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Anthropogenic sources and environmentally relevant concentrations of heavy metals in surface water of a mining district in Ghana: a multivariate statistical approach

FREDERICK A. ARMAH¹, SAMUEL OBIRI², DAVID O. YAWSON³, EDWARD E. ONUMAH⁴, GENESIS T. YENGOH⁵, ERNEST K. A. AFRIFA¹ and JUSTICE O. ODOI⁶

¹Department of Environmental Science, School of Biological Sciences, University of Cape Coast, Cape Coast, Ghana

²Water Research Institute, Accra, Ghana

³School of Agriculture, University of Cape Coast, Cape Coast, Ghana

⁴Department of Agricultural Economics and Agribusiness, University of Ghana, Legon – Accra, Ghana

⁵Lund University Centre for Sustainability Studies, Lund, Sweden

⁶Ghana Nature Today, A 25 Standard Estates, Sakumono, Osu, Accra, Ghana

The levels of heavy metals in surface water and their potential origin (natural and anthropogenic) were respectively determined and analysed for the Obuasi mining area in Ghana. Using Hawth's tool an extension in ArcGIS 9.2 software, a total of 48 water sample points in Obuasi and its environs were randomly selected for study. The magnitude of As, Cu, Mn, Fe, Pb, Hg, Zn and Cd in surface water from the sampling sites were measured by flame Atomic Absorption Spectrophotometry (AAS). Water quality parameters including conductivity, pH, total dissolved solids and turbidity were also evaluated. Principal component analysis and cluster analysis, coupled with correlation coefficient analysis, were used to identify possible sources of these heavy metals. Pearson correlation coefficients among total metal concentrations and selected water properties showed a number of strong associations. The results indicate that apart from tap water, surface water in Obuasi has elevated heavy metal concentrations, especially Hg, Pb, As, Cu and Cd, which are above the Ghana Environmental Protection Agency (GEPA) and World Health Organisation (WHO) permissible levels; clearly demonstrating anthropogenic impact. The mean heavy metal concentrations in surface water divided by the corresponding background values of surface water in Obuasi decrease in the order of Cd > Cu > As > Pb > Hg > Zn > Mn > Fe. The results also showed that Cu, Mn, Cd and Fe are largely responsible for the variations in the data, explaining 72% of total variance; while Pb, As and Hg explain only 18.7% of total variance. Three main sources of these heavy metals were identified. As originates from nature (oxidation of sulphide minerals particularly arsenopyrite-FeAsS). Pb derives from water carrying drainage from towns and mine machinery maintenance yards. Cd, Zn, Fe and Mn mainly emanate from industry sources. Hg mainly originates from artisanal small-scale mining. It cannot be said that the difference in concentration of heavy metals might be attributed to difference in proximity to mining-related activities because this is inconsistent with the cluster analysis. Based on cluster analysis SN32, SN42 and SN43 all belong to group one and are spatially similar. But the maximum Cu concentration was found in SN32 while the minimum Cu concentration was found in SN42 and SN43.

Keywords: Gold mining, heavy metals, multivariate statistics, Obuasi, water bodies, Ghana.

Introduction

Anthropogenic use and natural processes together, lead to decline of surface water quality.^[1] Heavy metals are of particular concern in surface water quality as a result of their environmental persistence, biogeochemical recycling and

biological risks. Pollution of the natural environment by heavy metals is a universal crisis as these metals are lasting and have poisonous effects on living organisms when they surpass critical thresholds concentration.^[2] In Ghana, contaminations of surface water bodies have predominantly been observed in gold mining communities.^[3–5] Although over the past century gold mining has been an essential element of the gross domestic product (GDP) of Ghana^[6,7] in recent times, it has become unpopular in host communities. It is regarded as a significant source of Hg, Pb and heavy metal contamination of the aquatic environment due to activities such as mineral exploitation, ore transportation,

Address correspondence to Frederick Ato Armah, Department of Environmental Science, School of Biological Sciences, University of Cape Coast; Cape Coast, Ghana; E-mail: atoarmah@yahoo.com

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smelting and refining, disposal of the tailings and waste waters around mines.^[8–10]

Heavy metal pollution in mining environments of Ghana is receiving a growing body of literature.^[11–13] However, the application of multivariate statistical techniques in the analysis of heavy metals in surface water in mining environments of Ghana is scant and nascent. The application of multivariable statistical methods offers a better understanding of water quality for interpreting complicated data sets.^[14,15] Consequently in this study, data sets on surface water obtained between February and June 2009 from the Obuasi mining area in Ghana were analyzed with Principal Component Analysis after using a rank transform to eliminate non-normality.

