Investigating Soil and Water Contamination of Trace Metals in Tarkwa-Nsuaem Municipality, Ghana

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Abstract

Tarkwa-Nsuam Municipality in the Western Region of Ghana has a long history of mining activity. In the Tarkwa area, small-scale mining is found all around; both in the forest and along the rivers. The study aimed at ascertaining the level of heavy metal pollution of water resources and soils in Tarkwa. The general objective of the project was to investigate the extent of health risk posed by heavy metals in mine drainage in the Tarkwa area. Soil and water samples were collected from 15 communities in the Tarkwa mining area and the concentrations in parts per million (ppm) of Mercury (Hg), Arsenic (As), Cadmium (Cd), and Lead (Pb) were determined in each sample using Instrumental Neutron Activation Analysis (INAA). The samples and the controls were irradiated in the Ghana Research Reactor-1 (GHARR-1) at the Ghana Atomic Energy Commission (GAEC), operating at 15KW at a thermal flux of 5×10^{11} n s^{-1} cm^{-2}. Selected communities in the Tarkwa mining area, especially, Teberebie, Mile7, Akyempim, Mile 8, Mile 10½, and Mile 9 however, have their water sources fairly contaminated with elevated levels of arsenic, mercury, and cadmium due to 'galamsey' activities. Since most of the bore holes have very low yields and do not serve the purpose for which they are provided, it is recommended that the focus on construction of bore holes as a cooperate social responsibility of mining companies should be shifted to extension of pipe-borne water rather

Key Words: Arsenic, Cadmium, Lead, Mercury, Galamsey, Gold, Mining, Tarkwa

Introduction

Mining transforms fertile, cultivated land into waste land or bog, and causes serious environmental pollution of land, air and water (Miao and Marrs .(2000). Less developed Countries such as Ghana lack functioning systems of environmental control and supervision of the mining industry (Warhurst, 1994) even in the midst of small-scale and informal enterprises (Warhurst, 1994). The overall impacts of mining activities are severe, but had not been subjected to thorough scientific investigation (Hilson, 2001). The relationship between the environment, more specifically, between the geochemistry of the environment and the health of plants, animals and humans have been appreciated for a considerable period of time, and there is a growing awareness of the significance of such relationships (Bell, 1998). Although geochemical anomalies which affect health occur naturally, humans themselves can adversely affect the environment by the disposal of mine waste such as arsenic, cadmium, mercury and lead (Bell, 1998). Plants that take up heavy metals eventually pass them onto animals and for that matter, humans within the food chain (Keller, 2000). Mining and smelting plants release metals from the bedrock into the environment (Walker and Sibly, 2001). After implementation of an Economic Recovery Programme (ERP) in the 1980s, the mining industry in Ghana saw a phenomenal growth which mainly can be attributed to the adoption of World Bank recommendations that the government leaves the mine operation, management and ownership to the private sector (Addy, 1998). In 1989 the Small Scale Gold Mining Law legalized small-scale gold mining as an industry in Ghana (Hilson, 2002). Tarkwa mining area have the largest agglomeration of mines in Africa (Kusimi, 2007).

In Ghana, there are both small-scale mining and large-scale mining. The general processing techniques are handpicking, amalgamation, cyanidation, flotation, electrowinning and roasting of ore (Akosa et al., 2002). The technique differs between large- and small-scale mining and also varies depending on the type of deposit and its location (Ntibery et al., 2003). The area under study has three main gold deposits: Placer or alluvial deposit, non-sulphidic paleoplacer or free milling ore, and oxidized ore (Kortatsi, 2004). Small-scale miners account for approximately 10% of the gold production in Ghana (Ragnar and Bjorn, 2005). They are locally referred to as galamsey operators (Hilson, 2002). The technique mostly used is amalgamation (Akosa et al, 2002). In this process, mercury is mixed with gold concentrate to form gold amalgam which is heated to separate the gold (Nitibery et al., 2003). This study is focused on an Tarkwa-Nsuam Municipality in the Western Region of Ghana which has a long history of mining activity. This study seeks to ascertain the level of heavy metal pollution of water resources and soils in Tarkwa.

