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# Natural radioactivity and heavy metal distribution in reservoirs in Ghana

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**ABSTRACT:** The present paper has determined the radioactivity concentrations, which are due to natural occurrence of radionuclides along with heavy metal concentration in water, sediment, and fish from 2 reservoirs in Ghana. Heavy metal concentrations in all samples were generally within the WHO safe limits with the average activity concentrations of $^{238}$U, $^{232}$Th, and $^{40}$K in water being respectively 0.42±0.20, 0.33±0.31, and 1.59±1.07 Bq/L in case of Lake Bosomtwe and 0.26±0.14, 0.67±0.34 and 1.47±0.62 Bq/L for Bui Dam in Ghana. The average annual effective dose due to ingestion of radionuclides in water ranged from 20.5 to 156 for Lake Bosomtwe and 26.5 to 162 μSv/year for Bui dam and the absorbed dose rate and annual effective dose, measured for Lake Bosomtwe, was 15.45±2.00 nGy/year and 18.95±2.95 μS/year respectively while in case of Bui dam it accounted to 10.44±4.11 nGy/year and 12.88±5.01 μS/year respectively, found to be within the UNSCEAR recommended limits of 59 nGy/year and 100 μS/year respectively. The observed metal concentrations, within safety limits, imply that metal-associated diseases cannot be expected among patrons of these reservoirs. Therefore, radionuclides and heavy metals levels in the reservoirs are not expected to cause any significant health problem for humans.

**Keywords:** Bosomtwe, Bui, dose, hazard, health risk, pollution.

## INTRODUCTION

Human beings are often exposed to radiations from naturally-occurring radioactive substances, found in the environment. Further exposure comes from food and drinking water. Water from sources, rich in naturally-occurring radioactive materials exhibit high levels of radioactivity (Akoto et al., 2011; Pakade et al., 2012). Natural waters contain isotopes like $^{226}$Ra, $^{232}$Th, $^{137}$Cs and $^{238}$U, $^{40}$K, which are more abundant in the environment. During the process of radioactive decay, these radionuclides can emit alpha (α), beta (β), and gamma (γ) radiation (Khayet & Matsuura, 2013).

Ingested radionuclides are usually absorbed into the bloodstream and accumulate in tissues such as the kidneys and bones from where they exert both chemical and radioactive toxicities (Avwiri et al., 2007; Bonotto et al., 2009). Even small concentrations of a radioactive substance may have the ability to produce a damaging

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biological effect (El-Mageed et al., 2011). Exposure to low levels of radioactivity has been associated with forms of leukaemia and many other types of cancer (Degerlier & Karahan, 2010; El-Mageed et al., 2011). Estimation of radiation doses in the environment is, therefore, important in the assessment of health-related risks to the population, serving as the baseline for checking changes in environmental radioactivity due to anthropogenic activities. The concentrations of the radionuclides as well as their associated health risks in the environment require a particular attention as a result of their high radiotoxicities. Thus, it is important to determine the activities of radionuclides in drinking water as exposure to them is harmful to human health. Information about the people's exposure to radiations through drinking water and food will therefore affect decisions to set and maintain safety standards. Earlier studies, dealing with radionuclides in water in Ghana, include distribution of radionuclides in the lower basin of River Pra (Adukpo et al., 2014a) and underground water in Kumasi (Darko et al., 2014b).

Pollution of the aquatic environment, as a result of high concentrations of heavy metals, has also become a global issue. Metals, which are indestructible and persistent in the environment, tend to accumulate in the ecosystem and exert toxic effects on living organisms like humans. Fish has been identified as a good bio-indicator of pollutants in the aquatic environment due to their feeding habits. High concentrations of heavy metals in the bottom sediments of a water body could be a good indicator of human-induced pollution. Knowledge of the concentrations and distribution of the heavy metals and radionuclides in water, fish, and sediments is important, since it provides useful information to evaluate environmental quality and monitor the contaminants and their effects on living organisms. Some of the recent studies, focusing on heavy metals in reservoirs of the country, include Akoto et al. (2008) on the Owabi reservoir, Asante et al. (2014) on the Red Volta, and Adu et al. (2011) on Lake Bosomtwe. In this work, we have determined the activity of some naturally-occurring radionuclides ($^{238}$U, $^{232}$Th and $^{40}$K) in water and sediments, and the concentrations of heavy metals in water, fish, and sediments from two reservoirs (Lake Bosomtwe and Bui Dam) in Ghana. Health risks, associated with the consumption of heavy metals in fish and water, as well as hazard indices due to radionuclides in the reservoirs have also been deduced.

## STUDY AREA

Lake Bosomtwe is a natural inland lake in the Ashanti Region of Ghana, between longitudes 01° 25′ W and latitudes 06° 32′ N, with a radial drainage system of 106 km$^2$ and a diameter of about 11 km at its widest part and a maximum depth of 78 m. Lake Bosomtwe covers an area of about 52 km$^2$. There are 24 communities around the lake, relying heavily on fishing for income and food, as well as water for household use and farm irrigation. The Bui Dam, on the other hand, is a man-made hydroelectric dam, built on the Black Volta River in the Bui Gorge. The reservoir floods about 20% of the Bui National Park and impacts the habitats for the rare black hippopotamus as well as a large number of wildlife species. Water from the lake is used by the indigenous groups as a source of drinking water and irrigation as well as for transportation, to connect various communities along the lake. Eleven sampling sites have been randomly selected out of the 24 communities, surrounding Lake Bosomtwe (Fig. 1) to represent the entire catchment area in addition to 5 sampling sites, at Bui Dam to represent the area.

