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Evaluation of pollution indices in Gold Mining communities in the Central Region of Ghana

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Abstract
The impact of artisanal small-scale gold mining (galamsey) is of global concern due to its threat to soil, water resources, food production and human health. For this reason, pollution indices of heavy metals in soils at the mining communities of Twifu Ati-Mokwaa District in the Central Region of Ghana where illegal mining is gaining notoriety were evaluated. An agricultural soil auger was used to collect 27 samples to a depth of 20 cm. Physicochemical properties including soil organic matter, moisture, pH, soluble salts, electrical conductivity and ash were determined. The concentrations of As, Cd, Hg and Pb were determined with Agilent AA 240 and AF 70 Atomic Absorption Spectrophotometer. Cadmium was not detected in any of the soils. Concentrations of Pb (0.62 - 12.7mg/kg) were all below pre-industrial values and FAO/WHO guidelines. Levels of As (3.64 - 39.84mg/kg) varied greatly with nine sites recording concentrations above the FAO/WHO permissible limit. Concentrations of Hg (0.02 – 6.47 mg/kg) were also high with eighteen of the twenty-seven site levels above FAO/WHO permissible limit. The observed differences in means from each site were statistically significant ($p < 0.05$) in all three communities. Degree of contamination, geoaccumulation and ecological risk indices were high for Hg and As but low for Pb. The $PI_{Nemerow}$ and PLI values however signalled slight pollution to severe pollution at 85.2% of the sample sites. The implication of these findings is that artisanal gold mining should be discouraged and lands should be thoroughly remediated before cultivated for agricultural production.

Keywords
Artisanal small-scale gold minig, contamination degree, geoaccumulation index, ecological risk factor, poluution load index

Introduction

Artisanal small-scale gold mining (ASGM) popularly known in Ghana as “galamsey” has hit media headlines since 2017 over the vast forest, land and water resources it destroys in its operations. Prior to the recent government intervention to ban galamsey and reclaim lands, several research publications, ordinary citizens, environmental (green) movements as well as Civil Society Organizations (CSOs), had bemoaned the alarming rate at which these natural resources were getting degraded and polluted by the operations of small-scale and illegal gold miners (Afriyie *et al.*, 2016; Boateng *et al.*, 2014; Donkor *et al.*, 2004; Teschner,

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2012). What seemed to have been a temporal ban on all forms of small-scale mining activities by the government of Ghana in the second quarter of 2017 developed into an indefinite one aimed at halting the devastating effect of mining gold from rivers, river basins, forests, parks and farm lands into the year 2019. In spite of this, normalcy was not satisfactorily restored and the successes or otherwise leaves much to be desired.

Communities that make up the Twifu Ati-Mokwaa (TAM) District have been peasant farmers since time immemorial. Mining in the district on small-scale basis begun in the year 2010 (GIS, 2014) and it is gradually reducing food production. Communities banned from illegal mining were expected to see improvement in the quality of the environment to reduce the cases of congenital diseases, heavy metal poisoning, upper respiratory infections, skin disorders, foetal abnormalities, low intelligent quotient, stunt and retarded growth in children associated with pollution from mining operations. Previous research (Boateng *et al*., 2014; Bonzongo *et al*., 2004; Tcham, 2013; Kpan *et al.*, 2014; Oppong *et al.*, 2010; Teschner, 2012) had determined levels of chemical contamination and signalled disturbances in water bodies where illegal mining takes place across the country. Findings from this research indicate the dominance of As, Cd, Hg and Pb in water and sediments within mining enclaves. Soil Pollution from ASGM is a serious environmental and global health concern also worth investigating. Data on pollution indices of soils in the district were not found in literature in spite of the magnitude of ecological risk envisaged. This current research therefore had the objective of determining the levels of heavy metals (As, Cd, Hg and Pb) and evaluate the pollution status of soils from three mining communities.

Materials and Methods

Study Area

Twifu Ati-Mokwaa is a district in the Central Region located southwest of Ghana covering 1°50'0"W to 1°25'0"W and 5°50'0"N to 5°30'0"N marked red (Fig. 1). It is drained by the Pra River which runs through the district from Awisam to Mampong. The route of the river is lined with Tarkwaian rocks known to be rich in gold. The district is made up of 28 towns and over 31 villages (GIS, 2014). Mining takes place in six of the communities three of which were systematically chosen for this study. The 2010 Population and Housing Census estimated the total population to be 61,743, representing 2.9% of the population of the Central Region (GIS, 2014). Significantly, 73.7 % of the locals are economically active, 96.7 % of these are gainfully employed while 3.3 % are unemployed. The level of education is satisfactorily high in the district with nearly 73.3% literates. However, the major job opportunity in the district is farming. Major crops cultivated in the district and sold across the country include cocoa, oil palm, plantain, cassava, maize, rice, oranges and vegetables (GIS, 2014). The report also indicated that nearly 20% of employment currently attracting the youth is mining for alluvial gold. The communities used for this research are Twifu Aduabeng (TA), Twifu Praso (TP) and Twifu Mokwaa (TM).

Study Design

A multistage sampling technique was used in the study. Three of the mining communities were systematically chosen for the collection of samples. Three cardinal points of over 200 m away from each residential area of the mining community were selected as sample locations. At each galamsey site, soil at three coordinates 50 m from the alluvial gold mining enclave were sampled. Locations and measurements of distances were done on a mobile tablet with two android platform applications (GPS coordinates v3.07 and GPS tape measure v3.05).