Problem statement and Relevance of the Study

Both legal and illegal small-scale mining is practiced in the Municipality (Avotri et al., 2002). In the Tarkwa area, small-scale mining is found all around; both in the forest and along the rivers. It is practiced all year round and numbered about 20 000 in the Tarkwa mining area. Of these small-scale miners, about 90 % are illegal. As at 2005, 168 small-scale mining concessions were valid in the area (Ragnar and Bjorn, 2005). Major cyanide spillages occurred in 1989, 1991, 1994, 1996, 1999 and 2001 (Akosa et al, 2002). As observed by Ragnar and Bjorn (2005), the concentration of mercury in fish fillets in most communities exceeds the United States Food and Drug Agency limit. Estimated 5 tonnes of mercury is released from small-scale mining operations in Ghana each year (Hilson, 2001). The concentration of mercury in most fish fillets in these areas exceeds the recommendations of the United States Food and Drug Agency (Babut et al., 2003). Heavy metals can have devastating effects on aquatic life and act as metabolic poisons in humans (Keller, 2000).

Mining and smelting plants release metals from the bedrock into the environment (Walker and Sibly, 2001). Tarkwa mining area in the Tarkwa-Nsuaem Municipality of the Western Region has a long history of mining activity. The general processing techniques include, among others, amalgamation, cyanidation, and roasting of ore. The mining activity in the area may cause serious metal pollution to soils and water resources. Earlier studies have shown that metal levels in ground water exceeded WHO guidelines for drinking water in many areas in the Western region (Ragnar and Bjorn, 2005) This represents a threat to public health Therefore, it is important to investigate the level of heavy metal pollution and associated health problems in the Tarkwa mining area..

It is hoped that data and information generated from the research would be useful for effective health risk management for heavy metals, and rehabilitation and restoration of the ecology of other mining areas in the country during and after mining, to promote the health and socioeconomic wellbeing of the local communities. The Environmental Protection Agency (EPA), the Tarkwa-Nsuaem Municipal Assembly, Ministry of Health, and other environmental managers in the mining sector will also find this research very useful. Again, the research will serve as an important reference material for further research into the subject matter.

The general objective of the project was to investigate the extent of health risk posed by heavy metals in mine drainage in the Tarkwa area. The specific objectives of the study are:

- To investigate heavy metal pollution in water resources (both underground and surface water) and soils in selected communities;
- To elicit people's perception about these metal- related problems and the remedial measures being applied in the areas;
- To suggest scientific and technical management approaches appropriate for addressing health risks posed by heavy metal contamination through mine drainage in the local communities. This will include precautionary, preventive and curative measures.

Study Area and Methodology

The study area

Tarkwa mining area is located in the Tarkwa-Nsuaem Municipality (Fig 1) in the Western Region of Ghana. The Municipality lies within latitudes 4°N and 5° 40"N, and 1° 45' W and 2° 10' W. The total land area of the district is 92,354 km^2 (Kusimi, 2007).