The Obuasi area has a long-standing history of gold mining in Ghana dating back to the 1800s. Mainstream mining by Trans-National Corporations (TNCs) coupled with small-scale mining (popularly known as *galamsey* operations) both legal and illegal, is widespread in the area. Small-scale miners are for the most part self-employed indigenous youth, with low financial and technical capacity. Within the small-scale sector is a form of illegal mining activity also known as *galamsey*; the practice of cautiously accumulating minerals found either at or just below the soil surface and selling them in breach of state laws.^[16] Although illegal, this activity dominates the small-scale artisanal gold sector, with an estimated 60,000 people involved in it across Ghana.^[16]

In comparison, large-scale mines are generally operated by foreign owned, international companies (with the exception of one: AngloGold Ashanti at Obuasi) with operations that are large both in physical size and capacity, utilizing heavy equipment and the latest mining technology.^[16] Some of the other major industrial activities in the municipality are forest/wood-based and related industries, blacksmithing and metal-based industries, construction and quarrying-based industries. Used metal scraps from the mining industry are salvaged by scrap dealers for the manufacturing of farm implements and equipment. Effluents from these mining activities are discharged into water bodies within the municipality^[17] and constitute risks to aquatic organisms and human health. The human risk dimension is attributed to the fact that some communities use the water bodies as a source of drinking water.

Constant monitoring of surface water is necessary to improve the water quality of the water bodies in Obuasi. For this reason, there is the need to measure environmental impacts of heavy metals as well as pH, land use changes, and natural processes leading to spatial and temporal variability in water quality. The objectives of the present study were first to determine the levels of heavy metals in surface water within the Obuasi mining area and compare with the World Health Organization (WHO) and Ghana Environmental Protection Agency (GEPA) permissible limits and, secondly to analyze the potential origin (natural and anthropogenic) of contaminants in surface

Table 1. GEPA and WHO permissible limits for surface water parameters.

Parameter	GEPA	WHO
Manganese (mg/L)	–	0.4
Lead (mg/L)	0.1	0.01
Copper (mg/L)	–	2.0
Arsenic (mg/L)	1.0	0.01
Zinc (mg/L)	10	3.0
Mercury (mg/L)	0.2	0.01
Iron (mg/L)	–	0.3
Cadmium (mg/L)	–	0.003
pH	6.5–8.5	6.5–8.5
Turbidity (NTU)	5	5
Electrical conductivity ($\mu\text{S}/\text{cm}$)	–	–
Colour	15	15
Total dissolved solids (mg/L)	1000	1000

water in the Obuasi mining area using multivariate statistics (see Table 1).

Materials and methods

Site description

The Obuasi Municipality lies in the southern part of Ashanti Region of Ghana between latitudes 5°35'N and 5°65'N, and longitudes 6°35'W and 6°90'W (Figure.1). It covers a land area of about 162.4 square km (Obuasi Municipal Assembly Medium Term Development Plan. It is bounded to the south by Upper Denkyira District of the Central Region, east by Adansi South, west by Amansie Central, and north by Adansi North. There are 52 communities in the municipality. Generally, the Municipality has an undulating terrain with more of the hills higher than 500 meters above sea level. The Municipality is drained by streams and rivers which include; Pompo, Nyam, Akapori, Kwabrafo and Jimi, all within the catchment of the AngloGold Ashanti mine concession.^[18]

Soils in the municipality are predominantly forest ochrosols developed under forest vegetation with rainfall between 90 cm and 165 cm. Rocks in the Municipality are mostly of Tarkwaian (Pre-Cambrian) and Upper Birimian formation that are noted for their rich mineral bearing potentials.^[5] Areas around the contacts of the Birimian and Tarkwaian zones known as reefs are noted for gold deposits. The Obuasi mine (AngloGold Ashanti), which works on steeply dipping quartz veins over a strike length of 8 km, has since 1898 produced over 600 tons (18 million ounces) of gold from ore averaging about 0.65 ounces per ton.

Sample collection and analysis

Using Hawth's tool an extension in ArcGIS 9.2 software a total of 48 sample points were randomly selected.

