Arsenic Intensity Risk Assessment at AngloGold Obuasi Goldmine, Ghana, West Africa: Using Sorption and Geotechnical Factors

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Abstract

This research evaluated arsenic (As) intensity risk using sorption and geotechnical factors in the AngloGold Obuasi mine environment in Ghana. Water samples from tailings dam boreholes and surface stream were analysed for As contents over a time period of 24 months and over a distance of about 9 km respectively, under closed conditions, where there are no more discharges of waste. The porosity and bulk density of the subsurface material were also determined. Data generated from the mass-time and mass-distance analysis were used to establish As intensity risk assessment model based on documented global As impact data. From the model, a period of about 4 years is required in monitoring boreholes and a distance of about 12 km is required along the stream profile for As concentration to reduce from the maximum value of about 2.50 mg/l to 0.01 mg/l. Using the porosity, bulk density and combined degradation properties of the monitored media of the mobile As, the estimated retardation factor was 1.96 and the solute velocity estimated to be 1.53×10^{-7} ms^{-1} in the borehole environment, and 1.074 and 9.25×10^{-1} ms^{-1} along the streambed, respectively. This study shows that the pollution risk assessment model can be used to spatially estimate exposure to As contamination in the environment, while the transport characteristics can be used to determine clean-up criteria for effective As remediation in drainage.

Introduction

Mining industry constitutes a major source of inorganic contamination of natural resources (da Rosa & Lyon, 1997, Ramani, 2001). According to Eppinger *et al.* (1999), the composition of the ores present at mine sites determines the contaminants present. The AngloGold-Ashanti Obuasi mine in Ghana officially opened in 1895 and has for many decades treated primary ores that consist of predominantly sulphides with minor quartz, composed of about 33% dry wt. of As (e.g. Oberthur *et al.*, 1994).

At the mine, As contamination in the environment has been widely reported (Smedley *et al.*, 1996; Akabzaa *et al.*, 1997). For example, Akabzaa *et al.* (2007) noted that As concentration ranged from < 0.01 to 6.32 mg/l in streams. Potentially at risk to As exposure are: i) mine workers who are in frequent contact with the arsenopyrite-rich ores and mine spoils; ii) persons and animals whose water supply contains high levels of As; and iii) unborn babies of potential mothers exposed to As contamination (ATSDR, 2000).

To minimise the As contamination in the environment, a clear understanding of As behaviour in the mine drainage is

West African Journal of Applied Ecology, vol. **24**(2), 2016: 1–17.

required for effective remediation planning. For example, Kaye (2005) shows that As mobilises under circum-neutral pH conditions where it may be taken up by environmental receptors through environmental pathways. These pathways include i) sources of release; ii) mechanisms of release; iii) migration pathways and exposure routes; and iv) receptor exposure (Asante-Duah, 1996). Among the above-listed pathway elements, mechanism of As release is very important for establishing a risk assessment criterion for As management in drainage, through a modelled monitored natural attenuation programme.

Empirical models provide mathematical descriptions of observed experimental data (EPA, 2007). For example, DEP (2004) has indicated that most degradation reactions in groundwater follow an approximate first-order kinetic behaviour and are analogous to isotherm expressions for sorption processes involving inorganic species. According to an EPA (2007) report and Lovanh *et al.* (2000), the above scenario can be expressed as:

$$-\frac{dc}{dt} = k.C. \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1);$$

where C = concentration, t = time and k= degradation rate constant. Integrating with the initial concentration 'C_O', the equation can be expressed as:

$$\int \frac{dC}{C} = k\int dt;\ \text{or}\ \ln\frac{C}{Co} - k\,t, = \text{or}\ \log C = -\frac{k}{2303},\ t + \log C_O \ldots\ldots\ldots\ldots\ldots (2).$$

This relationship can, therefore, be used to determine whether concentration and time data from monitoring boreholes follow first-order decay behaviour and to determine site-specific decay constants, where the decay rates for the contaminants can be obtained from borehole data along the plume axis (e.g. DEP, 2004).

According to Asante-Duah (1996), the retardation of contaminant species through sorption is influenced by the retardation factor (*Rf*) during the assessments under reversible equilibrium conditions and can be estimated from the Freundlich model, defined as:

$$q = AC_i^m \text{ (Yong, 2001)} \ldots\ldots\ldots\ldots\ldots\ldots (3);$$

where q is the concentration of adsorbate on the solid phase at equilibrium and C is the concentration remaining in solution (EPA, 2007). The plot of log q versus log C is a straight line, with 'A' as the intercept on the q-axis and m is the gradient. 'A' and 'm' are adjustable and 'm' has a value between 0 and 1. From the above, retardation factor (*Rf*) can be estimated as:

$$Rf = 1 + \frac{\beta AmC^{m-1}}{\theta} \text{ (Sharma \& Reddy, 2004)} \ldots\ldots\ldots (4);$$

where β is the bulk density, θ is the porosity of the transport media, while the other constants remain as stated in equation (3). The retardation factor is also related to groundwater velocity (Nyer, 1993) as:

$$Rf = \frac{\text{groundwater velocity}}{\text{solute velocity}} \ldots (5).$$

The likelihood and consequence of an event form the basis for risk assessment of the danger posed by an environmental aspect (BCI Pty Ltd., 2007). Duoben (1998) has stated that the risk assessment process may be one of data analysis or modelling or a combination of the two and utilises available scientific knowledge and data to establish case-specific responses to site management problems (Asante-Duah, 1996). In order to achieve maximum remediation of As in the Obuasi environment, the need for an effective risk evaluation methodology based on As contamination and also the geochemical and geotechnical characteristics of As behaviour in drainage and the subsurface are required.