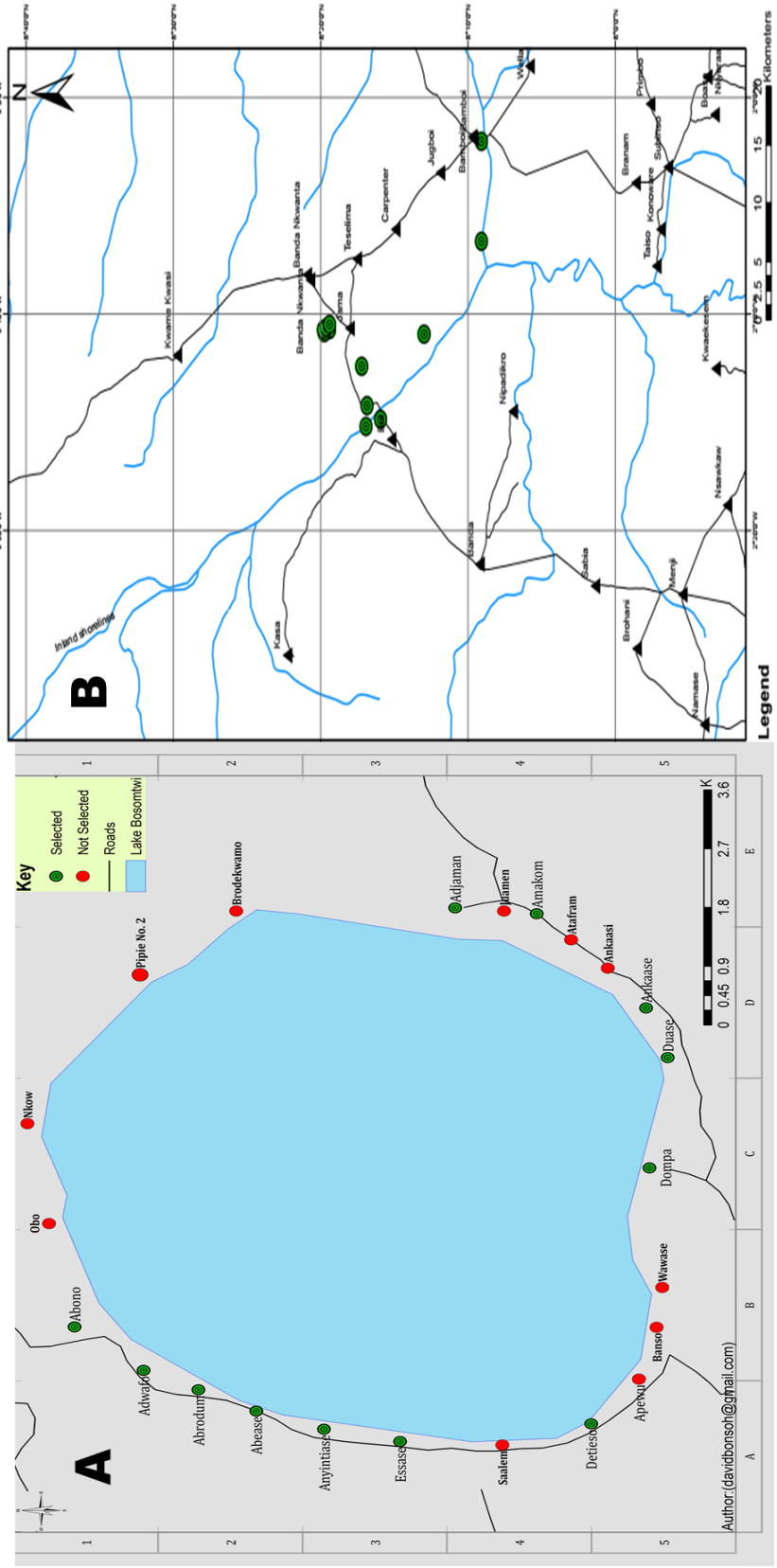


**Fig. 1. Map showing sampled communities around Lake Bosomtwe (A) and on the Bui dam (B)**

## MATERIALS AND METHODS

### Sampling and sample preparation

Water samples (n= 64) from the reservoirs were collected at the selected sampling points, using a spot sampling equipment with 1.5 l of aliquots, stored in previously-cleaned bottles to the brim, without any top space for radioactivity and heavy metal concentration measurements in the laboratory. Similarly, 64 sediment samples were collected (up to about 10 cm deep), using a sediment auger along with 56 fish samples, which were stored in ice and transported to the laboratory. The average mass and length of fish samples from Lake Bosomtwe were 11.0 cm and 15.30 g respectively, while these rates for Bui Dam accounted to 14.6 cm and 52.60 g. Samplings at the 2 reservoirs were conducted in May-June, 2014 (1st batch) and October-November, 2014 (replicate). Physical parameters, such as temperature, pH, conductivity, and TDS of the water samples were determined in-situ (on site) using a pH/Conductivity/TDS meter, coupled with an HI98129 glass electrode (Hanna, USA). In the laboratory, sediment samples were air-dried for 3 days, homogenized, and then oven-dried at 105°C to a constant weight. They were then crushed into fine powder with a ball mill, sieved through a 2 mm pore size mesh, and were finally stored. The fish samples were oven dried at 105°C to a constant weight and then ground into powder using mortar and pestle to be stored in paper envelopes for further processing.

