiankoma	65	5.32	6.13	287.5	<0.1	3.0	44.0
	Dangase	4	3.88	0.05	23.4	<0.1	<0.1	19.0
	Odumto	15	5.40	5.01	65.8	<0.1	5.0	31.0
	Sabe	22	6.55	0.30	205.8	83.0	<0.1	365.0
	Mile 18	8	5.48	0.07	184.6	<0.1	<0.1	18.0
	Mamfo	28	6.28	0.83	234.6	28.0	<0.1	46.0
	Dekyewa	24	5.73	15.14	264.9	<0.1	<0.1	1475.0
	Afoako	42	5.86	0.09	23.5	5.0	29.0	33.0
	Aketekyiso	3	5.20	0.56	26.4	<0.1	7.0	47.0
	Tweapease	43	5.68	0.72	97.3	17.0	5.0	21.0
	Abuakwa	48	6.38	0.83	368.5	8.0	3.0	18.0
Obuasi Municipal Assembly	Nhyiaso	18	5.42	<0.01	48.3	<0.1	5.0	21.0
	Akrofuom	32	3.13	<0.01	225.4	<0.1	24.0	72.0
	Sanso	42	6.15	7.56	164.5	24.0	9.0	17.0
	Brahabebome	19	5.85	0.08	22.5	9.0	81.0	633.0
	Diewieso	25	4.32	<0.01	239.5	<0.1	52.0	85.0
	Nyamso North	48	5.54	0.25	77.5	<0.1	<0.1	24.0
	Nyamso South	32	5.05	0.33	64.3	<0.1	5.0	37.0
	Konka New Town	30	5.25	<0.01	67.2	<0.1	<0.1	19.0
	Apitikokoo	40	6.63	0.07	87.6	<0.1	37.0	39.0
	Kokotenten	34	6.46	1.05	287.5	19.0	11.0	11.0
	Nyamekyere	43	5.72	0.78	45.8	<0.1	4.0	32.0
	Obuasi BH 3	100	6.45	16.33	583.8	28.0	9.0	275.0
	Mensakurom	9	4.20	3.06	43.7	5.0	6.0	21.0
	Obuasi BH 2	70	6.35	10.14	520.7	11.0	47.0	2854.0
	Obuasi BH 1	70	5.19	13.66	557.3	17.0	17.0	1055.0
	Wamase	4	5.12	1.32	34.7	<0.1	8.0	47.0
Bekwai Municipal Assembly	Old Edubiase	43	5.31	0.04	13.5	<0.1	14.0	23.0
	Dwondoso	5.5	5.93	<0.01	18.9	<0.1	3.0	85.0
	Aminase	4	5.75	0.06	67.5	<0.1	<0.1	38.0
	Amoamo	1.5	5.39	0.23	212.8	1.5	7.0	27.0
	Ankase	48	6.19	<0.01	17.8	<0.1	11.0	17.0
	Bogyawe	58	6.14	2.08	167.5	2.2	9.0	11.0
Statistical Data	**Minimum**		**6.02**	**<0.01**	**2.30**	**<0.1**	**<0.1**	**7.0**
	Maximum		**8.47**	**16.33**	**583.80**	**83.0**	**81.0**	**2854**
	Mean		**5.70**	**2.12***	**150.51**	**21.39***	**14.19**	**135.32**
	Median		**7.05**	**0.33**	**89.40**	**12.00**	**9.00**	**27.0**
	SD		**0.74**	**1.73**	**96.07**	**11.63**	**9.69**	**86.93**
	WHO (2004)	-	-	**0.3**	**500**	**10**	**500**	**5000**

DL = Limit of detection; SD = Standard deviation.

*Values designated by asterisks are higher than WHO permissible limit of drinking water. Each value is mean of three samples with three determinations.

6. Results and discussion

The results obtained for the physico-chemical analysis of the water samples collected from 63 community wells and boreholes during the dry and wet (rainy) seasons in the studied area (SW part of Ashanti Region in Ghana) and their statistical data are summarized in Tables 1 and 2, respectively.