MAP OF THE STUDY AREA

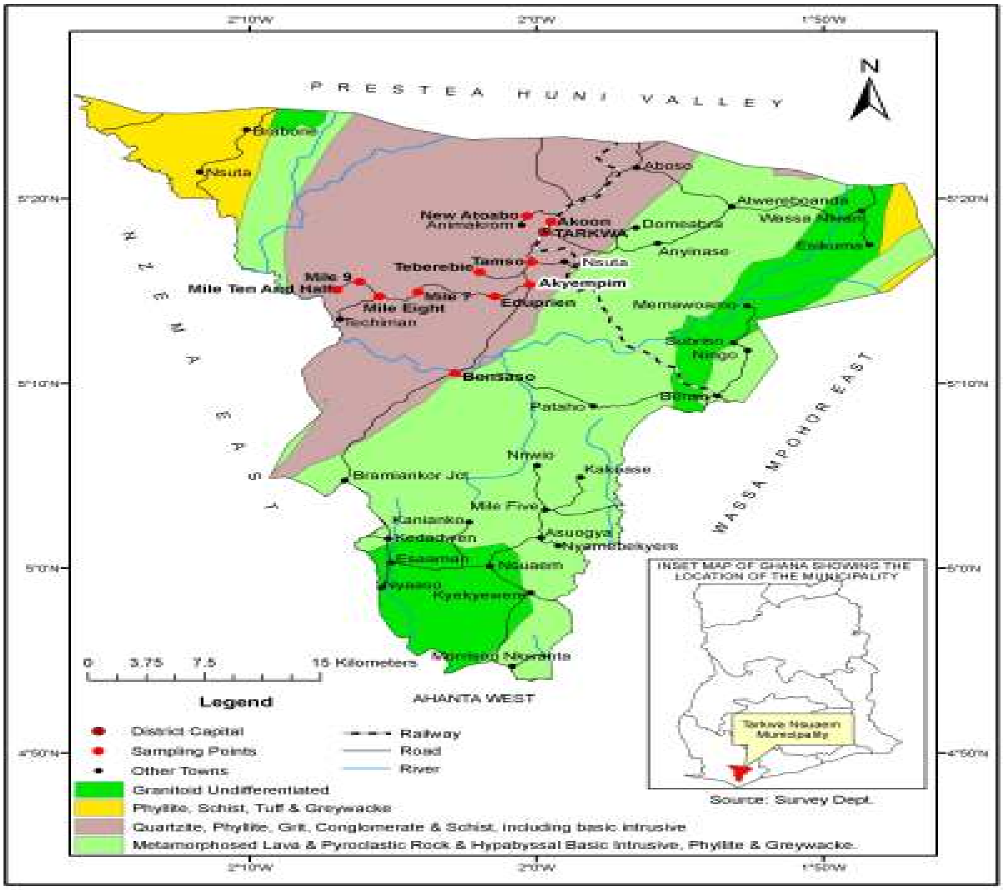

Fig 1: Map of Tarkwa-Nsuaem Municipality

Research Methodology

The methodology consisted of a desk study, primary data collection, and field and laboratory studies. The desk study was a literature review of works that have relevance to the subject matter at the community, district, regional, and national levels; and also in other African countries and elsewhere in the world. The primary data collection involved laboratory study by collection of soil and water samples from fifteen communities within the Tarkwa mining area. The water samples were stored in clean plastic bottles, and the soil samples in dry carriage bags and all transported to the Ghana Research Reactor-1 (GHARR-1) premises in Accra for analysis. A detailed description of how the samples were prepared and analyzed is provided in chapter four of this report.

Soil and water samples were collected from 15 communities in the Tarkwa mining area and the concentrations in parts per million (ppm) of Mercury (Hg), Arsenic (As), Cadmium (Cd), and Lead (Pb) were determined in each sample using Instrumental Neutron Activation Analysis (INAA). In addition, hundred individuals selected at random from the local communities were interviewed using a questionnaire survey to elicit their perception about heavy metal-related problems and the remediation measures being applied in the study area, and also to examine the exposure pathways of the heavy metals and how that differ among people in the local communities. Analytical treatment of data was made in Excel, and Arcview. When analyzing in Arcview, values below the detection limit were set to zero.

Sample collection

Soil and water samples were collected from fifteen communities within the Tarkwa mining area. The soil samples were collected from farmlands at a depth of 0-20 cm using hand auger and plastic trowel. The samples were stored in dry polythene bags and sent to the Ghana Research Reactor-1 (GHARR-1) laboratory at Ghana Atomic Energy Commission (GAEC) for analysis. The water samples were collected from both underground (wells and boreholes) and surface (streams and ponds) sources. The samples were collected into clean plastic bottles (obtained after thorough rinsing) and carried to the GHARR-1 laboratory for analysis.

Sample preparation

The soil samples were air dried for five days. They were then ground and homogenized after which they were sieved through a micro mesh of size 180 μm to obtain fine grains. 100 mg of soil sample was weighed in six folds for each test material on a clean polythene film, folded with forceps and heat-sealed with a hair dryer. Each sample was in turn put into a rabbit capsule and smoothly heat-sealed with a soldering rod. Standard Reference Materials IAEA-Soil 7 and Estuarine Sediment were equally weighed as the test samples.

For water samples, 500 mg was transferred into small (rabbit) capsules, heat-sealed and the small capsules packed into larger ones and smoothly heat-sealed (double encapsulated) using soldering rod. The standards were single standard elements and were prepared into 10 ppm, 20 ppm, and 50 ppm for validation and NAA comparator method.

Sample irradiation, counting, and analysis

The samples and the controls were irradiated in the Ghana Research Reactor-1 (GHARR-1) at the Ghana Atomic Energy Commission (GAEC), operating at 15KW at a thermal flux of 5×10^{11} n s^{-1} cm^{-2}. The samples were transferred into irradiation sites via pneumatic transfer system operating at a pressure of 0.60 mpa. The irradiation was done according to the half lives of the elements of interest. All the elements of interest- Hg, Cd, and As are medium lived hence, both the water and soil samples were irradiated for one hour and delayed for 24 hrs, with 10 mins counting time.