### Digestion of samples for metal analysis

Water samples were acid-digested prior to being analysed with atomic absorption spectrophotometer. A sum of 40 ml aliquot of water was mixed with 5 ml of aqua regia and 0.25 mL of $H_2O_2$. The mixture was digested on a hotplate at 60°C for 3 hours under reflux. Upon cooling, the digested sample was filtered into a 30 ml volumetric flask and made up to the graduated mark, using distilled water. Metal concentrations were then determined using a Varian AA240FS atomic absorption spectrophotometer. While Cd, Pb, Zn, Cu, Fe, Mn, Ni, Co, and Cr were analysed in an acetylene-air flame (Welz & Melcher, 1985), the analysis of As and Hg took place by means of hydride method, using argon and air (Cai, 2000; Liang et al., 2003). Metal concentrations were found from calibration curves of the working standards. Reagent blanks were used to zero the instrument, following manufacturer's recommended calibrations. The detection limits found from 3δ were: 0.002, 0.005, 0.003, 0.006, 0.002, 0.001, 0.001, and 0.001 mg/L for Cd, Co, Cu, Fe, Mn, Ni, Pb, and Zn respectively.

Sediment and fish samples were analyzed, using a Niton XL3 X-ray fluorescence (XRF) analyzer, in accordance with the United States' Environmental Protection Authority Method 6200, Field Portable X-Ray fluorescence spectrometry for measurements of elemental concentrations in sediments (US-EPA, 2007). The instrument was calibrated, with regards to the manufacturer's standards, and system-checked prior to use. An aliquot (~2 g) of 45 µm sieved sample was placed in a 30 mm polyethylene container, sealed with a Mylar film. The sample was then placed in the XRF shroud and scanned for 180 seconds.

### Biota-sediment accumulation factor

Biota Sediment Accumulation Factors (BSAF) were calculated for the fish to evaluate the extent of metal bioaccumulation in its tissues, being measured as the ratio between a metal's concentration in both the fish muscle and the sediment.

### Index of geo-accumulation

Müller's geo-accumulation index (Igeo) was used to measure the pollution intensities of metals in aquatic sediments. The index is a qualitative scale of pollution intensity, classifying the samples as unpolluted (Igeo< 0), unpolluted to moderately polluted (0≤ Igeo ≤1), moderately polluted (1≤ Igeo≤ 2),

moderately to strongly polluted (2≤ Igeo≤ 3), strongly polluted (3≤ Igeo≤ 4), strongly to extremely polluted (4≤ Igeo≤ 5), and extremely polluted (Igeo≥ 5). Igeo was determined using Equation (1).

$$I_{geo} = \log_2\left[\frac{C_S}{1.5 \times C_B}\right] \quad (1)$$

where $C_S$ is the concentration of an element in the sample and $C_B$, the natural background concentration. Natural background concentrations in use were Cr= 90 mg/kg; Fe= 4.67 mg/kg; Mn= 850 mg/kg; Cu= 45 mg/kg; Zn= 95 mg/kg; Co= 15 mg/kg; Cd= 0.3 mg/kg; As= 18 mg/kg; Pb= 20 mg/kg; Hg= 0.2 mg/kg; and Ni= 68 mg/kg (Boszke et al., 2004).

**Contamination factor**

The extent of anthropogenic pollution and accumulation of heavy metals in sediments was estimated through the contamination factors (CF), which can be calculated as the ratio between the concentration of a certain metal in sediment to that of natural background (Banu et al., 2013). Contamination is classified as: low (CF<1), moderate (1≤CF<3), considerable (3≤CF≤6), and high (CF>6).

**Pollution load index**

Pollution Load Index (PLI) is used to assess sediment quality, thus allowing us to know the pollution intensity. PLI is calculated as follows:

$$PLI = \left(CF_1 \times CF_2 \times CF_3 \times ... \times CF_n\right)^{\frac{1}{n}} \quad (2)$$

where n is the number of the studied metals and CF, the contamination factor of each metal on the site. The PLI range and pollution intensity are classified as perfect (<1), baseline (1), or deterioration (>1) (Banu et al., 2013).

**Activity measurement in sediment samples**

Dried sediment samples were transferred into 1.0 l Marinelli beakers (Deutsher Kalibrierdient-3 QSA Global GmBH, Germany), weighed to determine the mass, and then sealed and stored in the laboratory for 30 days to allow the secular equilibrium between the long-lived parent radionuclides of $^{238}U$ and $^{232}Th$ decay series and their short-lived daughter radionuclides. Activity concentrations were determined on a Canberra 1510 high resolution gamma-spectrometer, as described in Faanu et al. (2013). The measurements took place at 16$^{o}$C and a relative efficiency of 40%, with an energy resolution of 2.0 keV and a gamma ray energy of 1332 keV of $^{60}Co$.

**Calculation of activity concentration**

The activity concentration of $^{238}U$ in the samples was determined by means of the energy peak, which accounted to 609.31 keV of $^{214}Bi$. Similarly, $^{232}Th$ was determined using the 911.21 keV peak of $^{228}Ac$, whereas $^{40}K$ was determined from the 1460.83 keV peak from $^{40}K$, itself. The activity concentration (A) was calculated in Bq/kg by means of Equation (3).

$$A = \frac{N e^{t\lambda}}{p T \eta m} \quad (3)$$

where N is the net counts of the radionuclide in the samples, t the delay time between sampling and counting, p the gamma ray emission probability (gamma ray yield), η the absolute counting efficiency of the detector system, T the sample counting time, m the sample mass (kg) or volume (L), $\exp^{(\lambda t)}$ the decay correction factor for the delay between sampling time and counting, and λ the decay constant of the parent radionuclide.