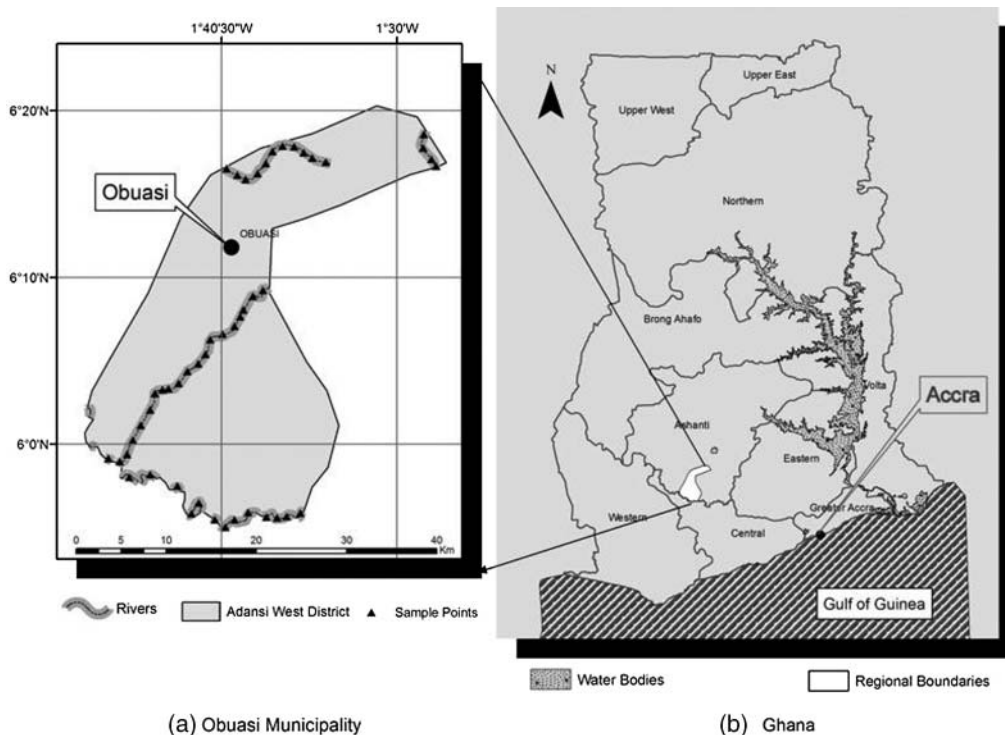


Fig. 1. Map of study area.

Forty-eight (48) samples were randomly collected between February and June 2009 from tap water and surface water bodies in the Obuasi mining area. The water samples were labelled from SN1 to SN48. Samples collected for each month were analyzed separately for As, Cu, Mn, Fe, Pb, Hg, Zn and Cd and their mean values were computed at the end of study. First, 1.5L of the water samples were collected from each sampling point into plastic bottles that had been pre-washed with detergent and rinsed with 1:1 nitric acid and double-distilled water.

At each site additional samples of water were taken for analysis of electrical conductivity, pH, total dissolved solids and turbidity. The temperature of the water was also determined during sampling. The samples were acidified with 10% nitric acid, stored in an ice chest at 4°C and were conveyed to the laboratory for analysis. This procedure averts microbial growth, flocculation and reduce any adsorption on container surfaces.

A flame AAS (Atomic Absorption Spectrophotometer) Shimadzu model 6401F was used for analysis of the samples after preparation of appropriate calibration standards. Due to expected low concentrations of the metals in the natural water samples and limited instrument sensitivity, pre-concentration of the water samples was done by evaporating 100 ml of the water to 4 ml on a hot plate. The digestion of the water samples was then achieved by adding 5 ml of 11.1 M HNO₃ and heating on the hot plate for 30 min. Some 10 ml of 16.3 M HCl was added and digestion continued until the solution remained light brown or color-

less. The volume was then adjusted to 25 mL with distilled water.

Reproducibility and recovery studies were conducted. In the reproducibility studies, 1.0 mg/L standard solutions of each heavy metal were measured (10 times) using flame Shimadzu model 6401F. The percentage of heavy metals recovered in the recovery studies ranged between 93.6 to 99.6% (standard error \pm 0.005 to 0.560). The standard error is less than 1, which suggests that the analysis methods employed were reproducible. The detection limit of heavy metals except mercury is 0.01 mg/L. The detection limit for mercury is 0.001 mg/L.

Data management and multivariate statistics

Multivariate analysis of surface and groundwater data was subjected through Principal Component Analysis (PCA).^[15,19,20] The data sets were first summarized (Table 2). From Table 2 it is observed that the values of the coefficients of variation of the variables (Cond., Turbidity, TDS and others) were much larger than 1/3 (33.33%), except the variable pH. This suggests that the data is positively skewed—very few of the measurement scores lie below the average measurement scores. A rank transform was used to eliminate non-Normality.^[15,20] Standardization tends to increase the influence of variables whose variance is small and vice versa. Principal component analysis (PCA) was then applied to summarise the statistical correlation among components in the water samples.

Table 2. Descriptive statistics of heavy metals and water quality parameters of samples (n = 48).