Worldwide, acute As toxicities from ingestion of water containing 1.2–21.0 mg/l shows early clinical symptoms in humans (Feinglass, 1973; WHO, 2003). For example, pigment changes occur in populations consuming water containing As concentrations $\geq$ 0.40 mg/l (ATSDR, 2000). Dermal lesions occur after a minimum exposure period of about 5 years (Tseng, 1977; Guo & Valberg, 1997).

In Taiwan and China, well water with As concentrations > 0.60 mg/l indicated a clear dose-response relationship between exposure and the frequency of dermal lesions and skin cancer (Tseng, 1977). In northern Chile, defects were observed in children consuming water of As concentration of 0.6 mg/l over a period of about 7 years (Zaldivar, 1980; WHO, 2003). Tseng (1977; Guo & Valberg, 1997) observed that the long-term ingestion of elevated levels of As are causally related to increased risks of cancers in humans (WHO, 2001; FAO/WHO, 2011a) and can be classified in relation to compliance concentration ranges (e.g. BCI Pty Ltd., 2007; Foli *et al.,* 2012).

WHO (2001) and FAO/WHO (2011a and b) reports indicate that As concentrations $\leq$ 0.050 mg/l or in the range 0.05–0.01 mg/l is classified as the zone where As impacts are possible (Murphy *et al.*, 1981). Values greater than 0.5 mg/l are classified as the zone within which As impacts are very certain, while about 0.1–0.5 mg/l is also classified as the zone where impacts are certain to occur (Tseng 1977; Zaldivar, 1980; ATSDR 2000). Values ranging from 0.10 to 0.05 mg/l are considered as zones of non-conclusive impacts (Murphy *et al.*, 1981; Wesbey & Kunis, 1981; WHO, 2003). To define the above ranges, therefore, standard environmental compliance values are necessary to serve as a guide.

For example, the concentration values of 0.5 mg/l and 0.05 mg/l exist as drinking water standard for As in water for livestock consumption and the primary maximum contamination limit (MCL) for drinking water (Wilson & Salomon, 2002) respectively. The value of 0.01 mg/l conforms to the World Health Organisation guideline for As concentration in Drinking water (WHO, 2010), while the value of 0.1 mg/l is the EPA standard for Industrial/facility discharges into water bodies and water courses (EPA [Ghana], 1994). The above limits constitute the compliance value ranges that can be used for impact rating purposes during the As impact risk assessment.

At the Obuasi mine, risk assessment evaluations are dependent on likelihood by consequence risk matrix (Foli *et al.*, 2012). Expressions of this kind are, however, not very informative because they equate scenarios that have low probability but catastrophic effects to those that are of high probability but have only minor consequences (Landis *et al*., 1998). Furthermore, chemical pollutions at the mine are managed using environmental management plans (Foli *et al*., 2010), which are only focused on effluent discharges, without adequate evaluation of the subsurface material characteristics (Anon, 2007). The objectives of this research are, therefore, to 1) use mass-time and distance analysis to establish an empirical model for determining As impact intensity in the environment, 2) evaluate bulk density and porosity of the subsurface material to be used for estimating compliance values for As in water.

Study area

The research area is located in the Obuasi municipality in the Ashanti Region of Ghana. The total land coverage is about 162.4 km^2. A sketch map of Ghana showing the location of Obuasi is presented in Fig. 1.

The area is situated within the semi-equatorial climatic zone which is characterised by high rainfall and temperature. The rainfall pattern is of the double maxima regime. The wet South-West monsoon trade winds and the dry dust-laden North-East trade winds affect the climate of the area. The wet season spans April to July and September to