After the irradiation, radioactivity measurement of the induced radionuclide was performed by a PC- based gamma ray spectrometry set-up which consists of an n-type HPGe detector, coupled to a computer based multi-channel analyzer (MCA) via electronic modules. The relative efficiency of the detector is 25% and its energy resolution is 1.8 keV at gamma ray energy of 1,332 keV, belonging to ^{60}Co. Through appropriate choice of cooling time, detector's dead time was controlled to be less than 10%. Identification of the gamma ray of product radionuclide was done using the energies and the quantitative analysis of the elements was achieved by the use of gamma ray spectrum analysis software, ORTEC MEASTRO-32. The quantitative analysis involved the conversion of the area under the photo peaks of the identified elements into concentrations.

For the determination of lead, 1.5 g of soil sample and 5.0 ml of water sample were digested in a microwave oven at a maximum power of 450 W for 10s, using a Teflon closed Parr bomb. The reagents used included a combination of 6.0 ml of 65% HNO_3, 3.0 ml of 35% HCl, and 0.25 ml of 30% H_2O_2. After that, samples were filtered carefully through Whatman 541, and quantitatively transferred into 50 ml plastic flasks and undertaken to AAS measurements.

Results and Discussion

The concentrations of arsenic, cadmium, mercury, and lead in μg/g for soil and mg/l for water as obtained from the laboratory analysis are shown in Figs. 2 and 3. The sampling points are represented with the letters A-O. In all cases Akoon was choosing as the control site and the remaining sites as experimental sites. All sampling sites were located at Tarkwa Nsuaem district.

The sampling points for soil are:

A= Mile 8, B= Naboaso (Tarkwa), C= Post Office Sq.(Tarkwa), D= Tamso, E=Eduprien, F= Awunaben Basin, G= Akoon, H= Akyempim, I= Teberebie, J= Mile 9, K= New Atuabo, L= Mile 7, M= Bonsaso, N= Mile 10½, O= Old Town (Tarkwa).

The sampling points for water are:

A= Mile 8 (borehole), B= Akyempim (Well), C= Mile 10½ (stream), D= Tamso (bore hole), E= Eduaprin (pond), F= Mile 8 (stream), G= Teberebie (borehole), H= Akyempim (stream), I= Akoon (borehole), J= Mile 9 (well), K= New Atuabo (borehole), L= Mile 7 (borehole), M= Bonsaso (River Bonsa), N= Mile 10½ (borehole), O= New Atuabo (well).

Discussion for soil

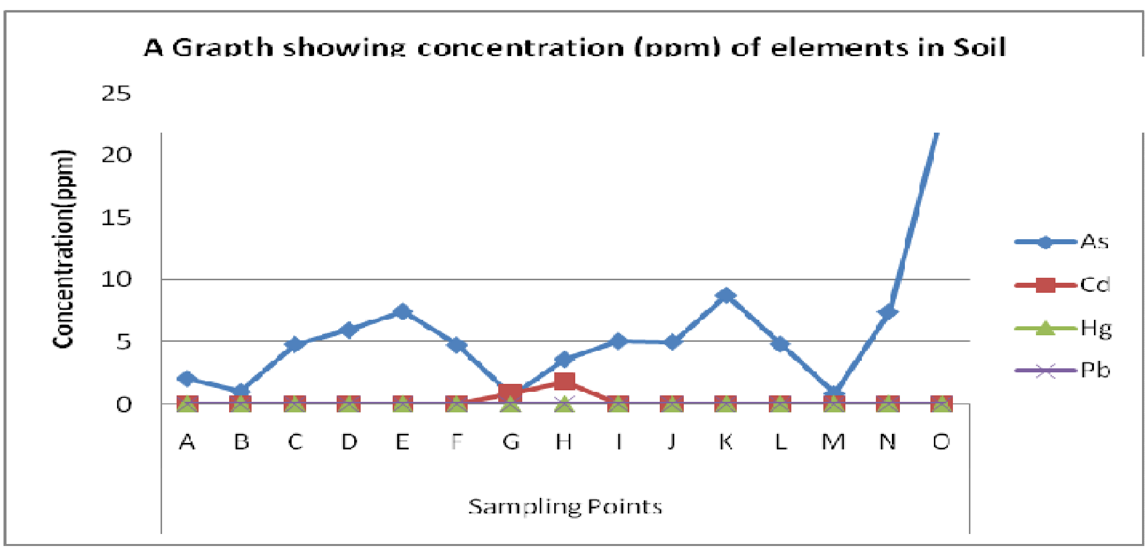

Fig. 2: A graph showing concentration (ppm) of elements in soil

This discussion was based on the premise that quality control bodies such as International Atomic Energy Agency (IAEA) have come out, after a series of research, with specific guidelines regarding heavy metal (trace element) concentration in soils; and that at concentrations higher than the guideline value, there is the possibility of plants (including crop plants) taking up these metals and eventually transferring them to humans through the food chain. Fig 2 above shows the concentration of Arsenic, Cadmium, Mercury, and Lead in soil samples picked at 15 locations within the Tarkwa Mining Area.