Data Collection

Sampling. Soil samples were collected 50 m away from each mining site. Three spot samples were collected at an interval of 50 m as indicated on the district map (Figure 1). The triplicate soil samples were taken within a 150 m triangular

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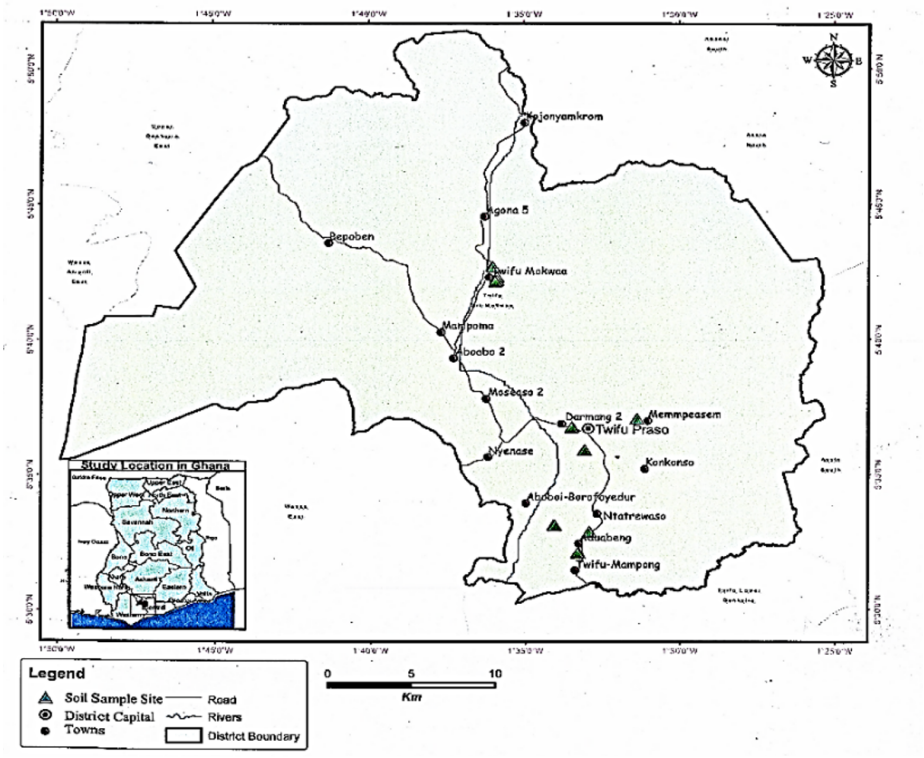

Figure 1 - Study area showing soil sample sites.

frame to ensure the data was representative of the site soil. Nine spot samples were obtained from each community. This sums up to a total of twenty-seven (27) samples used for the entire research. A 3ft agricultural auger was used to collect soil samples to a depth of 20cm. They were carefully disgorged into PET zip bags, concealed in biohazard polyethylene and transported for the analyses.

Determination of physicochemical properties. Soil pH was determined according to the method described by Yash (1995) with amendment. Moisture was determined by the thermogravimetric method also known as loss on drying method in the protocols of Carter and Gregorich (2008).Total ash determination was done with a Carbolite furnace set to 550 ^{o}C. The samples were ignited for 8 hours, allowed to cool in a desiccator and weighed to a constant mass. The residual ash was calculated by difference. Soil organic matter (SOM) was determined using a modified Walkley-Black method described by Rory *et al*. (2011). After the incubation, aliquots of the supernatant were transferred to 1cm quartz cuvettes and the transmittances read at 645 nm wavelength. The percentage of organic matter was determined from a Walkley-Black organic matter reference table. Total dissolved solids (TDS) determination described by Rory *et al*. (2011) was adopted using PH-2603 conductivity meter. The TDS were estimated from the equation: TDS in soil (ppm) = EC x 6.4 x 2 where 6.4 is the conversion factor to ppm and 2 is the dilution factor.

Determination of As, Cd, Hg and Pb by AAS. Each sample was loosened and mixed carefully in the clear PET zip bag. Triple acid wet ashing method described by Mustafa (2003) was used with amendment for pre-treating the samples. From each soil sample, the quantity weighed (2 g) was placed in a 100 mL pyrex digestion flask. A 3:1 solution of concentrated HCl and HNO_3 (32mL) was added and secured with a reflux kit. The mixture was heated gently to boil in a

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mantle for 2 hours. A solution of $HClO_4$ (12 mL) was added, reheated for 5 minutes to stabilize the complexes and allowed to cool. The resultant mixture was filtered through Whatman No.1 filter paper. The clear filtrate was diluted to 50 mL with distilled water and stored in an acid rinsed PET bottle for AAS analysis. Arsenic (As), Cadmium (Cd) and Lead (Pb) concentrations were determined with GFAAS whiles total mercury (Hg) was determined by the CV-AAS technique to avoid losses due to Hg volatility. Mercury was analysed by reduction to vapour in a $SnCl_2$/HCl mixture. HP Agilent AA 240 spectrophotometer and Agilent AF 70 were used for the analysis at the Environmental Chemistry laboratory – CSIR in Accra, Ghana. International multielement standard 2A (Labking – Netherland, Agilent 8500-6940) containinig As, Cd, Hg and Pb of 10mg/mL concentration in 2% nitric acid waqs used for calibration and data quality control.

Evaluating pollution indices

Degree of contamination. The degree of contamination was calculated as concentration factor as established by Qingjie *et al*. (2008). The concentration of each heavy metal (not mean from five sites) was divided by its corresponding baseline value. Pre-industrial reference levels (baseline values) and toxic response factors of Hakanson (He *et al*., 2015) in Table 1 were used in the computation. This was adopted due to the unavailability of pristine values from the study area.

Table 1. *Hakanson's pre-industrial reference level and toxic response factor of metals*

Elements	Hg	Cd	As	Cu	Pb	Cr	Zn
Pre-industrial reference level in mg/kg (C_b)	0.25	1.0	15	50	70	90	175
Toxic-response factor (Tr)	40	30	10	5	5	2	1

Degree of contamination (otherwise contamination factor) formula used is:

$$CF = C_m/C_b \qquad [1]$$

where C_m is the concentration of the metal and C_b is the baseline concentration of the heavy metal. The interpretation of values in Table 2 was applied.

Table 2. Descriptions of degree of contamination values.