**External dose rate**

The external gamma dose rate ($D_\gamma$**)** at 1.0 m above the ground surface for the sediment samples was calculated as the sum of the products of radionuclides' activities and their conversion factors: 0.0417, 0.462, and 0.604 for $^{40}K$, $^{238}U$, and $^{232}Th$ respectively (Uosif et al., 2014).

**Average annual effective dose**

The average annual effective dose in sediments was calculated from the absorbed dose rate, by applying the dose conversion factor, equal to 0.7 Sv/Gy, and an outdoor occupancy factor of 0.2 (UNSCEAR, 2000).

**Committed effective dose**

In order to estimate the committed effective doses for water, we used the activity concentrations of each individual radionuclide, applying the yearly water consumption rate of 730 L/year for adults (Gorchev & Ozolins, 1984) on it. The dose conversion factors for $^{238}U$, $^{232}Th$, and $^{40}K$ had been taken from the Basic Safety standards (IAEA, 1996).

**Estimation of total annual effective dose**

The total annual effective dose ($E_T$) in water was estimated by means of the International Commission for Radiological Protection dose calculation method (ICRP, 2007), shown in Equation (4).

$$E_T = E_y(^{238}U, ^{232}Th, ^{40}K) + E_{ing}(W) \quad (4)$$

where $E_T$ is the total annual effective dose in Sievert (Sv), $E_\gamma$ ($^{238}U$, $^{232}Th$, $^{40}K$) the external gamma effective dose from sediment samples, and $E_{ing}$ (W) the effective dose from water consumption.

**Determination of radium equivalent activity**

The radiological risk of naturally-occurring radioactive materials in the sediments that may be used to make materials was assessed by calculating their radium equivalent activity ($Ra_{eq}$) as well as the external and internal hazard indices. Radium equivalent activity is a widely used hazard index, which was calculated using Equation (5):

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (5)$$

where $A_{Ra}$, $A_{Th}$ and $A_K$ are the activity concentrations of $^{226}Ra$, $^{232}Th$, and $^{40}K$ respectively.

In the definition of $Ra_{eq}$, it is assumed that 370 Bq/kg of $^{226}Ra$, 259 Bq/kg of $^{232}Th$, and 4810 Bq/kg of $^{40}K$ produce the same gamma ray dose rate. The maximum recommended $Ra_{eq}$ to make materials and products is <370 Bq/kg. This means that the external gamma dose must be less than 1.5 mSv/year (Faanu et al., 2006).

**External hazard index**

The external hazard index ($H_{ex}$) was calculated in sediment samples, using Equation (6).

$$H_{ex} = \frac{A_{RA}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (6)$$

where $A_{Ra}$, $A_{Th}$ and $A_K$ are the activity concentrations of $^{226}Ra$, $^{232}Th$, and $^{40}K$ respectively.

The value of the external hazard index must be less than one for the external gamma radiation hazard to be considered negligible (Agbalagba & Onoja, 2011). The radiation exposure due to the radioactivity from construction materials must be less than 1.5 mSv/y.

**Internal hazard index**

Internal hazard index ($H_{in}$), due to radon and its daughters' exposure, was calculated in sediment samples from Equation (7).

$$H_{in} = \frac{A_{RA}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (7)$$

where $A_{Ra}$, $A_{Th}$ and $A_K$ are the activity concentrations of $^{226}Ra$, $^{232}Th$, and $^{40}K$ respectively. For a material to be considered safe for the construction of human dwellings, the internal hazard index should be less than unity (Agbalagba & Onoja 2011). This is based on the fact that radon and its short-lived daughters are hazardous to the respiratory organs.

## RESULTS AND DISCUSSION

**Physical parameters**

Table 1 shows the results of the physical parameters, measured on water samples from the two reservoirs. Water from Lake Bosomtwe was alkaline, with an average pH value of 8.86±0.04, whereas water from the Bui Dam was circumneutral with pH values, ranging within 6.78±0.05. The alkaline nature of water from Lake

Bosomtwe may be attributed to chemical weathering of rocks and human activities, notably bathing, swimming, and clothes washing along the banks of the lake. The water pH of the Bui Dam is within the WHO limits, whereas the water pH Lake Bosomtwe is outside the recommended limit of 6.5 to 8.5 (US-EPA, 2012). The average electrical conductivity of water from Lake Bosomtwe was 1245±3.45 µS/cm, which is above the recommended limit, while that of Bui Dam was 81.8±1.09 µS/cm, below the recommended limit for drinking water which is equal to 700 µS/cm (Gorchev & Ozolins, 1984). Average total dissolved solid (TDS), recorded in Lake Bosomtwe, was 846 mg/l, whereas that of Bui Dam was 52 mg/L.

**Heavy metals in water**

Concentrations of heavy metals in water samples have been represented in Figure 2. The concentrations of Cu, Ni, Hg, and Co in Lake Bosomtwe fell below the method's detection limits. The average concentration of Pb was well above the safe limit for drinking water, equal to 0.010 mg/l. This could be attributed to domestic effluents, atmospheric deposition, and- to a large extent- the use of leaded petrol in outboard boat engines, automobiles, and car batteries. The concentrations of all other metals stood below their safe limits for drinking water. The average concentration (mg/l) of heavy metals in waters from the Bui Dam gave the general trend as Fe (0.058)> As (0.045)> Pb (0.026)> Mn (0.014)> Cd= Zn (0.003)> Cr (0.002). Concentrations of Mn, As, and Pb in the water samples were above the world average values for drinking water, which is 0.400, 0.010, and 0.010 mg/l respectively. Equally, the concentration of Cd was above world average of 0.003 mg/l for drinking water (Carr, 2009). The high levels of Mn, As, Pb, and Cd could be attributed to anthropogenic activities that go on around the lakes, which include improper disposal of lead acid waste from artisans in the catchment areas, amongst other activities. Average metal concentrations from Bui Dam were generally lower than that of Lake Bosomtwe, with the exception of As.