Arsenic

Arsenic concentration in soil ranges from 0.65 μg/g to 23.78 μg/g (Fig 2). The highest concentration was obtained at Old Town (Tarkwa). The least concentration of 0.65 μg/g was recorded at Akoon which was the control site and had no mining activity. The second highest concentration (8.75 μg/g) occurred at New Atuabo. New Atuabo and Old Town lie along the same geological plane with a steep slope and the fact that the two stations recorded high arsenic concentrations can be explained by the geology of the area and not the mining activity in the area. Arsenic level in soil increased from Tamso (5.95 μg/g) to Eduprien (7.44 μg/g); it then decreased from Teberebie (5.07 μg/g) to Mile 9 (5.00 μg/g), and further to 4.82 μg/g at Mile 7. However, the concentration fluctuated again to 7.40 μg/g at Mile 10½. The decrease trend may be due to geological factors whilst the sharp increase could be blamed on some anthropogenic factors. The IAEA-Soil-7 recommended value for arsenic concentration in soils is 13.50 μg/g. This implies that only the control site had arsenic levels below the IAEA guideline value. The high arsenic concentration recorded at Old Town can be blamed on the fact that the sampling point used to be a refuse dump hence; there could be some other anthropogenic introduction of arsenic into the soil besides mining.

Mercury

The highest mercury concentration in soil (0.05 μg/g) occurred at Mile 10½. This was followed by Mile 8 which recorded 0.03 μg/g (*Fig.2)*. Nine stations including Akoon had mercury levels less than 0.01 μg/g. Stations where mercury was detected- Mile 10½, Mile 8, Eduprien, Teberebie and Bonsaso are places where galamsey operations are very common. The IAEA-Soil-7 recommended value for mercury level in soils is 0.04 μg/g. This means that all the stations have mercury levels within limits except Mile 10½ which had a concentration (0.05 μg/g) slightly above the recommended value. The sample was taken from a farmland. However, a critical observation of the trend of mercury occurrence in soils in the study area shows that mining activities, especially galamsey operations, play a significant role in mercury concentration in soils in the study area.

Cadmium

Cadmium level in soils at all the stations including Akoon was less than 0.01 μg/g except at Akyempim which recorded 1.82 μg/g (*Fig.2)*. The low concentrations could be due to geological factors. The IAEA-Soil-7 recommended value for cadmium concentration in soils is 1.30 μg/g. Akyempim had a concentration of 1.82 μg/g which is above the IAEA guideline value and the control site of (0.86). This isolated case could be due to variations in the geochemistry of the place. Generally, it could be seen from the results that though these are typical mining areas, mining activities do not have any significant effect on soil cadmium levels in the study area.

Lead

Lead concentration in all the samples including that of Akoon was below 0.01 µg/g (Fig 2). The low concentration is probably due to the minute quantities in which lead minerals occur in the rocks of the area. The IAEA-Soil-7 recommended value for lead concentration in soils is 60.00 µg/g. This means that the recorded concentrations are far below the IAEA guideline value. Hence, no soil contamination in terms of lead is occurring in the study area.

Discussion for water

The discussion is based on the premises that specific guidelines are given by the WHO for heavy metal concentration in drinking water and that by the intake of certain concentrations known as the lethal dose, heavy metals can have fatal consequences on the victim.