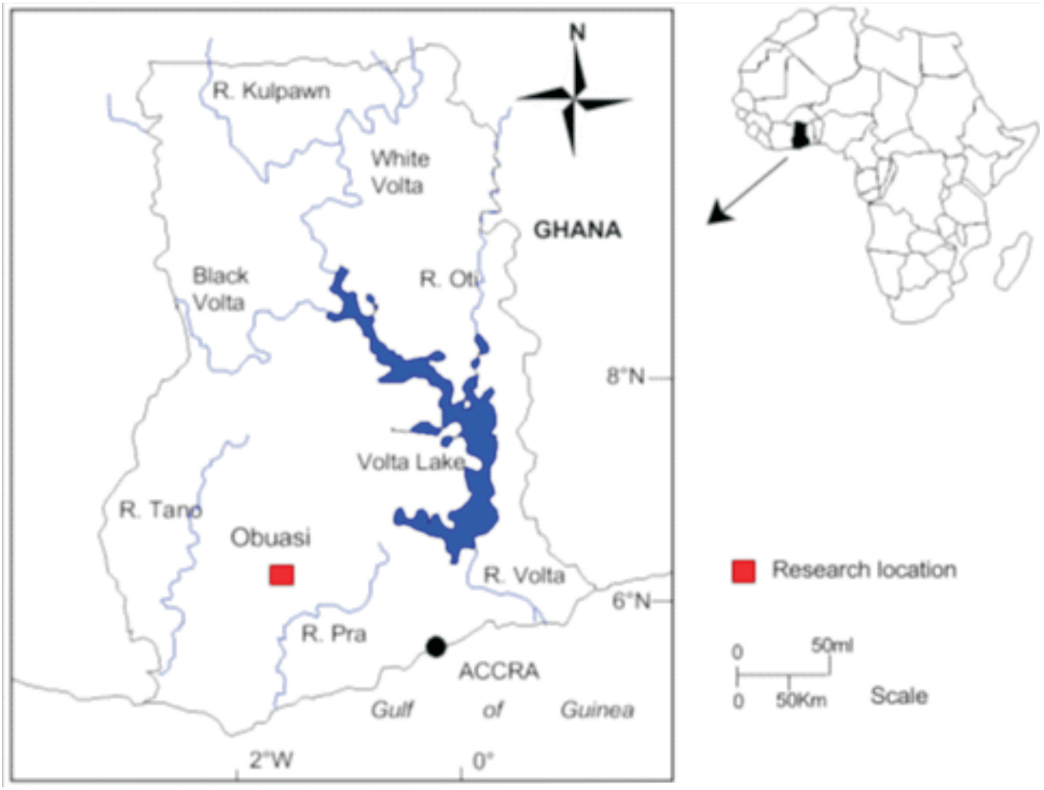

Fig. 1. A sketch map of Ghana showing location of Obuasi

October and a dry season from November to March. Mean annual rainfall ranges between 1250 mm and 1750 mm while the average annual temperature is 25.5 °C. Annual means of humidity and evaporation values are 78% and 3.3mm/day respectively; while the vegetation is a degraded and semi-deciduous forest type with topographic heights ranging between 200 m and 500 m above sea level (Anon, 2009).

Stream flow rates vary between 0 and 2 000 m^3/hour in the dry season with average value as 1 000 m^3/hour for 5 months in the year, and between 374 and 10 454 m^3/hour in the wet season with an average flow rate of 5 410 m^3/hour for 7 months in the year (Foli *et al.,* 2012). Annual flow velocity is determined as 0.993 m/s, while permeability varies from 1.0×10^{-7} m/s in the mottled zone to 5.0×10^{-7} m/s in the pallid zone (Kumapley, 1983)

Obuasi is underlain by the Birimian formations which are classified into meta-sedimentary and meta-volcanic groups (Kesse, 1985; Taylor *et al.,* 1992). The meta-sedimentary rocks occupy the north-western half of the area and comprise of low-grade metamorphosed rocks, that are associated with mica-rich ‘basin’ type granitoid (Kesse, 1985; Taylor *et al.,* 1992).The meta-volcanic group, separated from the meta-sedimentary group by the main Obuasi mineralised shear zone, is dominated by basalts with intercalated pyroclastic rocks, are also associated with the hornblende-rich ‘belt-type’ granitoid (Kesse, 1985; Taylor *et al.,* 1992).

Overlying the Birimian is the younger arenaceous and clastic Tarkwaian group, which occupy the south-eastern corner of the area (Kesse, 1985; Taylor *et al.,* 1992). Superficial deposits occur as alluvium, soils, laterite and terrace gravel. Three major types of gold ore occurrences exist within the Ashanti belt; these are quartz reef and disseminated sulphides associated with the Birimian formation (Kesse, 1985). The geology of the Obuasi area is presented in Fig. 2.

The gold ores contain varieties of sulphide minerals such as arsenopyrite, pyrite, pyrrhotite chalcopyrite and galena (Oberthur *et al.,* 1994) with key geochemical signature as Fe-As-Pd-Sb-Cu-Zn-S-Au system. Ore treatment methods are by both pyrometallurgy and hydrometallurgy, while the tailings are discharged to a repository, where, they may be rewashed to retrieve some residual gold.

Methodology

Water sampling and analysis

Tailings dam monitoring boreholes and a stream draining through the network of the tailings dams were sampled for As-mass time and As-mass distance analysis respectively. Sampling and analysis were designed according to APHA (1998) and AngloGold Ashanti Mine Laboratory Manual (Anon, 1994). The tailings monitoring borehole sites are labelled as g1, g2, g3, g4, g5 and g6, while the stream sampling sites are labelled as P1, P2, P3, P4, P5, P6, P7 and P8 over a distance of about 9.0 km. The sampling map for borehole monitoring, stream profile monitoring, as well as key environmental receptors such as tailings dams, streams,