The groundwater in the SW part of Ashanti region was predominantly slightly acidic to alkaline (pH value, 6.02-8.47), and more acidic to slightly alkaline (pH value, 3.13-7.55) during the dry and wet seasons, respectively, as a result of the presence of fine aquifer sediments mixed with clay and mud, which were unable to flush-off the salts during the rainy season, and hence, retained longer on other seasons [21]. In sedimentary formations, iron occurs as pyrite, and in oxidizing conditions, pyrite is oxidized, as described by the following equation:

$$FeS_2 + \frac{15}{4}O_2 + \frac{7}{2}H_2O \leftrightarrow Fe(OH)_3 + 4H^+ + 2SO_4^{2-}$$

This reaction shows acid formation, which expresses the acidic nature of the groundwater samples during the rainy season [22]. The chemical characteristics of the groundwater compositions on the basis of major ion concentrations were evaluated on the Piper diagrams (Figure 3). Plots of the major ions on a Piper diagram during both seasons (dry and wet) show that the majority of the samples from the SW part of Ashanti region grouped into a cluster that might be characterized as temporary hardness (marginally higher calcium + magnesium and bicarbonate) and alkali carbonate class (higher sodium + potassium and bicarbonate). Although during the dry season, few samples from Obuasi municipal are more toward the permanently hard category (higher calcium + magnesium, accompanied by higher sulphate + chloride) and a sample from Bekwai municipal was quite central (denoting no one dominating ion), whilst in the wet season, a handful of samples from Obuasi municipal and Amansie central districts are quite toward the permanently hard category.

According to the concentrations of major cations and anions, the groundwater composition varies from the Ca-Mg-HCO3 to the Na-K-HCO3 type, as a result of alumino-silicate weathering as well as dissolution of carbonate minerals, followed by Ca and/or Mg ion exchange with Na on clay minerals [23].

The information regarding the permeability of the Proterozoic rocks in the Birimian meta-sedimentary ore-bearing zone has shown variations ranging from 10-6 to 10-9 cm/s, indicating permeable to low-permeability. This result indicates that permeability is controlled by fractures in the ore formation. This situation has changed the chemical composition of groundwater.

The primary source of drinking water within the studied area is groundwater, and it is therefore important to compare the concentrations of metals (Fe, Mn, As, Cu, and Zn) with the limits established by WHO guideline values [20] for drinking water. Comparisons have shown that the Mn, Cu, and Zn concentrations are below the WHO guideline values for drinking water, and this is attributed to the high velocity of the groundwater flow, which does not give enough time for minerals to dissolve [2], although the weathering process is high. Unlike the other metals, the As and Fe concentrations are above the WHO guideline values. One of the possible reasons of high As and Fe concentrations may be the fractured controlled, which aided high dissolution of As and Fe within the studied area. In addition, as a result of the mining activities and illegal artisanal mining operations within the vicinity, the minerals may come into contact with groundwater, which in turn, increases the concentrations of As and Fe in groundwater. Moreover, Fe concentration has been found to be naturally high, although its concentration is distinctly increased in the mined areas of SW Ashanti due to an increase in the desorption sites [7].

The values for peak ions and trace elements recorded during the wet (rainy) period may likely be due to inputs of trace element-contaminated particles from the run-offs, particularly, from the trace element-contaminated tailing dams from the AngloGold mines and the illegal artisanal mining activities. Top surface soil and frequent flooding seeping through the semi-permeable rock layer can also contribute to high levels of ions and trace elements during the wet season. In addition to this, some metals could also be leached out from the vadose zone of the unconfined aquifer into groundwater as a result of the generally higher groundwater table during the wet season.