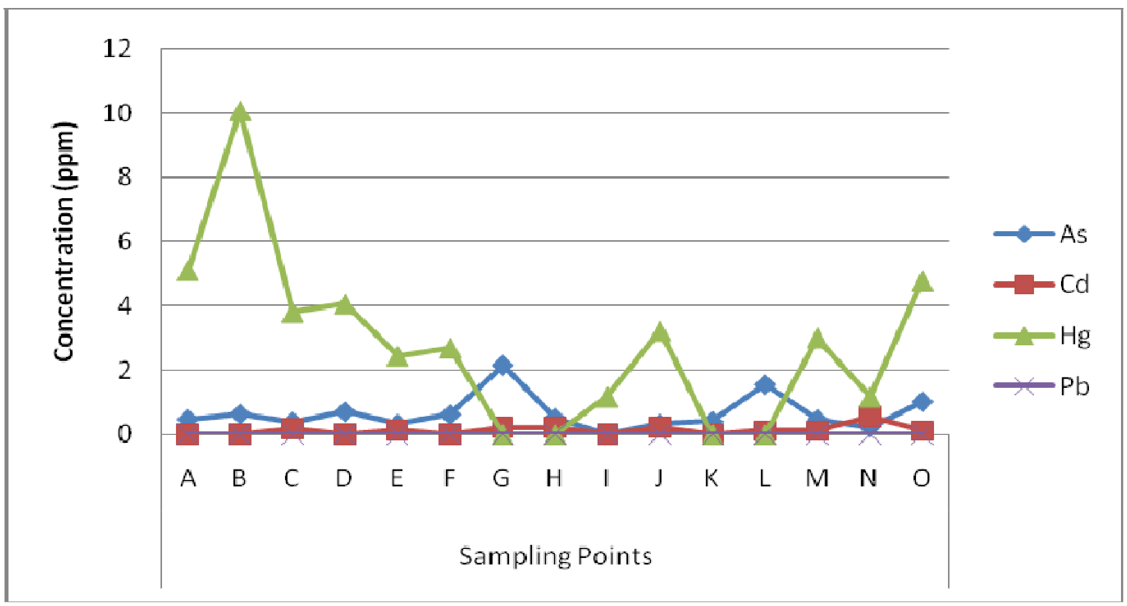

Fig. 3: A graph showing concentration (ppm) of elements in water

Arsenic

Concentration of Arsenic at the 15 sampling points ranges from <0.01 mg/l to 2.14 mg/l (*Fig 3)*. The highest concentration, 2.14 mg/l was recorded at Teberebie (bore hole) and the lowest concentration of less than 0.01 mg/l was recorded at Akoon (bore hole). Concentration of As in ground water declines from Tamso (0.70 mg/l) to Akyempim (0.63 mg/l), and to Mile 8 (0.47 mg/l); then finally, to Mile 9 (0.32 mg/l). Given the fact that Mile 10½ recorded a concentration of 0.22 mg/l, the sequential decline in concentration could be due to geological factors. However, Mile 7 which is located between Akyempim and Mile 8 recorded a higher arsenic level of 1.54 mg/l. This gives a strong suspicion of an anthropogenic cause such as mining. Furthermore, streams sampled at Akyempim and Mile 8 contained higher arsenic levels than the groundwater counterparts. This could be attributed to the fact that these streams are used for gold processing by the local miners; hence, introduction of chemicals into them is possible.

The WHO guideline value for arsenic concentration in drinking water is 0.01 mg/l (WHO, 2006). The body has its own mechanisms of breaking down and eliminating trace elements especially through urine. However, if the rate of intake exceeds the rate of elimination, accumulation occurs in the soft tissues, posing threats of metal intoxication and metal-induced diseases. The International Agency for Research on Cancer (IARC, 1994a) has determined that inorganic arsenic is carcinogenic to humans.

Mercury

Mercury concentration as observed from Fig. 3 ranges from <0.01 mg/l to 10.07 mg/l. The highest concentration (10.07 mg/l) occurred at Akyempim in a well. The second highest concentration was 5.09 mg/l, and this was recorded at Mile 8 in a bore hole; followed by New Atuabo which recorded a concentration of 4.78 mg/l also in a well. Concentrations less than 0.01 mg/l being the lowest occurred at Akoon, Mile 7, and New Atuabo, all in bore holes. This suggests that bore holes at these stations are quite safe for consumption. The disparity in mercury concentration between the well and the bore hole sampled at New Atuabo may be attributed to changes in groundwater flow and geological factors. The well is much shallower and is likely to receive contaminated water emanating from disturbances caused to the rock matrix through mining activities, especially galamsey operations.

The WHO guideline value for total mercury in drinking is 0.001 mg/l (WHO, 2006). With the exception of four stations which had mercury concentrations below the detection limit, all other stations have concentrations far above the WHO guideline value. Research has shown that naturally occurring levels of mercury in groundwater and surface water are less than 0.5 µg/l (Bell, 1998). This gives a strong signal that the hike in mercury concentration in the study area is due to anthropogenic causes mainly, mining.

Cadmium

Six stations including Akoon out of the fifteen, have cadmium concentrations below the detection limit (<0.01 mg/l), suggesting that cadmium is either completely absent in the samples or the concentrations are extremely low. The highest concentration was 0.55 mg/l recorded at Mile 10½ while the least recorded concentration was 0.11 mg/l, occurring concurrently at Mile 7, New Atuabo, and Bonsaso (*Fig 3).* The WHO guideline value for cadmium in drinking water is 0.003 mg/l (WHO, 2006). This means that all the stations where Cd was detected, the concentrations are well above the WHO recommended value.