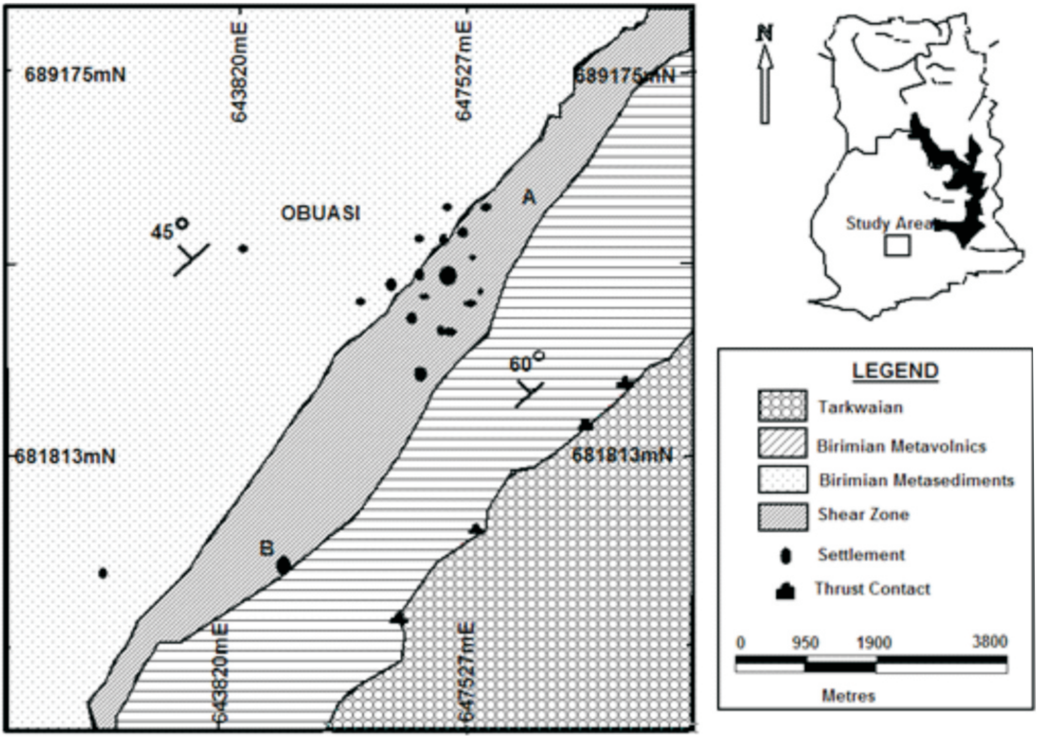

Fig. 2. Geological sketch map of the study area

retaining pond and road infrastructure is presented in Fig. 3.

A total of 108 monitored water samples were taken from the six (6) borehole sites (g) for the purpose of As mass-time analysis. During the water sampling, about 500 ml-sized water bottles were washed using nitric acid, distilled water and de-ionised water and then dried in the sunshine. At each site, the water samples were drawn from the boreholes with about 1-litre plastic bottles attached to a sling; the bottles were flushed three times with sample water before samples were taken. The samples were taken in multiples of six (6) for eighteen (18) sampling events that were spread over 24 months (Foli *et al*., 2013) indicating six (6) missing data, short of achieving a monthly sampling regime, due to seasonal factors. Results were consolidated per event and considered as one sample on each occasion, as done by Newell *et al.* (2007).

According to Newell *et al*. (2007); 1) a minimum of four boreholes is adequate for measuring contaminant per borehole during at least six sampling events spread over the monitoring period, 2) missing periods must not exceed two consecutive sampling times, 3) a minimum monitoring session of a year on quarterly basis was needed to establish a trend. In this research, however, sampling conditions were in excess of the minimum

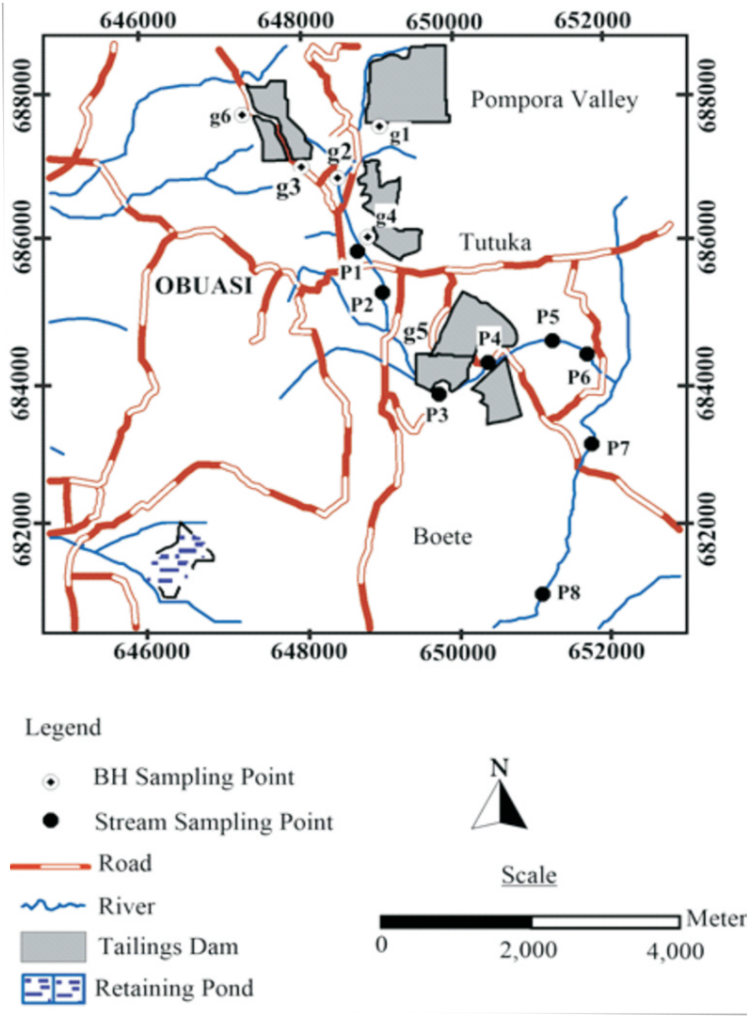

Fig. 3. Locations of tailing dam sites and sampling points.

requirements stated above, in order to obtain a more statistically meaningful correlation between the contaminant mass and time, as done by Barcelona *et al.* (1994).