Value	Description
$C^i f < 1$	low contamination
$1 \leq C^i f < 3$	moderate contamination
$3 \leq C^i f < 6$	considerable contamination
$C^i f \geq 6$	very high contamination

Geoaccumulation index. Geoaccumulation index was estimated in accordance with literature (Qingjie and Jun, 2008) by comparing the observed concentrations with pre-industrial levels using the formula:

$$\text{Igeo} = \log_2\left[\frac{Cm}{(1.5Cb)}\right] \qquad [2]$$

where *Cm* is the measured concentration of the metal in the sample, and *Cb* is the geochemical baseline or reference value of the metal. Factor 1.5 was used in the formula to account for possible variations in background values for each metal in the environment as well as anthropogenic influences. The interpretation of values in Table 3 was applied.

Table 3. Muller classification of pollution based on Igeo.

Index	Category	Interpretation
Igeo ≤ 0	Class 0	Unpolluted
0 < Igeo ≤ 1	Class 1	Unpolluted to moderately polluted
1 < Igeo ≤ 2	Class 2	Moderately polluted
2 < Igeo ≤ 3	Class 3	Moderately to strongly polluted
3 < Igeo ≤ 4	Class 4	Strongly polluted
4 < Igeo ≤ 5	Class 5	Strongly to extremely polluted
Igeo > 5	Class 6	Extremely polluted

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Ecological risk factor. The ecological risk factor was used to quantitatively express the potential ecological risk of each metal in the soils. The Håkanson formula used to estimate ecological risk was:

$$Er = Tr\ x\ C_f \quad [3]$$

where Tr is the toxic-response factor for a given metal and Cf is the contamination factor (degree of contamination). The interpretation of values in Table 4 was applied.

Table 4. *Description of ecological risk values.*

Value	Description
Er <40	low potential ecological risk
40 ≤ Er < 80	moderate potential ecological risk
80 ≤Er<160	considerable potential ecological risk
160 ≤Er<320	high potential ecological risk
Er ≥320	very high ecological risk

Pollution Load Index. PLI was calculated from the degree of contamination as the nth root of the product of the *n* single indices as described in literature (Qingjie *et al*, 2008; Sey and Belford, 2019). It provided a simple and comparative criterion for assessing the level of all heavy metal pollutants being investigated. The equation below proposed by Tomlinson was used to compute the C_f PLI values for each site.

$$\text{PLI rp} = \left(\prod_{i=1}^{n} \text{Cf}\right) 1/n = \sqrt[n]{(\text{Cf1} * \text{Cf2} * \text{Cf3} \ldots * \text{Cfn})} \quad [4]$$

where Cf_1 is the degree of contamination for the first heavy metal; C_{fn} is the degree of contamination for the nth heavy metal. According to Qingjie *et al*. (2008), values of PLI ≤ 1 indicate heavy metal loads close to the background level, and values above 1 indicate pollution.

Pollution index. The second integrated index used was the Nemerow pollution index ($PI_{Nemerow}$) which comprise a 5-grade system. $PI_{Nemerow}$ was calculated from the degree of contamination of the metals using the formula described by Qingjie *et al.* (2008) below:

$$PI_{Nemerow} = \frac{\sqrt{(\frac{1}{m}\sum_{i=1}^{m} \text{P})^2 + \text{P max}^2}}{2} \quad [5]$$

where P is the single pollution index of heavy metals; Pmax is the maximum value of the single pollution indices of all heavy metals the understudy, and *m* is the total count of the heavy metal species. The quality of soil was described as stated in Table 5.

Table 5. *Description of $PI_{Nemerow}$ grades.*

Grade	Description
$PI_{Nemerow} < 0.7$	safe
$0.7 \leq PI_{Nemerow} < 1.0$	precaution
$1.0 \leq PI_{Nemerow} < 2.0$	slightly polluted
$2.0 \leq PI_{Nemerow} < 3.0$	moderately polluted
$PI_N \geq 3.0$	seriously polluted

Data Analysis

The data obtained were analysed with Statistical Package for Social Sciences (SPSS) version 20 and Microsoft (MS) professional plus 2013 Excel applications. The observed data was presented in tables with their mean values and standard deviation. Tukey's ANOVA was computed on the concentration of heavy metals to establish honestly significant differences (HSD) in mean values at α = 0.05. The degree of contamination, geoaccumulation index, ecological risk and pollution load indices were calculated with MS excel.

Results and Discussion

Physicochemical characteristics of soils

Physical and chemical properties observed (Table 6) were indicative of adverse impact. Soil pH were found ranging from 4.32 to 6.81 with majority (representing 88.9%) of the soils recording pH below 6.5 (acidic). Electrical conductivity (EC) values were relatively low (0.01 to 0.15 mS/cm) in contrast to FAO limits of 0.75 – 2 mS/cm. The corresponding TDS (0.128 to 2.432 mg/L) as a measure of chemical constituents of the soil

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or ionic compounds readily soluble in water at the time of the study were also low. The mineral content was high (67.73 to 90.04% ash) but the organic matter needed to enrich the soil were very low (0.1 to 2.25%).

According to the report on guidelines for soil description, it is desirable to have SOM between 4 and 6 (FAO, 2006). Nonetheless, the results of this study are far lower at all sites. Moisture content which is water retained by the soil were found in the ranges of 8.17 to 28.09%. With the exception of ash and moisture contents all other soil properties did not satisfy the FAO guidelines. Natural processes of weathering in the tropics and application of fertilisers in crop farming are known to be key contributors to soil acidity in areas where mining does not take place.