Lead

Laboratory analysis for lead in the 15 samples including Akoon taken from various locations within the study area was very low (*Fig 3).* Not a single station had Pb concentrations equal to or above 0.01 mg/l which is the WHO guideline value, and of course, the detection limit of the equipment used. This implies that either Pb is completely non-existent in the samples or the concentrations are extremely low.

Summary of Findings, Conclusions and Recommendation

Heavy metal concentrations in the Tarkwa mining area, especially in soils, were generally lower than expected of a typical mining area. The results of the study showed that except for isolated cases at Old Town, Akyempim, and Mile 10½ respectively, arsenic, cadmium, and mercury, levels in soil were far below the limits set by the International Atomic Energy Agency- Soil-7 and in most cases higher than the control site (Akoon). Lead was within limits in both water and soils at all the sampling stations. It may, therefore, be concluded that contamination of soils by the named heavy metals was as a result of geological and anthropogenic activities like small scale mining.

On the other hand, analysis of water samples showed that concentration of arsenic exceeded the WHO guideline value at 14 out of the 15 sampling stations; mercury exceeded it at 11 stations, and Cadmium, at 9 stations out of the 15. The highest concentration of As in water was 2.14 mg/l (Teberebie) as against the WHO guideline value of 0.01 mg/l; mercury was 10.07 mg/l at Akyempim as against the WHO guideline value of 0.001 mg/l; and that of cadmium was 0.55 mg/l, recorded at Mile 10½ as against the WHO guideline value of 0.003 mg/l. The high levels of metals in ground water suggest that gold refinery by small scale miners infiltrate into ground water and pose a health hazard to the people of Tarkwa. All these concentrations occurred in groundwater (boreholes and wells) which, according to a survey carried out during this research, serves as the main source of potable water for the people in the study area.

The results of the soil and water analysis led to the conclusion that:

1. There is no evidence of serious metal contamination of agricultural soils in terms of As, Hg, Cd, and Pb in the Tarkwa mining area.

2. Selected communities in the Tarkwa mining area, especially, Teberebie, Mile7, Akyempim, Mile 8, Mile 10½, and Mile 9 however, have their water sources contaminated with elevated levels of arsenic, mercury, and cadmium due to 'galamsey' activities.

3. Many people in the study area perceive mining activities, especially 'galamsey' operations, as having serious health implications yet they do not seem to be taking any precautions to avert the risks.

4. An intersectorial approach involving the Traditional Authorities, Ministry of Water Resources and Housing, Ministry of Lands and Forestry, Ministry of Food and Agriculture, Ministry of Environment, Science and Technology and Ministry of Local Government and Rural Development are needed to restore degraded lands (Odum, 1969; Qin et al., 1997; Li and Lai, 1994) in Tarkwa and mining areas in Ghana.

6.2 Recommendations

Based on the research findings and the conclusions drawn, it is recommended that:

1. Diagnostic testing for metal toxicity (preferably hair or urine test) should form an integral part of the daily clinical services so as to detect as early as possible, any incidence of metal intoxication to forestall detrimental consequences.
2. Periodic analysis of water sources in the area should be done to ascertain the concentration levels of heavy metals so that the local people as well as the miners could be advised accordingly.
3. There should be intensified education on precautionary measures to be taken by miners, especially galamssey workers (e.g.wearing of overalls, hand gloves etc., avoiding spillage, etc.) when dealing with chemicals such as mercury.
4. The Central Government and the Municipal Assembly should make frantic efforts to ensure that part of the income accruing from the mineral resource is used to extend pipe-borne water, as it is in the Tarkwa Township, to all the mining villages to ensure the safety and good health the local people.
5. Mining companies should adopt Passive Treatment methods such as natural and artificial wetlands in dealing with Acid Mine Drainage cases since the method is not only cost effective, but also very efficient in removing heavy metals from mine waste water.
6. Government and the Environmental Protections Agency (EPA) should be more proactive in the enforcement of mining environmental guidelines to ensure compliance by both large and small scale miners.
7. The Environmental Management Plan of the mining companies should be made public so that citizens can hold the companies responsible if they go contrary to what they stated on paper.
8. Since most of the bore holes have very low yields and do not serve the purpose for which they are provided, the focus on construction of bore holes as a cooperate social responsibility of the mining companies should be shifted to extension of pipe-borne water rather
9. In cases of accidental chemical spillage, security arrangements should be permanently put in place by the mining company concerned to ensure that the local people, especially women and children, do not fetch the affected stream for domestic use.
10. Further research is needed to find the levels of metals in plants and food crops and also identify the steps to restore the degraded lands in Tarkwa and other mining communities for economic use.
11. There should be a collaborative effort between governmental and nongovernmental organizations towards reducing the impact of mining on the environment.