For the As mass-distance monitoring, a total of 32 water samples, taken in batches of eight (8) which covered sampling points designated P1 to P8, was done along the stream monitored. The streambed was about 3.2 m from the ground surface. The sampling was done on a quarterly basis to minimise errors, as well as capture As behaviour at the specific sampling points over the periods (Newell *et al.,* 2007). This was at the time that all operational activities in the sampling area remained virtually the same.

Samples were not acidified in the field, but rather delivered to the laboratory within a maximum time of about one hour due to the proximity of the sampling locations to the laboratory. At the laboratory, samples were filtered with cellulose nitrate membrane filters of pore size 0.45 µm using vacuum filtration. The filtrates were acidified with concentrated HNO_3 at pH 2 to prevent precipitation of metals. Samples were analysed for As concentration in water, using the Varian 55 Atomic Absorption Spectrometry (AAS).

The certified reference material NIST CRM 1643d (National Institute of Standard and Technology) containing trace elements in water and total As at a certified concentration of 56.02 ± 0.73 mg/l (Anthemidis, 2005) had a measured value of 54.67 ± 0.89 mg/l with an accuracy of 96.41% from certified levels of $p > 0.05$ (e.g. Levman, 2011). The analytical characteristic for As determination was done by spiking with known concentrations to equal fractions. Samples spiked at 10 mg/l fortification level yielded mean ± standard deviation of 92.2 ± 0.55% in borehole data and 94.8 ± 0.37% in stream water data.

Bulk Density and Porosity of Subsurface Material

Bulk density (β) and porosity (θ) were determined to establish some contaminant transport characteristics from both a disturbed and an undisturbed subsurface environment. First, the soil material trapped in a sampling pipe was extracted at a depth of about 3.3–3.4 m, representing the disturbed soil environment and similar to the depth of the streambed. Second, a percussion drill rig was used to extract soil core samples from bores of depth ranging between 3.4 and 15.5 m which also correspond to tailing monitoring boreholes which are the undisturbed environment or the groundwater environment. Bulk density and porosity of the extracted material were determined using procedures described in the BS 1377 (1990).

Health impact and As pollution intensity assessment

The maximum threshold for lethal effect of As contamination is assumed to be > 0.50 mg/l (IPCS, 2001; FAO/WHO, 2011a). The least As contamination value considered is also assumed to be < 0.01 mg/l (WHO, 2010). A five-step intensity classification (BCI Pty Ltd., 2007) was defined by substituting the compliance value ranges listed in Table 1 below in As-related model equations developed in this research. Descriptive terminologies for the quantitative classifications such as; Very certain, Certain, Non-conclusive, Possible and Rare (IPCS, 2001 and FAO/WHO, 2011a) are assigned.

Results and discussion

Arsenic mass-time analysis

The arsenic mass-time analysis was done using borehole monitoring data. The purpose was to establish As degradation trend in the sub-surface. The results of As concentration in monitoring borehole samples ranged from 2.52 mg/l to 0.11 mg/l as presented in Table 2.

Based on Table 2, a linear regression analysis indicated that the regression coefficient between concentration and

TABLE 1

Variation of compliance values and remediation time range

[As] mg/l	*Impact*	*Health condition/Nature of impact*	*References*
> 0.50	Very Certain	Extreme dermal conditions and infections/ Life-threatening.	ATSDR (2000); Tseng (1977); Zaldivar (1980).
0.5–0.10	Certain	Cancers and skin lesions/Significant effects.	Guo & Valberg (1997); WHO (2003).
0.10–0.05	Not-conclusive	Toenail biomarker; Burning sensations; motor sensory defects/Moderate effect.	WHO (2011); Murphy *et al.* (1981); Wesbey & Kunis (1981); WHO (2003).
0.05–0.01	Possible	Early clinical symptoms/Minor effect.	Murphy *et al.* (1981); WHO (2003).
< 0.01	Rare	No discernible impacts	

TABLE 2

Arsenic degradation in monitoring boreholes (g) sites

Months	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
As mg/l	2.52	2.00	0.93	1.22	–	1.64	1.00	–	0.97	–	0.73	0.71
Months	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*
As mg/l	–	0.54	0.52	–	0.31	0.22	0.40	0.23	0.11	–	0.14	0.11

time is 0.797. This implied that approximately 80% of the data demonstrated statistical significance at 95% level of confidence (e.g. Levman, 2011). For the same 95% level of significance, the spread of the data is observed to be between 0.45 and 1.135, while a t-test statistic showed that the model is significant at a p-value of 0.000 (Foli *et al.*, 2012; Foli *et al.*, 2013). The As degradation curve and the Freundlich isotherm expression are compositely presented in Fig. 4.

From Fig. 4, the equations for the As degradation curve (left) and the Freundlich isotherm expression (right) are presented respectively as follows:

$\log [As] = 0.402 - 0.053t\ (R^2 = 0.913)$ .. (6);

$\log q = 0.615 \log C - 0.415$ .... ($R^2 = 0.912$ ……... (7).