	Cu	Mn	Cd	Fe	Pb	As	Hg (ppb)	Zn	pH	Conductivity	Turbidity	Dissolved solids
Range	83.11	96.87	53.7	181.9	15.199	34.60	25.30	51.03	2.8	511	93	669
Minimum	.002	.081	.045	.014	.001	.005	.001	.001	4.6	31	4	7
Maximum	83.11	96.95	53.7	181.9	15.200	34.60	25.30	51.03	7.4	542	97	676
Arithmetic Mean	14.5125	16.4626	12.413	16.087	1.58021	6.6004	4.0363	6.1220	6.532	129.25	28.98	143.69
Harmonic Mean	.0450	1.7275	1.574	.343	.02956	.1421	.0253	.0135	6.467	67.53	17.48	36.24
Geometric Mean	4.0942	8.6593	7.276	5.041	.38811	2.6147	.5816	.4821	6.501	87.91	22.53	68.02
First Quartile	2.4500	4.5895	4.182	2.422	.06125	1.3575	.0242	.0282	6.285	51.90	13.00	29.50
Median	6.0315	8.9200	6.735	7.050	.69300	4.3350	3.0200	1.3880	6.600	73.70	24.00	55.00
Third Quartile	18.3050	21.5175	13.500	12.075	2.09750	11.3500	6.4625	6.6715	7.018	105.00	34.00	213.25
Mode	.00a	5.76	.0 ^a	3.7 ^a	.021 ^a	7.34	.02	.00	6.6	105	34	58
Std. Deviation	20.63143	20.33203	14.0445	30.7851	2.933434	6.94047	5.10287	10.40044	.6143	139.843	23.159	189.267
Variance	425.656	413.391	197.248	947.724	8.605	48.170	26.039	108.169	.377	1.956E4	536.361	3.582E4
Skewness	2.286	2.480	1.911	3.925	3.657	1.829	1.918	2.627	-1.277	2.075	2.059	1.848
Kurtosis	4.791	6.400	2.680	18.243	14.345	4.652	5.198	7.685	1.760	3.337	4.183	2.426

^aMultiple modes exist. The smallest value is shown.

Table 3. Pearson correlation of heavy metals and water quality parameters of samples.

	Cu	Mn	Cd	Fe	Pb	As	Hg(ppb)	Zn	pH	Conductivity	Turbidity	Dissolved solids
Cu	1											
Mn	.552**	1										
Cd	.472**	.709**	1									
Fe	.348*	.426**	.743**	1								
Pb	.509**	.061	-.032	-.157	1							
As	.606**	.266	.236	.120	.593**	1						
Hg(ppb)	.211	.169	.242	.222	-.226	.351*	1					
Zn	.505**	.460**	.813**	.736**	-.061	.298*	.230	1				
pH	-.405**	-.179	-.168	-.111	-.554**	-.503**	.091	-.096	1			
Conductivity	-.115	-.068	-.041	-.108	.032	-.047	.177	-.131	.367*	1		
Turbidity	-.086	-.036	-.077	-.117	.006	-.054	-.022	-.123	-.058	-.172	1	
Dissolved solids	.037	-.015	-.065	-.056	-.098	-.125	.043	-.062	.261	.176	.171	1

**Correlation is significant at the 0.01 level.

*Correlation is significant at the 0.05 level.

Bold face implies strong associations.

The calculation was carried out based on the correlation matrix of chemical components and the PCA scores were derived from the analytical data. For classification of samples, cluster analysis (CA) was carried out based on the PCA scores to eliminate variate biases. The agglomerative method, a feature within hierarchical cluster analysis was applied for grouping, and the similarity is defined by Euclidean distance. Extensive treatise of these methods is given in [19–21] while the mathematical and statistical computations were made using Statistical Package for Social Sciences version 16.

Results and discussion

Concentration of heavy metals and descriptive statistics

From Table 2 above, the arithmetic mean values of the heavy metals analyzed are larger than the permissible levels by Ghana Environmental Protection Agency (GEPa) and World Health Organization (WHO) (see Table 1). The turbidity values were higher than the WHO and Ghana Environmental Protection Agency (GEPa) permissible limits. With the exception of Zn (which has a mean value higher than the WHO permissible level but lower than the GEPa permissible level), the mean values of the rest of the heavy metals analyzed are above the permissible levels, suggesting that the water bodies are contaminated. The results indicate that apart from tap water, surface water in Obuasi has elevated heavy metal concentrations, especially Hg, Pb, Zn and Cu, which are above the Ghana Environmental Protection Agency (GEPa) and World Health Organization (WHO) permissible levels; clearly demonstrating anthropogenic impact. The mean heavy metal concentrations in surface water divided by the corresponding background values of surface water in Obuasi decrease in the order of Cd > Cu > As > Pb > Hg > Zn > Mn > Fe. Of the 48 samples, only 2 samples satisfied the WHO permissible level for Mn, 9 for Cu, 3 for Fe and none for Cd. Regarding Hg, 14 samples satisfied the GEPa permissible level, while only 4 met the WHO permissible level in aquatic environments. Eleven samples satisfied the GEPa permissible level for Pb yet only 2 samples satisfied the WHO permissible level. Regarding Arsenic, 9 samples satisfied the GEPa permissible level while only 1 met the WHO requirement. Last, 11 samples satisfied the GEPa permissible level for Zn, yet as many as 23 samples satisfied the WHO permissible level in aquatic environment.