REFERENCES

Addy, S. N. (1998). 'Ghana: revival of the mineral sector', Resource policy, vol. 24, No.4, pp. 229-239

Agency for Toxic Substances and Diseases Registry (ATSDR) (2007). *Toxicological Profile for Lead.* US Department for Health and Human Services. pp. 1-4.

Akosa, A. B., Adimado, A. A., Amegbey, N. A.,. Nignpense, B. E.., Carboo, D., and Gyasi, S. (2002). Report submitted by Cyanide investigation committee, Ministry of Environment and Science.

Avotri, T. S. M., Amegbey, N. A., Sandow, M. A. and Forson, S. A. K. (2002). The health impact of cyanide spillage at gold fields Ghana Ltd., Tarkwa.

Babut, M., Sekyi, R., Rambaud, A., Potin-Gautier, M., Tellier, S., Bannerman, W. and Beinhoff, C. (2003). 'Improving the environmental management of small-scale gold mining in Ghana: a case study of Dumasi', Journal of cleaner production, vol. 11, pp. 215-221.

Bell, G. F. (1998). *Environmental Geology: Principles and Practice.* Blackwell Science Ltd. Osney Mead, Oxford, UK, pp 487-489.

Hilson, G. (2001). 'A Contextual Review of the Ghanaian Small-scale Mining Industry', Mining, Minerals and Sustainable Development, no. 76.

Hilson, G. (2002). 'Promoting sustainable development in Ghanaian small-scale gold mining operations', The Environmentalist, vol. 22, pp. 51-57.

International Agency for Research on Cancer (IARC), Lyon (1994). Arsenic and Arsenic Compounds, IARC Monographs on the Evaluation of Carcinogenic Risk to Humans, Vol. 58.

International Agency for Research on Cancer (IARC), Lyon (1994). Mercury and Mercury Compounds, IARC Monographs on the Evaluation of Carcinogenic Risk to Humans, Vol. 58.

Keller, E.A.(2000). *Environmental Geology* (8^{th} ed.). Upper Saddle River, Prentice Hall, N.J.

Kelly, M. (1988). *Mining and the Freshwater Environment*. Elsevier Applied Science. Amsterdam, The Netherlands. pp 22-30

Kortatsi, B. K. (2004). *Hydrochemistry of groundwater in the mining areas of Tarkwa-Prestea, Ghana.* PhD Thesis, University of Ghana, Legon-Accra.

Kusimi, J. M. (2007). *Groundwater Hydrochemistry and Land cover Change in the Wassa West District of Ghana.* Royal Institute of Technology, Stockholm, Sweden. pp 5-8.

Li, W. and Lai, S. (1994). Agroforestry in China, pp. 38–54. Beijing: Scientific Press of China.

Miao, Z.,Marrs, R.(2000). Ecological restoration and land reclamation in open-pit mine of Shanxi Province, China. Journal of Environmental Management 59: 205–215.

Nitibery, B. K., Atorkui, E. and Aryee, B. N. A. (2003). 'Trends in small-scale mining of precious minerals in Ghana: a perspective on its environmental impact' Journal of Cleaner production, vol. 11, pp.131-140.

Odum, E. P. (1969). The strategy of ecosystem development. Science 164, 262–269.

Qin, P. L., An, S. and Yan, J. (1997). The Sciences of Ecological Engineering, pp. 60–65. Nanjing: Nanjing University Press.

Ragnar, A. and Bjorn, E. (2005). *Contamination of water resources in Tarkwa mining area of Ghana.* Department of Engineering Geology, Lund University, Lund.

Walker, H. and Sibly, P.(2001). *Principles of Ecotoxicology*. Tailor and Francis, London, p.23 .

Warhurst, A. (1994). The limitations of environmental regulation in mining. In: *Mining and the Environment. International Perspectives on Public Policy*. Eggert, R.G. (ed.). Resources for the Future, Washington DC, USA. p.56

World Health Organization (WHO) (2006). *Guideline values for Drinking Water Quality*. WHO, Geneva.