**Table 1. Physical parameters of water samples**

| Location | pH | Temperature (°C) | TDS (mg/L) | Conductivity (µS/cm) |
|---|---|---|---|---|
| Lake Bosomtwe | | | | |
| Amakom | 8.88 | 27.20 | 850.00 | 1248.00 |
| Duase | 8.88 | 27.10 | 843.00 | 1245.00 |
| Dompa | 8.90 | 27.00 | 841.00 | 1240.00 |
| Ankaase | 8.89 | 27.20 | 843.00 | 1241.00 |
| Adjamam | 8.88 | 27.10 | 844.00 | 1247.00 |
| Abrodum | 8.88 | 27.10 | 844.00 | 1247.00 |
| Adwafo | 8.83 | 27.10 | 842.00 | 1243.00 |
| Abono | 8.85 | 27.00 | 847.00 | 1243.00 |
| Detieso | 8.80 | 27.20 | 850.00 | 1243.00 |
| Anyinatiase | 8.79 | 27.10 | 844.00 | 1245.00 |
| Esaase | 8.84 | 27.20 | 853.00 | 1252.00 |
| Average | 8.86 | 27.12 | 846.00 | 1245.00 |
| Standard deviation | 0.04 | 0.08 | 3.88 | 3.45 |
| Bui Dam | | | | |
| Banda Nkwanta | 28.0 | 6.76 | 52.00 | 82.2 |
| Bator | 28.1 | 6.73 | 52.00 | 81.6 |
| Donkokyina | 28.2 | 6.83 | 51.00 | 80.8 |
| Jama | 28.3 | 6.83 | 52.00 | 81.0 |
| Old soldier | 28.3 | 6.76 | 53.00 | 83.5 |
| Average | 28.2 | 6.80 | 52.00 | 81.8 |
| Standard deviation | 0.1 | 0.05 | 0.71 | 1.1 |