The result in Table 2 indicates a high variation in the values of the heavy metals and turbidity. With the exception of pH, all the parameters analyzed are positively skewed (with skewness values greater than 1). This means that the distribution of these parameters are significantly different from normal, symmetric distribution; implying that the values of the parameters are largely distributed to the right of the mean. As a result, the geometric means for these heavy met-

als present more probable data than the arithmetic means. Conversely, the negatively skewed pH indicates that most of the samples are acidic. Further, the positive kurtosis values indicate that values of the parameters analyzed cluster more and have longer tails than those in the normal distribution. Overall, these support the view that a larger number of the samples are polluted by heavy metals.

Correlation coefficient analysis

The Pearson's correlation coefficients for heavy metals in the surface water of Obuasi are presented in Table 3. Inter-element relationships offer remarkable information on the sources and pathways of the heavy metals. Good correlations (0.5 and above) are in bold face. Mn was significantly correlated with Cd and Cu. Cd was also significantly correlated with Fe and Zn while Fe and Zn were also strongly correlated. Cu in turn was strongly correlated with Pb, As and Zn. However, of the water quality parameters, only pH had a good but inverse correlation with Pb and As. This suggests the possibility of acid mine drainage into the water bodies. The highly significant positive correlations among the heavy metals suggest the possibility of common sources of origin which are anthropogenic. In all, the correlation matrix indicates that the correlations between the concentrations of different heavy metals are highly significant and, thus, provides a justification for the use of principal component analysis to simplify the data.

Results of multivariate analysis

Principal component analysis

The communality of a variable is the variance accountable for by the common factors. Hg had the highest variance

Table 4. Component matrix of heavy metals and water quality parameters.

	Component				
	1	2	3	4	5
Cu	.793	-.285	.216	.128	.139
Mn	.721	.164	-.006	.137	.201
Cd	.841	.381	-.105	.019	.122
Fe	.704	.457	-.209	-.049	.034
Pb	.287	-.830	.218	-.008	.267
As	.615	-.523	.358	-.021	-.273
Hg	.322	.297	.509	.034	-.702
Zn	.801	.366	-.120	-.031	.040
pH	-.452	.682	.267	-.005	.089
Conductivity	-.172	.219	.759	-.198	.235
Turbidity	-.123	-.108	-.197	.811	-.256
TDS	-.137	.223	.401	.659	.349

Extraction Method: Principal Component Analysis: 5 components extracted.

attributable to the rest of the other factors, and Mn had the least. However, all the variables had higher communalities, suggesting higher interrelationships and/or commonality of source. The component matrix of heavy metals and physical parameters is shown in Table 4.

The coefficients in the component matrix table specify the linear function of the observed variables that define each component and show the overall heavy metal loading of the water samples analyzed. Since the principal component analysis was based on the correlation matrix, the coefficients in the component matrix represent the correlations between the observed variables and the principal components (Table 4). The first component has a strong positive correlation with each of the heavy metals except Hg and Pb. However, Hg has a good correlation with the third component, and Pb is strongly correlated with the second component. The fourth component has a better correlation only with conductivity and total dissolved solids.

This suggests that the first 3 components best account for the variability in the heavy metal concentrations. The pattern and size component observed is common when the elements of the correlation matrix are all positive (Table 4). As observed in Table 5, the PC 1 accounts for approximately 32% of the variance in the data while PC 2 accounts for 18%. In total, 62% of the variance in the data is explained by the first 3 components and approximately 72% is explained by the first 4 components. As indicated by the scree plot (Fig. 2), the first three components capture the most significant variation in the data. However, the elbow occurs at PC 3, and so up to PC four is accepted to account for the variation in the data.

Table 5. Eigenvalues of components and total variance explained.

Component	Eigen values		
	Total	% of Variance	Cumulative %
Cu	3.825	31.875	31.875
Mn	2.220	18.497	50.373
Cd	1.396	11.636	62.008
Fe	1.172	9.769	71.777
Pb	.966	8.050	79.827
As	.679	5.661	85.488
Hg	.601	5.005	90.493
Zn	.424	3.535	94.028
pH	.278	2.318	96.346
Conductivity	.218	1.815	98.161
Turbidity	.152	1.263	99.425
Total Dissolved Solids	.069	.575	100.000

Extraction Method: Principal Component Analysis.