From equation 6, the negative gradient indicates that the As concentration reduced over time and under closed conditions, while from equation 7, the gradient value of 0.615, being closer to one (1) than zero (0) suggest that the As mass reduction is mainly as the result of adsorption (e.g. EPA, 2007). The remediation times in the borehole environment were estimated by

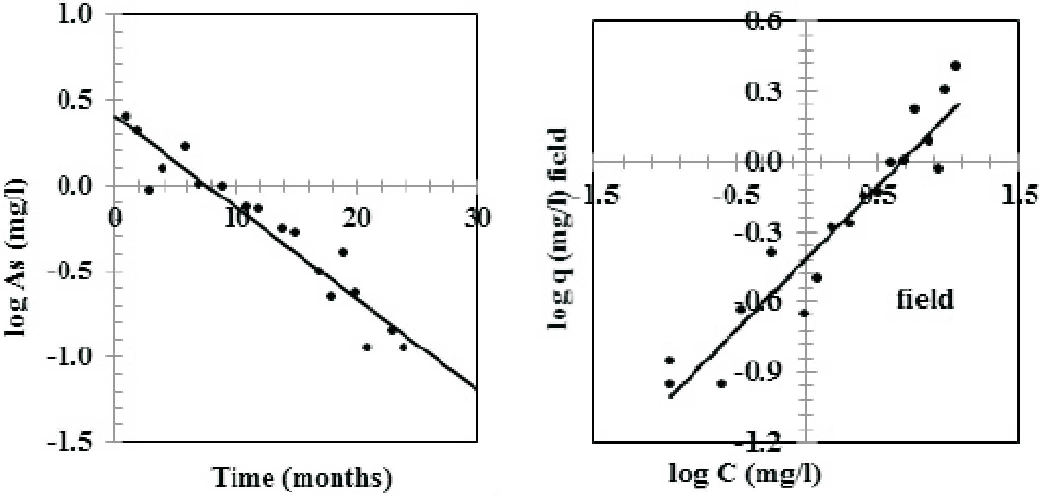

Fig. 4. As degradation curve (left) and Freundlich isothem expression (right)

substituting the compliance values of 0.5 mg/l, 0.1 mg/l, 0.05 mg/l and 0.01 mg/l into equation 6, and the corresponding approximate times obtained were; 1, 2, 3 and 4 years (Foli *et al.,* 2013). Equation 6 can, therefore, be used to establish a naturally monitored attenuation programme for the area, where the time expression for concentration changes can be used in setting environmental objectives and targets for use in environmental management plans for As in drainage.

Arsenic mass-distance analysis

Results of stream profile study for As degradation at specific sampling points and estimated Freundlich isotherm data are presented in Table 3.

From Table 3, ‘q’ is the concentration of adsorbate on the solid at equilibrium, and C is the total dissolved concentration remaining in solution at any observation point. The coefficient of variation (COV), defined as the ratio of the standard deviation to the mean of sample results is all less than 1, indicating that the data form a relatively close group about the mean value (Newell *et al.* 2007) and therefore consistent to be used. The initial concentration of As in the mass-distance monitoring is 2.49 mg/l and conforms to the average of 2.52 mg/l obtained for the mass-time analysis. The plots for As degradation and the Freundlich isotherm expression are presented in Fig. 5.

From Fig. 5 (left) As degradation with distance is described by:

$C = 2.49e^{-0.46d}$ .... ($R^2 = 0.744$) or, $d_n =$

$$2.174\,In\ \frac{(2.49)}{C_n}\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8),$$

where C is the concentration in mg/L and distance in kilometres. Also, the Freundlich isotherm (Fig. 5 right) for the degradation expression is given by:

$\log q = 0.542 \log C - 0.079$ .... ($R^2 =$ 0.850) .... (9).

From equation 9, gradient of 0.542 in

TABLE 3

Stream profile study results for As degradation

Sampling point	*P1*	*P2*	*P3*	*P4*	*P5*	*P6*	*P7*	*P8*
Distances (d) in km	0	1.13	2.42	3.49	4.49	5.23	6.97	9.00
As_1 (mg/l)	2.53	1.83	0.42	0.23	0.19	0.16	0.13	0.08
As_2 (mg/l)	2.47	0.84	0.41	0.22	0.20	0.15	0.11	0.10
As_3 (mg/l)	2.45	0.81	0.41	0.18	0.18	0.12	0.09	0.10
As_4 (mg/l)	2.51	0.80	0.42	0.20	0.17	0.13	0.11	0.09
Mean As (mg/l) [C]	2.49	1.07	0.42	0.21	0.19	0.14	0.11	0.09
Standard Deviation on [C]	0.04	0.51	0.01	0.02	0.01	0.02	0.02	0.01
Coefficient of Variance	0.01	0.47	0.01	0.11	0.07	0.13	0.15	0.11
MeanAs(mg/l)/km[q]	2.49	1.42	0.65	0.21	0.02	0.05	0.03	0.02
Log C	0.40	0.03	–0.38	–0.68	–0.72	–0.85	–0.96	–1.05
Log q	0.40	0.15	–0.19	–0.68	–1.70	–1.30	–1.52	–1.70