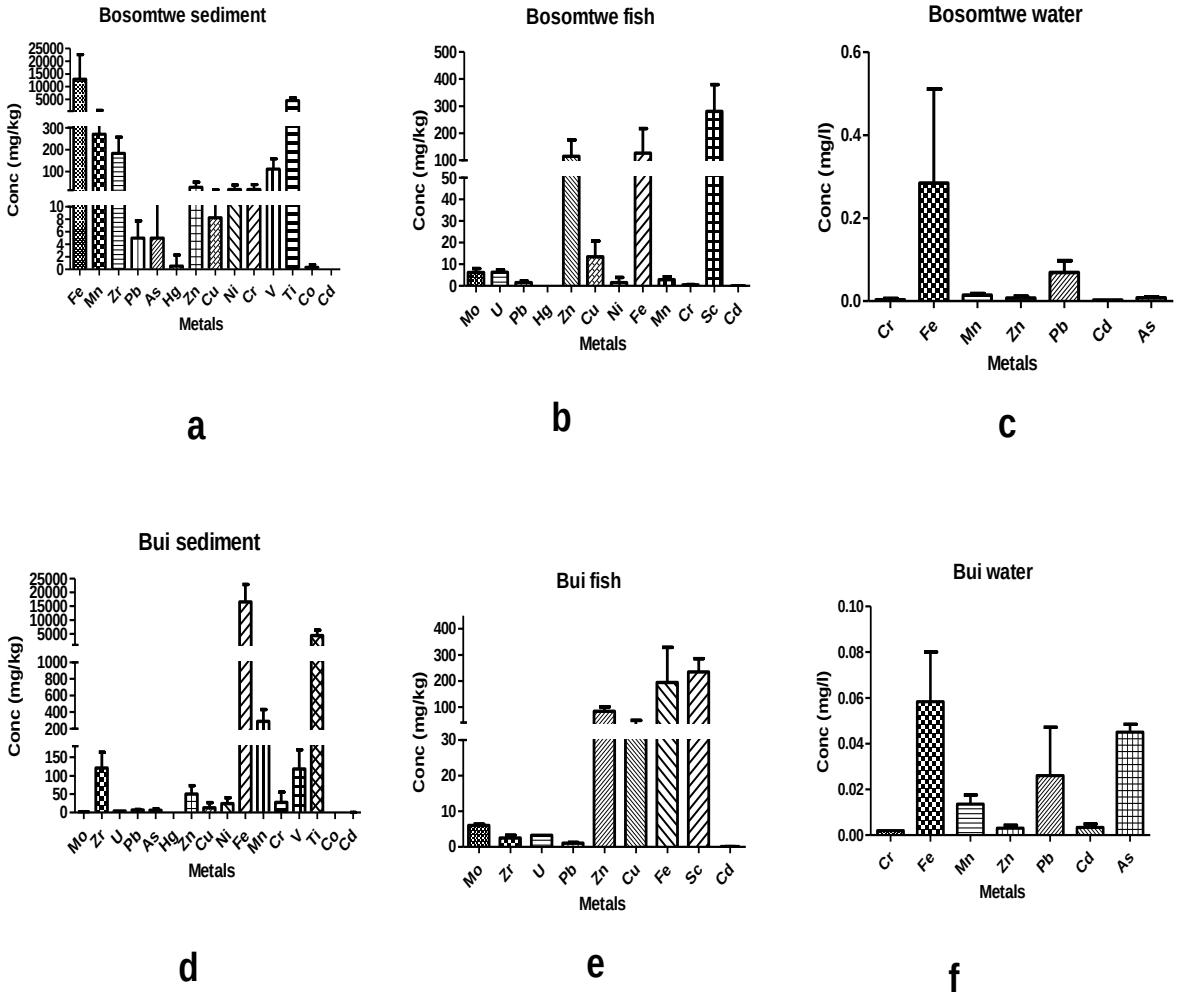


**Fig. 2. Representation of the concentration of heavy metals in (a) sediments from Lake Bosomtwe, (b) fish from Lake Bosomtwe, (c) water from Lake Bosomtwe, (d) sediment from Bui dam, (e) fish from Bui dam and (f) water from Bui dam**

## Heavy metals in sediments

The average metal concentration (mg/kg) for sediment samples from Lake Bosomtwe were in the following order: Fe> Ti> Mn> Zr> V> Zn> Cr> Ni> Sc> Cu> As> Pb> U> Hg> Co (Fig. 2). Metal concentrations in sediment samples were generally higher than the ones, measured in water, indicating that the sediments act as sinks for heavy metals as they can be bound to various compartments in different ways: occluded in amorphous materials; adsorbed on clay surfaces or iron/manganese oxyhydroxides; presenting in lattice of secondary minerals like carbonates, sulfates, or oxides; complicated with organic matter (OM), or lattice of primary minerals such as silicates. The average metal concentrations for Bui Dam were in the following order: Fe> Ti> Mn> Cd> Zr> V> Co> Zn> Cr> Ni> Cu> Sc> Pb> As> U> Mo> Hg. Results from this study were lower than heavy metal concentrations, found in Mwanza lake, Tanzania (Kishe & Machiwa, 2000), and Lake Victoria, one of the African Great Lakes (Ogoyi et al., 2011).

## Heavy metals in fish

The general trend of heavy metals concentration in fish from Lake Bosomtwe

was in the following order: Sc> Fe> Zn> Cu> Mo> V> Mn> Ni> Pb> Cr> Cd> Hg (0.03 mg/kg), whereas that of Bui dam was in the order; Sc> Fe> Zn> Cu> Mo> Zr> U> Pb> Cd> Hg (0.001 mg/kg). The metal concentrations in fish samples were generally within international limits, reported by Akan et al. (2012), except for Pb, Zn, Fe, and Cu which were above the limits.

**Biota sediment accumulation**

Biota sediment accumulation factor, the extent to which fish has accumulated heavy metals into their tissues, was also calculated. The factors ranged from 50.875 (Cd) to 0.010 (Fe) in Lake Bosomtwe and from 11.709 (Mo) to 0.012 (Fe) in Bui Dam, indicative of which metals were stored biologically in the fish tissues and how much of it was stored, as compared to the concentration of the metals in the sediments. The metals which have been bio-accumulated in the fish tissues for Lake Bosomtwe (Cd, U, Zn, Cu, Pb and Ni) and for Bui Dam (Mo, Cu, Zn, Cd and Pb) depend, to a large extent, on their essentiality to the fish or solubility in the water.

**Sediment pollution analyses**

Table 2 gives geo-accumulation indices for the reservoirs. Samples from Lake Bosomtwe and Bui Dam were unpolluted (Igeo<0), with respect to all analysed metals with the exception of As (unpolluted to moderately polluted), Pb (moderately polluted), Mn (strongly polluted), and Fe (extremely polluted). Table 3 shows the contamination factor that determines the degree of pollution and the way sediments are deteriorating. Lake Bosomtwe recorded a low level of contamination with respect to Mn, Pb, As, Zn, Cu, Ni, Cr, V, and Co; moderate contamination with respect to Ti, Zr, and Hg; and a high contamination level for Fe. The Bui Dam sediments had a low level of contamination (CF<1) for all metals except for Fe which recorded an average value of 3553.96 (highly contaminated) as well as Zn and Cr that showed moderate contamination, while pollution load index estimated on sediment samples from the 2 reservoirs was less than 1, indicating that they were unpolluted for all the studied metals.