Cluster analysis

The cluster analysis (agglomerative bottom-up approach) used to identify the spatial similarity between the sampling sites based on the levels of chemical concentration, grouped all 48 sampling sites into three statistically significant clusters as depicted by the Dendrogram (Fig. 3). Figure 4 illustrates the clustering between heavy metals. The Dendrogram is essential in determining variables of significant importance and source of contamination for appropriate mitigation.

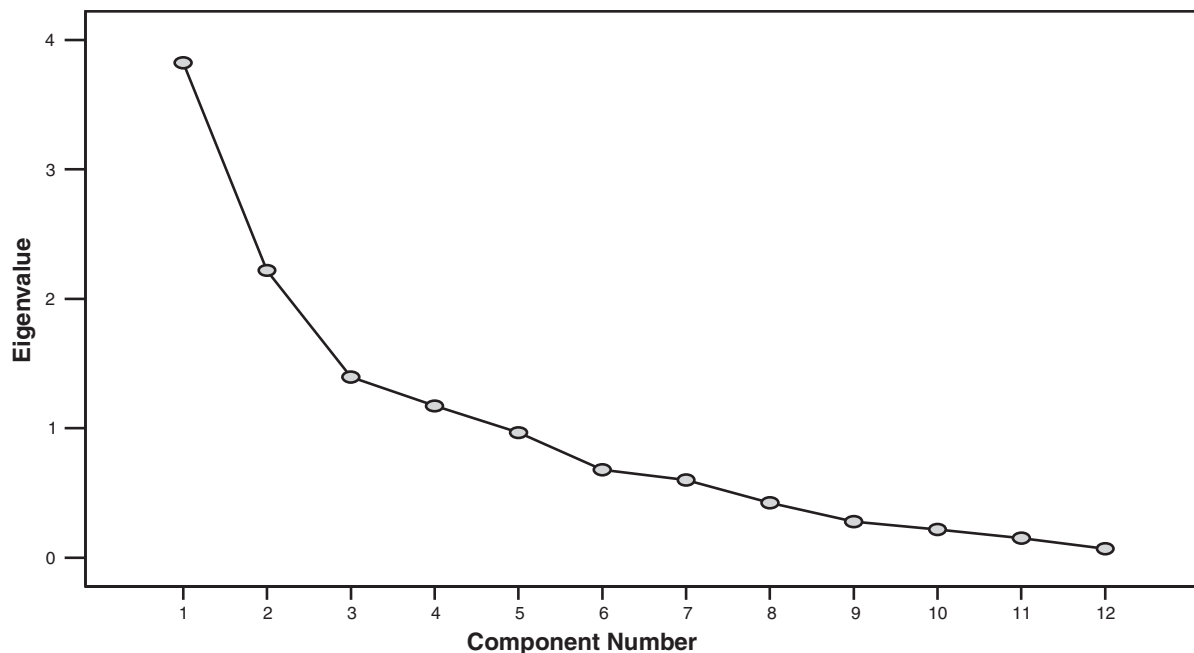


Fig. 2. Scree plot showing point (PC 4) at which the factor extraction is terminated.