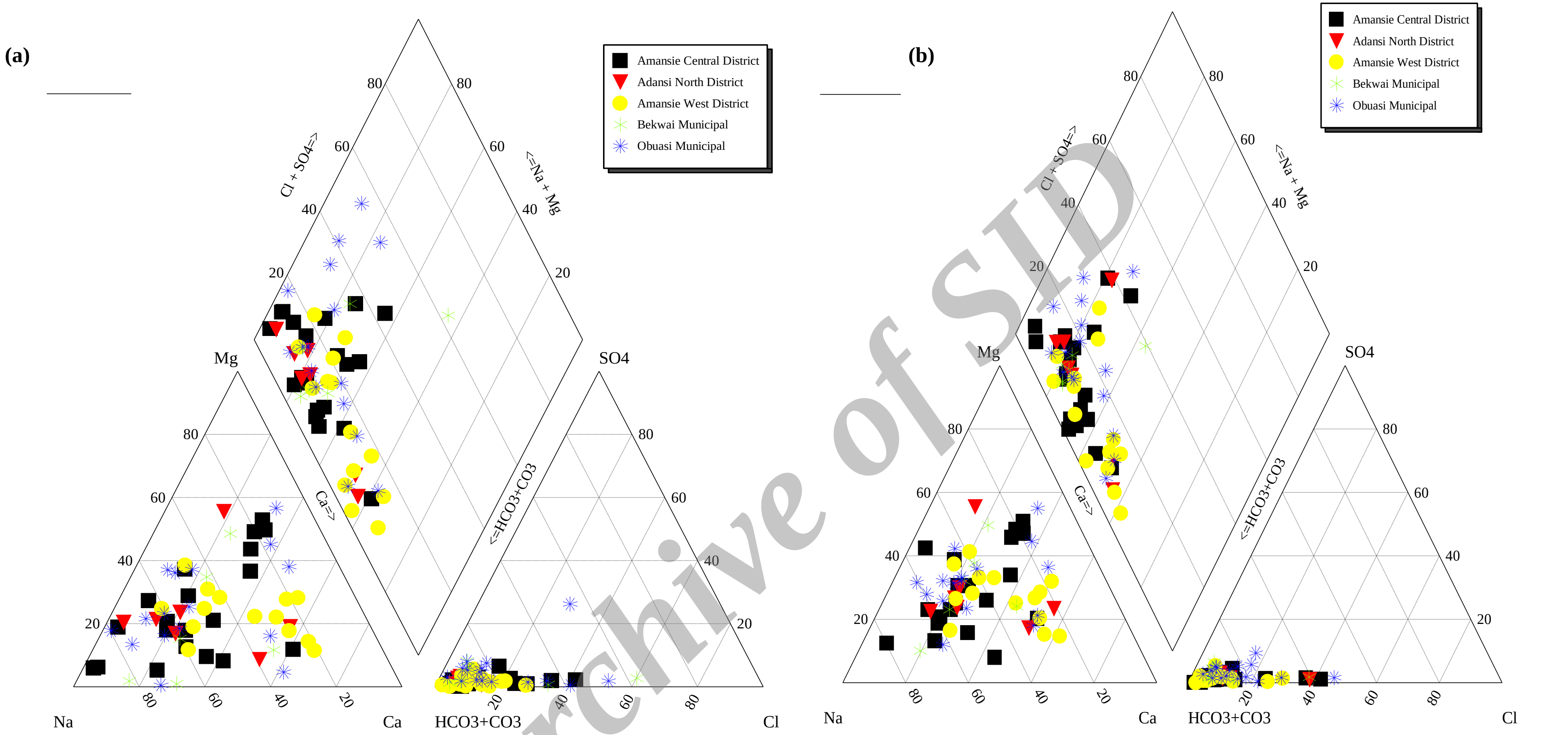

Figure 3. Piper diagram showing major ionic constituents in groundwater during both dry season (a) and wet season (b).