**Table 2. Index of geo-accumulation of sediment samples**

| LAKE BOSOMTWE | Fe | Mn | Pb | As | Zn | Cu | Ni | Cr | Zr | V | Ti | Co | Hg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Duase | 9.10 | 3.19 | 1.67 | 0.00 | -3.62 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -4.30 | 0.00 |
| Amakom | 9.67 | 3.27 | 1.71 | 0.00 | -3.40 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -5.16 | 0.00 |
| Essase | 9.17 | 3.20 | 1.68 | 0.00 | -3.31 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -7.97 | 0.00 |
| Dompa | 9.51 | 3.25 | 0.00 | 0.00 | -3.96 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -5.80 | 0.00 |
| Adjamam | 9.06 | 3.18 | 1.67 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -4.74 | 0.00 |
| Anyinatiase | 12.11 | 3.60 | 1.85 | 0.89 | -0.22 | 0.00 | 0.43 | -3.55 | -1.00 | -0.07 | -0.20 | 0.00 | 0.00 |
| Ankaase | 11.94 | 3.58 | 1.84 | 0.88 | -0.87 | -2.62 | 0.17 | -2.32 | -0.88 | 0.02 | -0.36 | -5.42 | 0.00 |
| Detieso | 11.03 | 3.46 | 1.79 | 0.84 | -0.93 | -3.15 | -1.11 | -3.65 | -0.65 | -0.56 | -0.13 | 0.00 | 0.00 |
| Adwafo | 11.19 | 3.48 | 1.80 | 0.85 | -0.22 | -3.36 | 0.00 | -3.38 | -0.69 | -0.83 | -0.87 | 0.00 | 0.00 |
| Abrodum | 11.38 | 3.51 | 1.81 | 0.86 | -0.74 | -2.53 | -0.51 | -3.63 | -0.65 | -0.57 | -0.44 | 0.00 | 0.00 |
| Abono | 10.69 | 3.42 | 1.77 | 0.83 | -1.21 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Average | 10.44 | 3.38 | 1.60 | 0.47 | -1.68 | -1.06 | -0.09 | -1.50 | -0.35 | -0.18 | -0.18 | -3.04 | 0.00 |
| Standard deviation | 1.17 | 0.16 | 0.53 | 0.45 | 1.55 | 1.49 | 0.40 | 1.76 | 0.42 | 0.31 | 0.28 | 3.05 | 0.00 |
| | | | | | | | | | | | | | |
| BUI DAM | | | | | | | | | | | | | |
| Banda Nkwanta | 11.91 | 3.57 | 1.84 | 0.88 | 0.12 | 0.00 | 0.00 | -2.31 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Bator | 11.30 | 3.50 | 1.81 | 0.85 | -0.38 | 0.00 | -0.44 | -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Donkokyina | 10.88 | 3.44 | 1.78 | 0.84 | -1.22 | 0.00 | -1.05 | -5.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Jama | 10.60 | 3.41 | 1.77 | 0.82 | -1.60 | 0.00 | -1.15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Old soldier | 11.00 | 3.46 | 1.79 | 0.84 | -0.44 | 0.00 | 0.00 | -3.47 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Average | 11.14 | 3.48 | 1.80 | 0.85 | -0.70 | 0.00 | -0.53 | -2.96 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Standard deviation | 0.50 | 0.06 | 0.03 | 0.02 | 0.69 | 0.00 | 0.55 | 1.92 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Table 3. Contamination factors and pollution load indices for sediment samples**

| LAKE BOSOMTWE | Fe | Mn | Pb | As | Zn | Cu | Ni | Cr | Zr | V | Ti | Co | Hg | PLI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Duase | 821.74 | 0.13 | 0.02 | 0.00 | 0.12 | 0.00 | 0.00 | 0.00 | 1.35 | 0.49 | 0.84 | 0.08 | 0.00 | 0.00 |
| Amakom | 1224.03 | 0.10 | 0.02 | 0.00 | 0.14 | 0.00 | 0.00 | 0.00 | 1.44 | 0.56 | 0.77 | 0.04 | 0.00 | 0.00 |
| Essase | 863.30 | 0.06 | 0.02 | 0.00 | 0.15 | 0.00 | 0.00 | 0.00 | 1.32 | 0.54 | 0.65 | 0.01 | 0.00 | 0.00 |
| Dompa | 1090.43 | 0.10 | 0.00 | 0.00 | 0.10 | 0.00 | 0.00 | 0.00 | 1.65 | 0.60 | 0.77 | 0.03 | 0.00 | 0.00 |
| Adjamam | 798.99 | 0.09 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.03 | 0.55 | 0.91 | 0.06 | 0.00 | 0.00 |
| Anyinatiase | 6643.84 | 1.49 | 0.06 | 1.09 | 1.29 | 0.35 | 2.02 | 0.13 | 0.75 | 1.43 | 1.30 | 0.00 | 0.00 | 0.00 |
| Ankaase | 5873.49 | 0.57 | 0.06 | 0.45 | 0.82 | 0.24 | 1.68 | 0.30 | 0.82 | 1.52 | 1.17 | 0.04 | 29.35 | 0.95 |
| Detieso | 3130.03 | 0.24 | 0.06 | 0.28 | 0.79 | 0.17 | 0.70 | 0.12 | 0.95 | 1.02 | 1.37 | 0.00 | 0.00 | 0.00 |
| Adwafo | 3499.83 | 0.26 | 0.07 | 0.38 | 1.29 | 0.15 | 0.00 | 0.14 | 0.93 | 0.85 | 0.82 | 0.00 | 0.00 | 0.00 |
| Abrodum | 4000.99 | 0.32 | 0.06 | 0.54 | 0.90 | 0.26 | 1.05 | 0.12 | 0.96 | 1.01 | 1.11 | 0.00 | 0.00 | 0.00 |
| Abono | 2478.90 | 0.14 | 0.05 | 0.18 | 0.65 | 0.00 | 0.00 | 0.00 | 0.41 | 0.88 | 1.05 | 0.00 | 0.00 | 0.00 |
| Average | 2765.96 | 0.32 | 0.04 | 0.27 | 0.57 | 0.11 | 0.50 | 0.07 | 1.15 | 0.86 | 0.98 | 0.02 | 2.67 | 0.09 |
| Standard deviation | 2083.93 | 0.42 | 0.02 | 0.34 | 0.49 | 0.13 | 0.76 | 0.10 | 0.46 | 0.36 | 0.24 | 0.03 | 8.85 | 0.29 |
| | | | | | | | | | | | | | | |
| BUI DAM | | | | | | | | | | | | | | |
| Banda nkwanta | 5753.24 | 0.61 | 0.07 | 0.76 | 1.64 | 0.41 | 1.50 | 0.30 | 0.89 | 1.58 | 1.33 | 0.00 | 0.00 | 0.00 |
| Bator | 3783.15 | 0.32 | 0.04 | 0.33 | 1.15 | 0.00 | 1.10 | 0.09 | 0.42 | 0.85 | 0.85 | 0.00 | 0.00 | 0.00 |
| Donkokyina | 2836.55 | 0.33 | 0.05 | 0.28 | 0.65 | 0.00 | 0.72 | 0.05 | 0.53 | 0.89 | 1.46 | 0.00 | 0.00 | 0.00 |
| Jama | 2329.94 | 0.14 | 0.04 | 0.19 | 0.50 | 0.00 | 0.68 | 0.00 | 0.89 | 0.55 | 0.58 | 0.00 | 0.00 | 0.00 |
| Old soldier | 3066.94 | 0.29 | 0.07 | 0.18 | 1.10 | 0.15 | 0.00 | 0.14 | 1.06 | 0.68 | 0.51 | 0.00 | 0.00 | 0.00 |
| Average | 3553.96 | 0.34 | 0.05 | 0.35 | 1.01 | 0.11 | 0.80 | 0.12 | 0.76 | 0.91 | 0.95 | 0.00 | 0.00 | 0.00 |
| Standard deviation | 1335.99 | 0.17 | 0.01 | 0.24 | 0.45 | 0.18 | 0.56 | 0.12 | 0.27 | 0.40 | 0.43 | 0.00 | 0.00 | 0.00 |