Table 6. Physicochemical characteristics of soils in the three mining communities

Site	pH	EC (mS/cm)	TDS (mg/L)	SOM (%)	Ash (%)	Moisture (%)
TAS1	6.69	0.03	0.38	0.1	80.40	19.40
TAS2	6.66	0.04	0.51	1.75	72.56	23.06
TAS3	5.59	0.04	0.51	0.55	72.71	22.31
TAS4	4.82	0.04	0.51	0.55	81.87	15.14
TAS5	5.48	0.03	0.38	0.5	78.64	18.16
TAS6	4.77	0.03	0.38	0.3	85.43	12.38
TAS7	5.76	0.06	0.77	0.4	74.75	20.48
TAS8	5.11	0.04	0.51	0.6	76.25	19.56
TAS9	6.81	0.05	0.64	0.95	67.73	28.09
TPS1	4.87	0.07	0.90	0.95	75.65	18.16
TPS2	4.79	0.09	1.15	1.25	78.40	15.00
TPS3	4.86	0.04	0.51	0.4	80.48	15.14
TPS4	5.71	0.06	0.77	0.1	78.04	21.36
TPS5	4.16	0.15	1.92	0.8	78.88	18.13
TPS6	4.57	0.19	2.43	0.8	81.31	16.70
TPS7	5.56	0.12	1.54	0.3	75.40	22.20
TPS8	4.95	0.1	1.28	1.4	81.51	15.11
TPS9	6.58	0.09	1.15	2.25	74.70	19.92
TMS1	4.44	0.05	0.64	0.2	81.91	15.71
TMS2	6.25	0.05	0.64	1.2	75.25	19.76
TMS3	4.92	0.05	0.64	0.2	68.00	26.80
TMS4	5.91	0.05	0.64	0.1	79.80	19.80
TMS5	4.44	0.08	1.02	0.95	76.69	19.12
TMS6	4.32	0.05	0.64	0.95	74.75	21.07
TMS7	5.46	0.01	0.13	0.3	88.89	10.52
TMS8	4.63	0.02	0.26	0.1	76.74	19.48
TMS9	5.62	0.15	1.92	0.2	90.04	8.17
Mean	5.32	0.07	0.84	0.67	78.03	18.55
FAO guide	5.2– 8.0	0.75 – 2	>2500	4 – 6	40 – 80	10 – 35

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Majority of the soils (88.9%) were found to be acidic with pH below 6.5. This is characteristic of soils with metal toxicities and nutrient deficiencies (Kamprath and Smyth, 2005). Some literature rather supports the hypothesis that, soil acidity increases during rainy days because rain water has a pH of 5.7 (Kamprath and Smyth, 2005). For this study, the soils are acidic as a result of waste from galamsey operations (≤6.5) similarly observed in literature (Appleyard *et al*., 2004; Adu, 2012; Kpan *et al*., 2014; Rajaee *et al*., 2015; Muche *et al*., 2015; Tuzen, 2003)an integrated assessment (IA. At reclaimed sites in Ahafo for example, soil pH of 5.1 – 7.5 were the findings of Adu (2012) but notable was that majority were acidic in support of this study. Consequently, the organic matter in the soils were very low implying low fertility which can make the land incapable of adequately supporting vegetation or agriculture. They are also supposed to be in high quantity (6-10%) to serve as substrate for soil microorganisms (Alfaro *et al*., 2015; FAO/WHO, 2011; Madella, 2017 and FAO, 2006; 2018). Very high values could have suggested use of petroleum products characteristic of heavy machine operated ASGM as recounted by Eugenio, Mclaughlin and Pennock (2018).

Concentration of As, Cd, Hg and Pb in Soil

Cadmium was not detected in any of the samples analysed (Table 7 - 9) in contrast to what was observed (103.66 mg/kg) along the west coast of Ghana (Fosu-Mensah *et al*., 2017) but compares with the 0.17 - 0.19 mg/kg reported by Owusu-Donkor (2011) in less impacted parts of Ashanti region where citrus fruits are cultivated. In addition to this, levels of Pb were found below preindustrial and FAO/WHO upper crust limits. In a very recent related study there were also high cadmium concentrations of 2.0-2.6 mg/kg (Sey and Belford, 2019) and 0.48-0.84 mg/kg (Opaluwa *et al*, 2012) with similar trend for lead. There was relatively high total mercury (0.02 – 6.47 mg/kg) which was not limited to only mining enclaves but widespread in all soils studied in the TAM District. It is the practice of miners to carry the unrefined nuggets away from the mine site to other secure unsuspecting places for amalgamation with mercury, a view corroborated by Owusu-Nimo *et al* (2018). This could be one of the reasons why Hg was detected in all the samples irrespective of proximity to mining sites which is articulated in other publications (Aryee *et al*., 2003; Boateng *et al*., 2014; Bonzongo *et al*., 2004; Kpan *et al*., 2014; Legg *et al*., 2015; Mishra and Kesharwani, 2018; Rajaee *et al*., 2015; Teschner, 2012; Tuzen, 2003)”type”:”article-journal”,”volume”:”11”},”uris”:[“http://www.mendeley.com/documents/?uuid=86d319d0-cb90-4379-b580-0dd27d3765ee”]},{“id”:”ITEM-2”,”itemData”:{“DOI”:”10.1016/S0026-265X(03.

Table 7. Mean concentration of heavy metals in soils at community TA

	Mean concentration (mg/kg)			
Site	Hg	Pb	As	Cd
TAS1	0.28±0.01^{b}	8.09±0.003^{d}	3.64±0.02^{b}	-0.37±0.001^{c}
TAS2	0.02±0.01^{a}	8.65±0.001^{de}	37.06±0.1^{g}	-1.02±0.001^{f}
TAS3	1.73±0.01^{cd}	12.70±0.001^{g}	39.84±0.03^{h}	-0.42±0.001^{d}
TAS4	5.35±0.03^{h}	3.74±0.002^{b}	20.96±0.2^{f}	-0.47±0.001^{d}
TAS5	4.39±0.01^{fg}	2.12±0.001^{a}	10.93±0.8^{c}	-0.32±0.001^{c}
TAS6	4.04±0.01^{f}	3.22±0.001^{b}	16.89±1.0^{e}	-0.27±0.001^{b}
TAS7	2.63±0.02^{de}	9.56±0.001^{ef}	-2.95±0.1^{a}	-0.85±0.01^{e}
TAS8	2.51±0.01^{d}	8.81±0.001^{de}	-2.90±0.1^{a}	-0.17±0.001^{a}
TAS9	6.47±0.01^{i}	6.64±0.002^{c}	13.01±0.4^{d}	-0.17±0.001^{a}
Mean	3.04	7.06	15.17	-0.45
FAO/WHO (Cb)	1(0.25)	50(70)	20(15)	3 (1)