7. Conclusions

Groundwater is a major resource and the primary source of drinking water in SW Ashanti. Since the drinking water quality is directly related to the human health, it is necessary to keep it within the allowable limits. In this manner, the quality of groundwater is within the WHO guideline values for drinking water limits, with only the As and Fe concentrations exceeding these limits. The high concentrations of As and Fe in the groundwater can perhaps be attributed to the widespread use of arsenic-containing chemical substances for ore processing [24] or as a result of precipitation, which can leach soluble As and Fe minerals from the mine wastes (known as spoils or tailings) into the groundwater. In addition to this, the major arsenic-containing minerals including arsenopyrite (FeAsS), realgar (As_4S_4), and orpiment (As_2S_3) are abundant in sulfide deposits like gold-containing sulfide deposits in the studied area [25]. The very low concentrations of Cu, Mn, and Zn would be the influence of the specific solubility and mobility of the trace elements in soil and groundwater on their transport. Thus the trace elements could be immobilized in the soil by the chemical reactions and adsorption processes. Another possible explanation is attributed to the dilution effect after the rainy season. The metal concentrations found through this investigation could be used as a reference for the future studies in monitoring trace elements in groundwater resources in the SW part of the Ashanti region and other unstudied mining regions in Ghana.

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اثر معدن‌کاری بر کیفیت آب زیرزمینی در جنوب شرقی آشانتی، غنا: مطالعه اولیه

C. Kofi Bempah[1, 2*], H-J. Voigt[2] and A. Ewusi[3]

1. Faculty of Environmental Sciences and Process Engineering, Chair of Environmental Geology, Brandenburgische Technische Universität, Cottbus, Germany
2. Nuclear Chemistry and Environmental Research Center, National Nuclear Research Institute, Ghana Atomic Energy Commission, Legon, Accra, Ghana
3. Geological Engineering Department, University of Mines and Technology, Tarkwa-Ghana

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* نویسنده مسئول مکاتبات: crentbempah@hotmail.com

چکیده:

هدف از این تحقیق، تعیین اثر معدن‌کاری بر کیفیت آب زیرزمینی در منطقه معدنی جنوب شرقی آشانتی غنا است. این تحقیق بـه تشـریح مشخصـات شـیمیایی سفره آب زیرزمینی موجود در تشکیلات ذخیره طلای آشانتی که به‌شدت هوازده و شکسته شده است می‌پردازد. در این تحقیق به کنترل شکستگی، نفوذپـذیری و عمق آب زیرزمینی در ناحیه مورد مطالعه پرداخته‌شده است. غلظت یون‌های عمده و عناصر کمیاب (As، Fe، Cu، Mn و Zn) در ۶۳ چاه در فصـول خشـک و مرطوب تعیین‌شده است. نتایج به‌دست‌آمده نشان می‌دهد که غلظت این یون‌ها و عناصر پایین‌تـر از مقـادیر اسـتاندارد موجـود در دسـتورالعمل سـازمان بهداشـت جهانی (WHO) در خصوص آب آشامیدنی قرار دارد؛ اما غلظت یون‌های As و Fe خیلی بـالاتر از مقـادیر موجـود در دسـتورالعمل فـوق‌الـذکر قـرار داشـت. در چاه‌هایی که مقادیر As و Fe در آن‌ها بالا است، ممکن است که این چاه‌ها در زون سنگ‌های شکسته و گسترده شده در نزدیکی معـدن قـرار داشـته باشـند. ایـن زون‌های شکسته شده اجازه می‌دهد که آب زیرزمینی از سمت معدن سریع‌تر حرکت کند و باعث ایجاد آلودگی شدیدتر در مسیر حرکتش شـود. نتـایج حاصـل از این تحقیق نشان می‌دهد که احتمال آلودگی آب‌های زیرزمینی در ناحیه مورد مطالعه به یون‌های سمّی As و Fe وجود دارد؛ در حالی که این آب‌های زیرزمینـی مهم‌ترین منبع تأمین آب شرب منطقه محسوب می‌شود.

کلمات کلیدی: ذخایر طلا، معدن‌کاری، آب زیرزمینی، عناصر کمیاب، جنوب شرقی آشانتی.