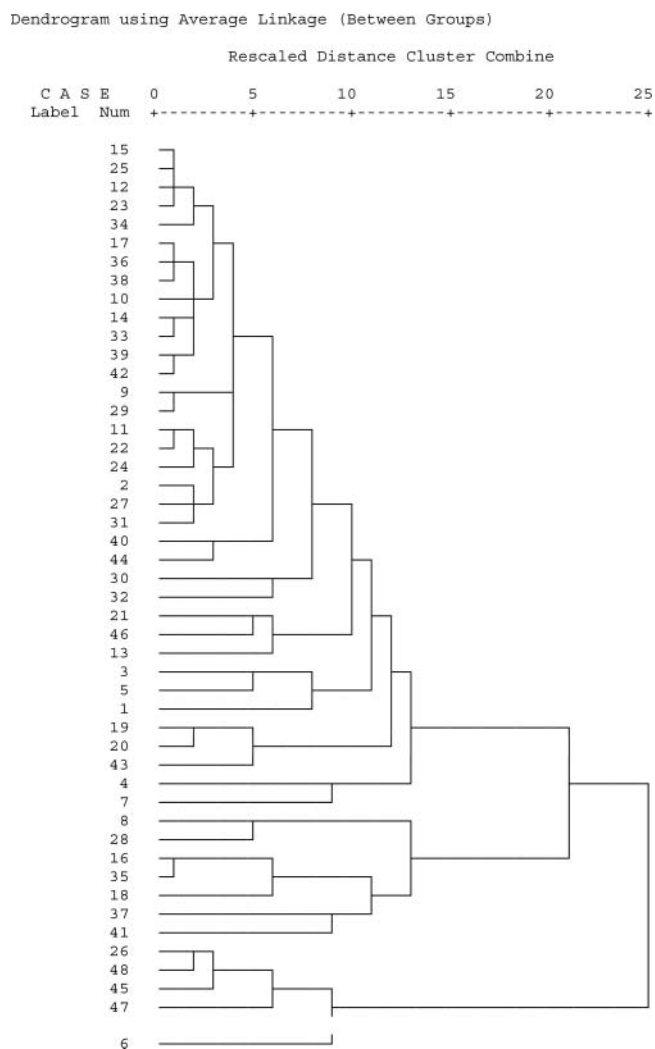


Fig. 3. Dendrogram showing clustering of sampling sites using Average Linkage (Between Groups).

In Figure 3, the 3-group cluster generated from the 48 sampling sites is as follows: group one consists of SN15 to SN7; group two consists of SN8 to SN41 and group three consists of SN26 to SN6. Five distinct clusters emerge from the grouping of heavy metals; and this is consistent with the PCA. Cluster 1 consists of Pb-Hg-As. Cluster 2 consists of Cd-Zn. Cluster 3 consists of Cu; while clusters 4 and 5 consist of Mn and Fe, respectively.

Identification of heavy metal sources

High concentrations coupled with high coefficients of variation suggest anthropogenic sources for arsenic, iron, mercury, zinc and lead. This finding confirms the results of previous studies in the area.^[22–24] In particular,^[23] previously reported As values ranging from 2.80 ppm to 10.40 ppm in surface water from Obuasi. Some of the water bodies sam-

pled including the alternate source of water have low pH values. This finding is consistent with the findings of ref.^[9,17] Regarding Cu, the maximum concentration (83.11 mg/L) was found in river Awurabena (SN6) and Pompo (SN32), while the minimum concentration (0.002 mg/L) was found in river Bowdie (SN42) and Mennam (SN43). The difference in concentration cannot be attributed to difference in proximity to a mining-related activity as shown in the cluster analysis. River pompo (SN32) is very close to the tailings dam of AngloGold Ashanti mine unlike rivers Bowdie and Mennam. River Nyam (SN1) recorded the highest concentrations of Mn and Cd (96.95 mg/L and 53.70 mg/L respectively), while the minimum concentrations were found in tap water at Obuasi.

River Nyam is within the catchment of the AngloGold Ashanti mine. Mine tailings seep into river Kwabrafo (SN30),^[23,24] which flows into river Jimi (SN27), which in turn flows into river Nyam. There is no significant difference in levels of heavy metals in rivers Jimi and Nyam, indicating that water from the two rivers mix. Consequently, the relatively high concentration of Mn and Cd in river Nyam is not entirely unexpected. This finding is consistent with the results of refs.^[9,17] The highest concentration of Fe (181.90 mg/L) was found in Akotosua (SN4) and the minimum was found in Kyerabodwese (SN41). Kwabrafo (SN30) had the highest concentrations of Pb and As (15.20 mg/L and 34.60 mg/L, respectively); Twepease (SN8) had the highest Hg concentration (25.3 mg/L) while Abebesua had the highest Zn concentration (51.03 mg/L).

Within the study area, the use of Hg in artisanal small-scale mining (*galamsey*) for the purposes of amalgamation is extensive.^[25,26] Twepease is very close to *galamsey* operations from which Hg in surface water originates. The considerable liquid effluents released from artisanal small-scale mining (*galamsey*) transform into toxic methylmercury, and gradually bioaccumulate in many environmental media and animal tissues. Small-scale mining activities currently account for over 10% of Ghana's national gold output and consequently feed into government revenue.^[25] This makes it imperative for the authorities to regulate the distribution and handling of the mercury, which yields this production. In conformity with the findings of^[24,27], it is observed that stream waters such as Kwabrafo which are very close to mine tailings have been most affected by mining activity and contain some of the highest Arsenic concentrations measured.