Means ± SD in the same column with different letter superscripts differs significantly ($p<0.05$)

The Hg levels (0.02 to 6.47 mg/kg) found in this study is comparable to figures reported at Kejetia, Gorogo (0.096 to 3.3 mg/kg) by Rajaee *et al.,* (2015), the Pra basin southwest Ghana (0.04-0.45 mg/kg) by Oppong *et al.,* (2010) and at Bogoso to Prestea (0.125 to 0.352 mg/kg) by Adjorlolo-Gasokpoh *et al.,* (2012). These researches were undertaken on galamsey impacted soils and not large-scale mining as in the case of Sey and Belford (2018) at Chirano. From neighbouring Dunkwa Offin districts in Ghana for example, Bonzongo *et al.*, (2004) reported 0.11-0.93 mg/kg (107.83-933.3 ng/g) of mercury in soils close to ASGM sites. The results of this study were statistically different ($p < 0.05$) among the community mean values but there were statistical differences in the mean Hg concentrations at all the sites ($p > 0.05$). Additionally, there were 16 (representing 59.3%) of the sites with Hg concentrations above the FAO/WHO guideline of 1 mg/kg and are high risk areas to exposed vulnerable groups. Arsenic was detected in all samples and the levels were also high.

Table 8. Mean concentration of heavy metals in soils at community TP.

	Mean concentration (mg/kg)			
Site	Hg	Pb	As	Cd
TPS1	4.83±0.02^{e}	4.48±0.004^{f}	23.69±0.2^{h}	-0.02±0.001^{a}
TPS2	3.69±0.01^{d}	2.39±0.006^{d}	19.33±0.03^{g}	-0.17±0.001^{c}
TPS3	4.98±0.03^{e}	0.97±0.004^{b}	11.58±0.3^{ef}	-0.37±0.001^{de}
TPS4	3.00±0.01^{d}	0.00±0.001^{a}	6.31±0.002^{b}	-0.17±0.001^{c}
TPS5	1.40±0.01^{bc}	2.92±0.001^{de}	8.66±0.02^{d}	-0.17±0.001^{c}
TPS6	0.90±0.02^{ab}	4.42±0.001^{f}	8.08±0.01^{c}	-0.07±0.001^{ab}
TPS7	0.91±0.01^{ab}	2.34±0.01^{d}	27.24±0.04^{i}	-0.32±0.001^{d}
TPS8	0.53±0.02^{a}	1.02±0.001^{bc}	4.20±0.01^{a}	-0.07±0.001^{ab}
TPS9	1.87±0.02^{bc}	5.97±0.001^{g}	11.17±0.03^{e}	-0.32±0.001^{d}
Mean	2.46	2.72	13.36	-0.12
FAO/WHO (Cb)	1(0.25)	50(70)	20(15)	3 (1)
Means ± SD in the same column with different letter superscripts differs significantly ($p<0.05$)				

Run offs are sources of contamination for the water bodies which invariably bioaccumulate in fish and other aquatic organisms. Roots of crops also take up heavy metals from the soil to edible parts. When consumed, these chemicals which easily accumulate in human systems, begin to pose danger to the liver, kidneys, triggering cancer and affecting the general wellness of the consumer. The mean As concentration was below FAO/WHO guideline of 20 mg/kg. A Tukey post-hoc test carried out on the heavy metal concentrations independently in each mining community further indicate that in majority of the sites, honestly significant differences exist ($p < 0.05$). With respect to mercury, there were significant differences in the pairwise treatment of means observed at Twifu Aduabeng (Table 8) and Twifu Praso (Table 9). There were however, three pairs (TMS1-TMS7; TMS2-TMS8 and TMS6-TMS9) from Twifu Mokwaa (Table 10) whose differences were not significant. Similarly, there were significant differences in site means with respect to lead concentration although six pairs showed no differences in their mean values for some alternative treatments across all three communities. There were also significant differences ($p < 0.05$) in the concentrations of arsenic between site means in all the communities except one at Twifu Aduabeng (TAS7-TAS8).

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Table 9. Mean concentration of heavy metals in soils at community TM.

	Mean concentration (mg/kg)			
Site	Hg	Pb	As	Cd
TMS1	0.89 ± 0.01^{bc}	4.82 ± 0.001^{f}	5.90 ± 0.02^{bc}	-0.02 ± 0.001^{a}
TMS2	0.71 ± 0.4^{bc}	1.80 ± 0.004^{c}	32.10 ± 0.01^{h}	-0.17 ± 0.001^{b}
TMS3	1.08 ± 0.02^{de}	4.10 ± 0.001^{e}	26.56 ± 0.2^{g}	-0.37 ± 0.001^{c}
TMS4	1.55 ± 0.03^{ef}	2.87 ± 0.003^{d}	4.72 ± 0.01^{a}	-0.52 ± 0.001^{de}
TMS5	1.15 ± 0.3^{def}	1.97 ± 0.001^{c}	12.00 ± 0.1^{d}	-0.47 ± 0.001^{d}
TMS6	0.37 ± 0.05^{ab}	4.36 ± 0.001^{e}	15.56 ± 0.3^{e}	-0.02 ± 0.001^{a}
TMS7	0.90 ± 0.7^{bc}	0.62 ± 0.001^{a}	5.46 ± 0.03^{b}	-0.02 ± 0.001^{a}
TMS8	0.69 ± 0.06^{ab}	0.90 ± 0.002^{ab}	37.07 ± 0.01^{i}	-0.35 ± 0.001^{c}
TMS9	0.32 ± 0.04^{a}	0.57 ± 0.001^{a}	20.95 ± 0.02^{f}	-0.75 ± 0.001^{f}
Mean	0.85	2.45	17.81	-0.30
FAO/WHO (Cb)	1(0.25)	50(70)	20(15)	3 (1)
Means ± SD in the same column with different letter superscripts differs significantly ($p<0.05$)				