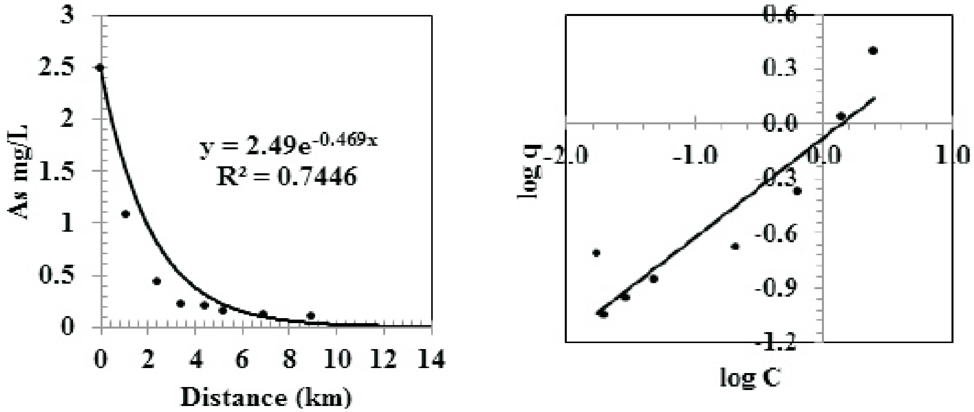

Fig. 5. As degradation curve (left) and Freundlich isothem expression (right)

the above equation, and also similarly as explained for the mass-time expression in equations 7, the reduction of As in the stream is mostly due to adsorption (e.g. EPA, 2007), as well as dilution from recharge sources or adsorption of the As to stream-sediment surfaces, as suggested by Carboo and Serfor-Armah (1997). From equation 8, the R^2 value of 0.745 indicate a 99% confidence interval (Cl) for the 8-data points used (e.g. DEP, 2004), and with the negative slope value and Cl > 95%, therefore, a decreasing trend is confirmed (Newell *et al.,* 2007). The remediation distances along the stream profile were estimated by substituting the compliance values of 0.5 mg/l, 0.1 mg/l, 0.05 mg/l and 0.01 mg/l, and the corresponding approximate distances obtained as 3 km, 7 km, 8 km and 12 km. Also, the compliance values and the intervals can be used to set objectives and targets for setting environmental objectives and targets in EMPs.

Sorption Process and Retardation Factor

The logs for both wet bulk density and porosity determined are shown in Table 4.

From Table 4, the wet bulk density and the porosity values are within the IOWA standard values for clay/silt material respectively (Domenico & Schwartz, 1990). The pit material is comparable to the streambed material because of the depths (3.0–3.3 m) at which they occur. From the estimated average log values of the bulk density (β) of the material in Table 4, the intercept on the *y*-axes (A) and gradient (m) from equations 7 and 9, and equilibrium concentration (C_e) of 0.5 mg/l (Foli *et al*., 2013), the retardation factor (*Rf*) and the solute velocity (sV) can be estimated. From equation 4, the retardation factor for the borehole and stream are estimated to be 1.96 and 1.074 respectively, while from equation 5, the solute velocities are (sVb), as: $\frac{3.0 \times 10^{-7}}{1.96}$ =

TABLE 4

Logs of wet bulk density and porosity in the subsurface material

Type	*Bulk density (g/cc)*	*Moisture content (%)*	*Dry density (g/cc)*	*Average bulk density (g/cc)*	*Average porosity*
Boreholes (3.4–15.5m)	2.064	22.5	1.69	2.029	0.411
	2.178	16.0	1.88		
	1.999	17.2	1.71		
	2.033	17.4	1.73		
	1.998	15.7	1.73		
	2.028	22.9	1.65		
	2.029	21.1	1.68		
	2.060	19.3	1.73		
	1.930	23.3	1.57		
	1.982	17.3	1.69		
	2.053	18.9	1.73		
	2.013	17.1	1.72		
	2.021	18.9	1.70		
	2.013	24.8	1.61		
	2.035	24.2	1.64		
Pits (3.3–3.4m)	1.903	23.0	1.55	1.975	0.599
	1.997	22.0	1.64		
	1.854	31.5	1.41		
	1.923	17.9	1.63		
	2.018	26.0	1.60		
	1.941	27.0	1.53		
	1.981	27.0	1.56		
	2.029	23.0	1.65		
	2.030	30.0	1.56		
	2.083	20.4	1.73		
	1.963	29.0	1.52		
IOWA standard values for clay/silt or fine sand material				1.0–2.4	0.26–0.60

$1.53 \times ms^{-1}$ and (sVb) as $\dfrac{0.993 m/s}{1.074} = 9.25$ ms^{-1} respectively.

Arsenic Impact Intensity

From Tables 2 and 3, the mean maximum As concentration for time (t) and distance (d), is 2.50 mg/l. From equations 6 and 8, the relative percentages of As intensity based on the compliance values estimated over the respective time and distance intervals are presented in Table 5.

From Tables 5, the relative percentages of As concentrations remaining in water corresponding to the time and distance intervals were re-arranged into a model data layout (Table 6) and plotted using the excel software and presented in Fig. 6.