Cadmium is usually present in all soils and rocks. It occurs naturally in zinc, lead, and copper ores, in coal, and other fossil fuels and shales.^[28] These deposits can serve as sources to surface waters, principally when they are in contact with soft, acidic waters.^[28] Given that most of the water samples were acidic; it is probable that these sources could also have contributed to the levels of Cd in surface water. The pH of the water samples ranged between very acidic (4.6) and neutral (7.4). Turbidity ranged between 4 (in tap

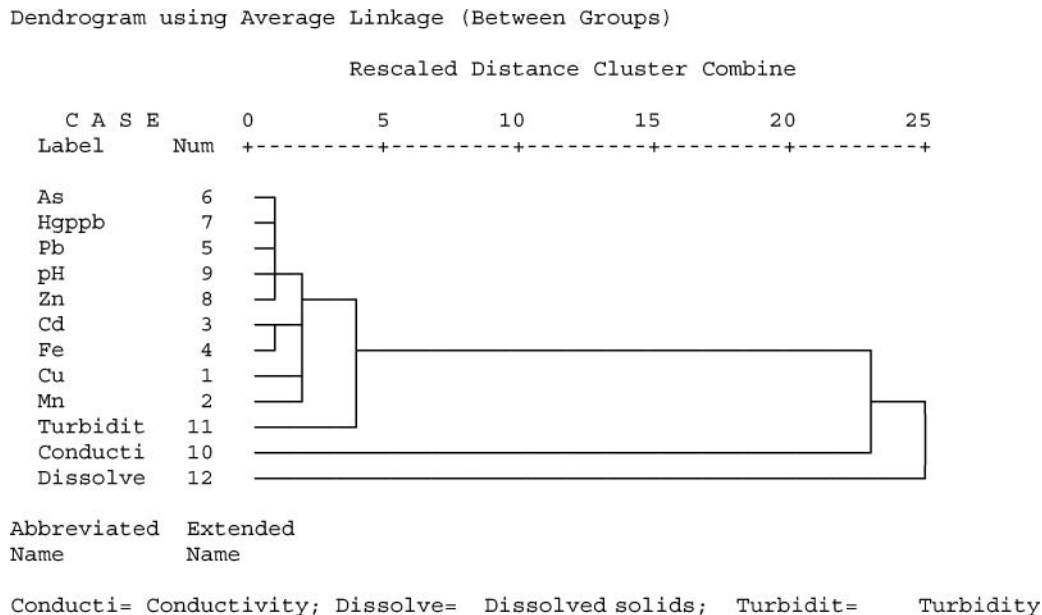


Fig. 4. Dendrogram showing clustering of heavy metals using Average Linkage (Between Groups).

water) and 97 in Nsuofufuo (SN13), Kyerabodwese (SN41), Kobi (SN45) and Akyenawe (SN43); while dissolved solids ranged from 7 mg/L in Danyame (SN29) to 676 mg/L in Akyenawe.

Conclusion

In this paper, we randomly selected 48 surface water sampling sites in Obuasi mining district and its environs to study the sources and environmentally relevant heavy metal concentrations. The data on heavy metal concentrations and other water quality parameters was subjected to multivariate statistical analysis. Pearson correlation coefficients among total metal concentrations and selected water properties showed a number of strong associations. The results indicate that apart from tap water, surface water in Obuasi has elevated heavy metal concentrations, especially Hg, Pb, As, Cu and Cd, which are not within the Ghana Environmental Protection Agency (GEPA) and World Health Organization (WHO) permissible limits; clearly demonstrating anthropogenic impact. The mean heavy metal concentrations in surface water divided by the corresponding background values of surface water in Obuasi decrease in the order of Cd > Cu > As > Pb > Hg > Zn > Mn > Fe.

The results also showed that Cu, Mn, Cd and Fe are responsible for large spatial variations explaining 72% of total variance, while Pb, As and Hg explain only 18.7% of total variance. Three main sources of these heavy metals were identified. As originates from nature (oxidation of sulphide minerals particularly arsenopyrite-FeAsS). Pb derives from vehicular fallouts, particularly water carrying drainage from towns and mine machinery maintenance

yards. Cd, Zn, Fe and Mn mainly emanate from industry sources. Hg mainly originates from artisanal small-scale mining. It cannot be said that the difference in concentration of heavy metals might be attributed to difference in proximity to mining-related activities because this is inconsistent with the cluster analysis.

For example, based on cluster analysis SN32, SN42 and SN43 all belong to group one and are spatially similar. But the maximum Cu concentration was found in SN32, while the minimum Cu concentration was found in SN42 and SN43. Consequently, we conclude that multivariate statistical techniques including Cluster analysis and principal component analysis have offered a suitable picture of the overall fate of heavy metals in surface water and give a better understanding about the sources of contamination. Tap water in Obuasi remains largely uncontaminated. However, some communities around Obuasi mining district have little or no access to tap water. Their major sources of drinking water include some of the polluted streams and rivers investigated in this study. As a result, it is imperative for constant monitoring of these water bodies and more importantly, provision of alternative drinking water supply in order to mitigate the risk posed to the riparian communities.

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