The contamination was diverse and was observed in both areas of active galamsey and areas of no known mining activity as observed by Donkor *et al.,* (2007) between 0.079 and 4.31 ppm at the Pra basin attributing it to the impact of ASGM. In spite of this, the differences in concentrations were statistically insignificant ($p < 0.05$) among the means from the three communities. For the purposes of properly evaluating each site however, the Tukey tests proves that all mean differences are statistically significant ($p < 0.05$) for all possible comparisons and signals a widespread contamination. In Cuban soils as high as 19 mg/kg As has been reported but this has constantly been attributed rather to source material, climatic, geomorphology and pedogenic processes (Alfaro *et al*., 2015). US lands also have about 5ppm As in majority of states although the USEPA superfund risk model sets 0.43 ppm as a minimum guideline for a cancer risk exposure through soil ingestion. Toxicities of soil As are known to increase with addition of phosphate in Bangladesh (Duxbury and Zavala, 2018). This means that, rehabilitation prior to crop farming in such lands should be done with low phosphate fertilisers. Targeted research in the district to identify point and non-point sources is necessary. Contamination by As is alarming and could be a major cause of over the 3236 to 3500 cases of skin legions reported annually at the district hospital alone (GHS, 2016 and TAMDA, 2015). It is widely published that *Papular erythematous* and buruli ulcers are prevalent in areas with As enriched soils.

The heterogeneity of the soils due to the presence of these heavy metals were affirmed to be widespread for As, Pb and Hg. The statistically significant differences ($p < 0.05$) established indicate that the heavy metals are not uniformly distributed in adjoining soils just 50m apart at the sample sites. It is also supported by the variations in the soil physicochemical characteristics, predominantly clay texture and general bad state of the soils (Table 6). Obviously, lead and arsenic levels were relatively high in the soils in these communities studied in spite of the mercury-amalgamation techniques employed. Pb concentrations (0.62 to 12.7 mg/kg) were high but far below pre-industrial values and the WHO guideline of 70 mg/kg and 50 mg/kg respectively. The results highlight As concentrations between 3.64 (TAS1) and 39.84 mg/kg (TAS3). With reference to the WHO limits, samples TAS2, TAS3, TAS4, TPS1, TPS7, TMS2, TMS3, TMS8 and TMS9 recorded concentrations above the guideline of 20 mg/kg. This is one worrying observation because of the impact As enriched soils have on disease burden already discussed.

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Pollution indices of soils by As, Cd, Hg and Pb

Degree of contamination. The degree of contamination (C_f) by Hg (Table 10) was ≤ 0 (described as low contamination) at only one sample site (TAS2) but the others were found between 1.1 (TAS1) and 25.9 (TAS9). Sites TAS1, TPS8, TMS2, TMS6, TMS8 and TMS9 had values within the 1 ³ C_f ≤ 3 domain and are therefore moderately contaminated with Hg.
Sample TPS5, TPS6, TPS7, TPS9, TMS1, TMS3, TMS5 and TMS7 values were found within the considerable contamination domain (3 ³ C_f ≤ 6). Degree of contamination was in the very high domain (³ 6) for samples TAS3, TAS4, TAS5, TAS6, TAS7, TAS8, TAS9, TPS1, TPS2, TPS3, TPS4, TPS9 and TMS4. The degree of contamination for Pb were 0 at majority of the sites and the maximum value was 0.2 (TAS3). The values are less than 1 indicating only background concentration and therefore no contamination with lead. Degree of contamination by As range from -0.2 (TAS7 and TAS8) to 2.7 (TAS3). The results show moderate As contamination at sites TAS2, TAS3, TAS4, TAS6, TPS1, TPS2, TPS7, TMS2, TMS3, TMS6, TMS8 and TMS9. The remaining sites had C_f < 1 and imply no contamination with As. In contrast, all the sites showed no contamination with cadmium (C_f = 0). The degree of contamination (C_f) by cadmium and lead were low at all sites. The soils are therefore not contaminated with these two heavy metals. There were significant number of soils falling within the moderate contamination domains per the degree of contamination index of As but a larger proportion of the soils had reached very high degree of contamination with Hg.

Table 10. Degree of contamination for each heavy metal at sample sites.

		Concentration factor (C_f)			
Community	Site	Hg	Pb	As	Cd
C1	TAS1	1.1	0.1	0.2	0.0
	TAS2	-0.1	0.1	2.5	0.0
	TAS3	6.9	0.2	2.7	0.0
	TAS4	21.4	0.1	1.4	0.0
	TAS5	17.6	0.0	0.7	0.0
	TAS6	16.1	0.0	1.1	0.0
	TAS7	10.5	0.1	-0.2	0.0
	TAS8	10.0	0.1	-0.2	0.0
	TAS9	25.9	0.1	0.9	0.0
C2	TPS1	19.3	0.1	1.6	0.0
	TPS2	14.7	0.0	1.3	0.0
	TPS3	19.9	0.0	0.8	0.0
	TPS4	12.0	0.0	0.4	0.0
	TPS5	5.6	0.0	0.6	0.0
	TPS6	3.6	0.1	0.5	0.0
	TPS7	3.6	0.0	1.8	0.0
	TPS8	2.1	0.0	0.3	0.0
	TPS9	7.5	0.1	0.7	0.0

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C3	TMS1	3.6	0.1	0.4	0.0
	TMS2	2.8	0.0	2.1	0.0
	TMS3	4.3	0.1	1.8	0.0
	TMS4	6.2	0.0	0.3	0.0
	TMS5	4.6	0.0	0.8	0.0
	TMS6	1.5	0.1	1.0	0.0
	TMS7	3.6	0.0	0.4	0.0
	TMS8	2.7	0.0	2.5	0.0
	TMS9	1.3	0.0	1.4	0.0
	Mean	8.5	0.1	1.0	0.0