From Fig. 6a, the model equations for both distance (d) and time (t) expressions are presented as:

$= 83.25e^{-1.33t}; = 87.57e^{-0.46d}$ .... (10),

with R² values as 0.986 and 0.990 respectively. The constants 83.25 and 87.57 represent the intensity of As in both

TABLE 5

Variation of compliance values in borehole and stream

As$_n$(mg/l)	*time (yrs)*	*distance km*	*Mass in water As$_n$/As$_i$%*	*As (mg/ l) Range*	*Time Range*	*Distance Range*	*% Range*
2.50	0	0	100	–	–	–	–
0.50	1	3	20	>0.50	0–1	0–3	100–20
0.10	2	7	4	0.50–0.10	1–2	3–7	20–4
0.05	3	8	2	0.10–0.05	2–3	7–8	4–2
0.01	4	12	0.4	0.05–0.01	3–4	8–12	2–0.4
–	–	–	–	<0.01	>4	>12	<0.4

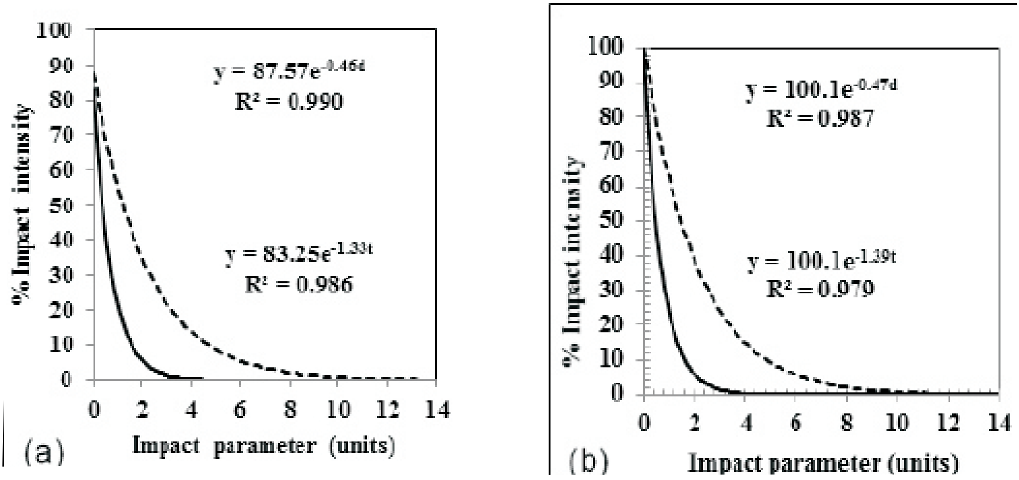

Fig. 6. Arsenic Impact Intensity Model [time: t (solid); distance: d (broken)]

media. The percentage of intensity, however, must indicate the maximum 100% as indicated in the model data-layout (Table 6a).

To obtain the maximum intensity in both cases, the initial data was adjusted to vary the intensity value upwards to 136% for the mass-time analysis and 124.5% for the mass-distance analysis to obtain the line-of-best-fit and also the maximum 100% intensity expressions in the model plots (Fig. 6b) and in equation 11:

$$= 100e^{-1.39t}; = 100e^{-0.47d} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (11),$$

with R^2 values as 0.979 and 0.987 respectively, where the constant value of 100 represents the maximum intensity.

The adjusted model plots described above can be used for establishing exposure frequency and duration for As impact intensity risk. Although the input data into this composite model and the concept, in general, are not new, the application of the model for the intended purpose of risk assessment is an innovation. The spatial model can be used as a key methodology to initiate As risk assessment criteria for sulphide-rich mine environment with similar characteristics as the Obuasi goldmine.

Conclusions and recommendations

From the model, a period of about 4 years is required in monitoring boreholes and a distance of about 12 km is required along the stream profile for As concentration to reduce from the maximum value of about 2.50 mg/l to 0.01 mg/l under closed conditions. The retardation factors and solute velocities of dissolved As in the environment were 1.96 and 1.53×10^{-7} ms^{-1} in the subsurface, and 1.074 and 9.25×10^{-1} ms^{-1} along the stream profile respectively. The As Pollution Intensity Risk model can be used for estimating the risk of As

TABLE 6

Arsenic impact intensity model data layouts

(a)	*Non-adjusted data*			*(b)*	*Adjusted data*		
Time in yrs	*% Intensity*	*Distance in km*	*% Intensity*	*Time in yrs*	*% Intensity*	*Distance in km*	*% Intensity*
0	100	0	100	0	136	0	124.5
1	20	1		1	20	1	
2	4	2		2	4	2	
3	2	3	20	3	2	3	20
4	0.4	4		4	0.4	4	
	5			5			
	6			6			
	7	4		7	4		
	8	2		8	2		
	9			9			
	10			10			
	11			11			
	12	0.4		12	0.4		

contamination for low concentrations of the order of 2.5 mg/l and below, within the time and distance frames of 4 years and 12 km respectively. The information can be used to establish environmental objectives targets for use in environmental management plans for remediation purposes. The As contaminant transport data can also be used to design water clean-up protocols for drainage sources. Finally, the information would serve as data for impact assessment and environmental inception plans, both of which are very important as inputs at the pre-project evaluation stages.

Acknowledgement

The authors acknowledge the Environmental Services Department of AngloGold Ashanti, Obuasi mine for their assistance in the laboratory work.

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