Geoaccumulation index. The geo-accumulation index for Hg ranged from -0.4 (TAS1) to 4.1 (TAS9); that for Pb range from -7.5 (TMS9) to 0 (TPS4) and that for As range from -2.6 (TAS1) to 0.8 (TAS3). Pollution status of the soils by Hg varied widely in the samples. Apart from samples TAS2, TAS3, TPS1, TPS7, TMS2 and TMS3 which fall within the unpolluted to moderately polluted domain ($0 > Igeo \leq 1$), all other samples show no As pollution (Table 11). With Igeo values ≤ 0 for Pb in all samples, the implication is that the soils are not polluted with Pb. All the Igeo values for Cd were 0 indicating that the soils are also not polluted at all with Cd. The samples were unpolluted with lead, arsenic and cadmium because the levels were either below detection or near background concentrations. Igeo is cited for minus anomalies (Qingjie *et al.*, 2011) which was also observed in the values for lead and arsenic as a logarithmic problem. However, Igeo indices for Hg in the soils classify the sites as moderate to strongly polluted, mainly at communities TA and TP. At community TM on the other hand, the soils rather fall within the class of moderately polluted with Hg. The findings here are in sharp contrast to results obtained from e-waste dumpsite soils at the Korle lagoon which significantly showed Igeo up to 8.43 with respect to Cd but safe index for other heavy metals (Fosu-Mensah *et al.*, 2017).

Table 11. Geoaccumulation index of each heavy metal at sample sites.

		Geoaccumulation index (Igeo)			
Community	Site	Hg	Pb	As	Cd
C1	TAS1	-0.4	-3.7	-2.6	0.0
	TAS2	0.0	-3.6	0.7	0.0
	TAS3	2.2	-3.0	0.8	0.0
	TAS4	3.8	-4.8	-0.1	0.0
	TAS5	3.5	-5.6	-1.0	0.0
	TAS6	3.4	-5.0	-0.4	0.0
	TAS7	2.8	-3.5	0.0	0.0
	TAS8	2.7	-3.6	0.0	0.0
	TAS9	4.1	-4.0	-0.8	0.0

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	TPS1	3.7	-4.6	0.1	0.0
	TPS2	3.3	-5.5	-0.2	0.0
	TPS3	3.7	-6.8	-1.0	0.0
	TPS4	3.0	0.0	-1.8	0.0
	TPS5	1.9	-5.2	-1.4	0.0
	TPS6	1.3	-4.6	-1.5	0.0
C2	TPS7	1.3	-5.5	0.3	0.0
	TPS8	0.5	-6.7	-2.4	0.0
	TPS9	2.3	-4.1	-1.0	0.0
	TMS1	1.2	-4.4	-1.9	0.0
	TMS2	0.9	-5.9	0.5	0.0
	TMS3	1.5	-4.7	0.2	0.0
	TMS4	2.0	-5.2	-2.3	0.0
C3	TMS5	1.6	-5.7	-0.9	0.0
	TMS6	0.0	-4.6	-0.5	0.0
	TMS7	1.3	-7.4	-2.0	0.0
	TMS8	0.9	-6.9	0.7	0.0
	TMS9	-0.2	-7.5	-0.1	0.0
	Mean	1.94	- 4.9	- 0.7	0.0

Ecological risk factor. The assessment of the potential ecological risk of the heavy metals (Table 12) shows that with the exception of Hg, all values for As, Cd and Pb at all sites were below 40. This is interpreted as low ecological risk with respect to As, Cd and Pb. The soils are not contaminated with these metals to pose danger to organisms (plants and animals including humans) in the ecosystem. Ecological risk of Pb range from 0 (TPS4) to 0.9 (TAS3); that of As range from below 0 (TAS7 and (TAS8) to 26.6 (TAS3) and that of Cd were all 0. Sites TAS2 was the only area that had low ecological risk factor below 40 for Hg.

Table 12. Ecological risk of each heavy metal at sample sites.

		Ecological risk (Er)			
Community	Site	Hg	Pb	As	Cd
	TAS1	44.8	0.6	2.4	0.0
	TAS2	-2.9	0.6	24.7	0.0
	TAS3	276.9	0.9	26.6	0.0
	TAS4	855.5	0.3	14.0	0.0
C1	TAS5	702.4	0.2	7.3	0.0
	TAS6	645.8	0.2	11.3	0.0
	TAS7	421.0	0.7	-2.0	0.0
	TAS8	401.5	0.6	-1.9	0.0
	TAS9	1034.5	0.5	8.7	0.0

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C2	TPS1	773.3	0.3	15.8	0.0
	TPS2	589.7	0.2	12.9	0.0
	TPS3	797.6	0.1	7.7	0.0
	TPS4	479.8	0.0	4.2	0.0
	TPS5	223.8	0.2	5.8	0.0
	TPS6	144.7	0.3	5.4	0.0
	TPS7	145.7	0.2	18.2	0.0
	TPS8	84.0	0.1	2.8	0.0
	TPS9	298.6	0.4	7.4	0.0
C3	TMS1	142.1	0.3	3.9	0.0
	TMS2	113.8	0.1	21.4	0.0
	TMS3	172.5	0.3	17.7	0.0
	TMS4	248.4	0.2	3.1	0.0
	TMS5	183.6	0.1	8.0	0.0
	TMS6	59.1	0.3	10.4	0.0
	TMS7	143.2	0.0	3.6	0.0
	TMS8	109.8	0.1	24.7	0.0
	TMS9	51.9	0.0	14.0	0.0
	Mean	338.6	0.3	10.3	0.0

In general, the values for Hg range from -2.9 (TAS2) to as high as 1034.5 (TAS9). Values from sites TAS1, TMS6 and TMS9 fall within the moderate potential ecological risk class. Values from sites TPS6, TPS9, TMS1, TMS2, TMS7 and TMS8 fall within the considerable potential ecological risk class. Er results from sites TAS3, TPS5, TPS9 and TMS4 fall within the high potential ecological risk. As many as 10 sites soils have Er values above 320 and indicate very high potential ecological risk with respect to Hg. All organisms within this ecosystem therefore stand the risk of exposure and adverse health implications. Since mercury is the main amalgam in ASGM in the District, the high outputs into the environment will also be confirmed in the other indices. Since mining had escalated and persisted for over a decade in the district, it is imperative that residents are screened, sensitized and provided with the needed medical attention against mercury and arsenic related health conditions. Such an exercise was carried out at Kejetia and Gorogo (Rajaee *et al.*, 2015) to obtain very credible data on accumulated heavy metals due to exposure to ASGM in urine, nails and hairs of volunteers.

Pollution load index and pollution index. The pollution load index by Tomlinson as described by Qingjie and Jun (2008) computed for each site to assess the pollution status of soils by As, Pb and Hg were revealing (Table 13). The values of C_f_PLI were all below 1 (interpreted as perfect or background concentration) except TAS3, TAS4, TAS9 and TPS1 showing 1.4, 1.1, 1.2 and 1.2 respectively. Thirteen (13) site soils recorded Igeo_PLI of 0 suggesting that, they are perfect or unpolluted and thus not adversely impacting soil geochemistry of the communities. However, all the other sites (TAS3, TAS4, TAS5, TAS9, TPS2, TPS3, TPS5, TPS6, TPS8, TPS9, TMS1, TMS4, TMS5 and TMS7) had values above 1 and signal strong contamination. The disagreement between these two algorithms was addressed with the Er_PLI estimated. The PLI based on Er of these heavy metals were found in the range of 0 to 9. By applying the same interpretation to these values, only 4 samples (TAS2, TAS7, TAS8 and TPS4) were perfect. All the other site soils (representing 85.2%) recorded high values (Er_PLI > 1) and therefore are classified as polluted. The highest index (9.0) was observed for TAS3 at community TA within its galamsey enclave. Apart from

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soil at site TMS7 whose status was not clearly categorised by this integrated index, majority of the soils signal progressive deterioration (polluted domain with PLI >1). Although very small concentrations of Pb and Cd might have been detected, they have an additive effect with Hg and As on casualties as evaluated by these integrated pollution indices.

Table 13. Pollution load index and Nemerow's pollution index at each site.

		Integrated Indices			
Community	Site	C_{f}_PLI	C_{f}_$PI_{Nemerow}$	Igeo_PLI	Er_PLI
C1	TAS1	0.4	22.9	0.0	2.8
	TAS2	0.0	17.1	0.0	0.0
	TAS3	1.4	13.2	0.0	9.0
	TAS4	1.1	18.4	1.2	7.5
	TAS5	0.8	11.4	2.1	5.3
	TAS6	1.0	6.3	1.6	6.4
	TAS7	0.0	4.0	0.0	0.0
	TAS8	0.0	3.9	0.0	0.0
	TAS9	1.2	6.2	1.9	8.1
C2	TPS1	1.2	8.1	0.0	7.9
	TPS2	0.9	4.8	1.4	6.0
	TPS3	0.7	5.2	2.2	4.5
	TPS4	0.0	4.7	0.0	0.0
	TPS5	0.6	5.7	1.9	4.1
	TPS6	0.6	4.2	1.7	4.0
	TPS7	0.7	1.8	0.0	4.6
	TPS8	0.3	3.2	1.7	2.0
	TPS9	0.8	3.0	1.8	5.5
C3	TMS1	0.6	1.5	1.8	3.7
	TMS2	0.6	7.6	0.0	4.2
	TMS3	0.8	1.4	0.0	5.5
	TMS4	0.5	1.5	2.2	3.6
	TMS5	0.6	1.2	1.7	3.8
	TMS6	0.6	0.6	0.0	3.7
	TMS7	0.3	0.9	2.1	2.2
	TMS8	0.5	1.2	0.0	3.6
	TMS9	0.3	0.6	0.0	2.3
	Mean	0.6	5.9	0.9	4.1

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The Nemerow pollution indices ($PI_{Nemerow}$) at each site were slightly larger than the Tomlinson model of pollution load indices (PLI) for majority of the samples, which is explained by the algorithm equations and similar to the observation made by Qingjie *et al* (2008). The indices for C_f–$PI_{Nemerow}$ range from 0.6 to 22.9 (Table 14). Comparable to the Er_PLI, as many as 14 sites out of the 27 have reached moderate pollution to severe pollution judging from the criteria of Nemerow. The only sites which were below precaution or within unpolluted status ($PI_{Nemerow}$ < 1) were TMS6, TMS7 and TMS9. With very large pollution index and evidence of wide spatially distribution, the communities in the TAM District are at risk of exposure.

Conclusions

The fear that unregulated ASGM will have severe impact on natural resources and human health is not farfetched. This study has revealed that soil quality of lands 50 m away from mining sites are deteriorating. Heavy metal levels were found in increasing order from Cd < Hg < Pb < As. The direct and indirect discharge of mining waste have resulted in disturbances in soil geochemistry evident in high degrees of contamination by mercury and arsenic (Cd < Pb < As < Hg in increasing order of C_f). The criteria of both Nemerow and Tomlinson agree that soils of all three communities are in a state of very high ecological risk mainly due to high mercury and arsenic levels. These heavy metals have contaminated soils in mining communities of TAM district. Although the findings show that a larger proportion of the soils are contaminated by small doses of the heavy metals, the summation from the PLI place them in slight pollution to severe pollution domains. The implications of these findings are that the ongoing artisanal gold mining has contaminated the hitherto arable lands and existing farmlands close to its operations to levels that require intervention. If this need is neglected, the consequences might be very catastrophic. Mercury and arsenic concentrations are high in the soils. They are very poisonous and causes of deaths, foetal deformities, cancer, chronic infections, severe skin lesions and predisposing other underlining health conditions. Apart from skin contact with soil and ingestion, they can bioaccumulate in pests, plants, food crops and erode into water bodies to pose risks through the food chain. There is the need for prompt action to restore soil quality, improve food security and save lives.

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