## Statistical analysis of metals in sediments

In order to establish the sources of heavy metals in the sediment samples from the two reservoirs, Pearson's correlation analysis was performed among all variables (Cr, Cu, Co, Fe, Pb, Mn, Zn, Cd, As, Ti, Zr, V, Sc, U, Hg, and Ni), closely associated with each other. There were high and statistically-significant positive correlations between these metals, indicating that the contaminants in the sediments have a similar source that originates from anthropogenic activities ($P<0.01$). Similar results have been reported previously for soils in Tirana (Albania) (Gjoka et al., 2011) and for agricultural soils in Beijing, China (Lu et al., 2012). Nonetheless, a single correlation analysis may not be sufficient for source identification of heavy metals and it should be combined with other analytical procedures. For this reason, a principal component analysis was used to study the metal pollution and identify their sources (Dragovic et al., 2008; Franco-Uría et al., 2009). Varimax rotation was used to obtain a maximum sum of variance of the factor coefficients, which better explained the possible groups or sources that influence the sediment samples. Components loadings have been classified by Liu et al. (2003) as "strong", "moderate", and "weak", corresponding to absolute loading values of >0.75, 0.75–0.50, and 0.50–0.30, respectively.

Based on eigenvalues (eigenvalue >1), four principal components (PC1, PC2, PC3, and PC4) were obtained for the studied metals which were cumulatively explained as 53.684%, 69.753%, 80.418%, and 86.864 % of the total variance, respectively. The various components in the two reservoirs are shown in Figures 3 and 4. The high positive loading on most metals in the reservoirs may be attributed to anthropogenic impacts on the sediment. The data reveal that these potentially hazardous elements would have been deposited on the sediments from effluents, discharged from industries and homes as well as other activities that go on around the reservoirs.

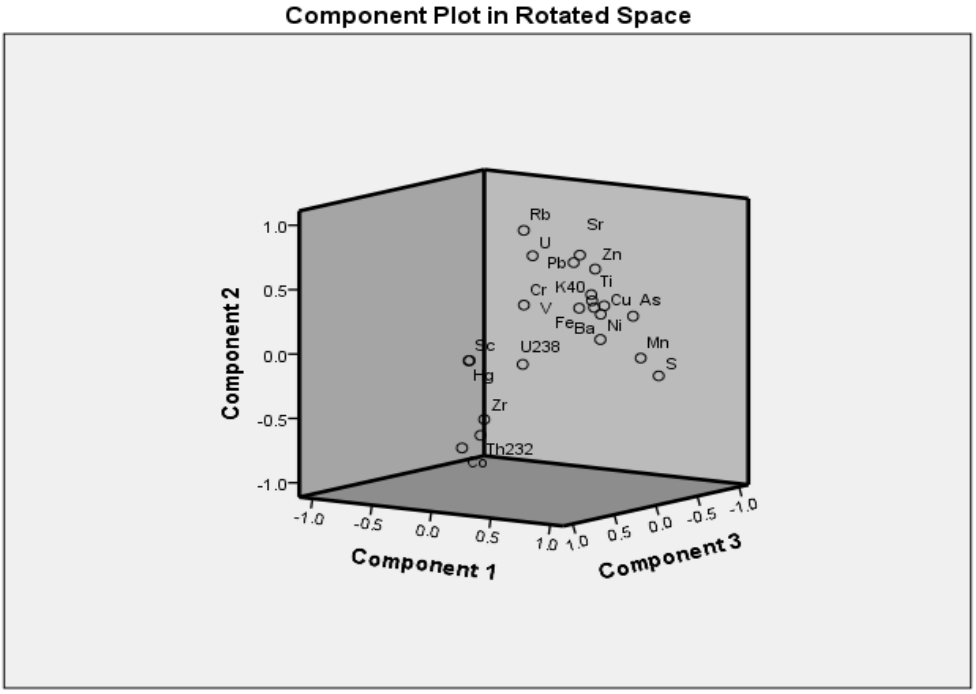


**Fig. 3. Component analysis for lake Bosomtwe**

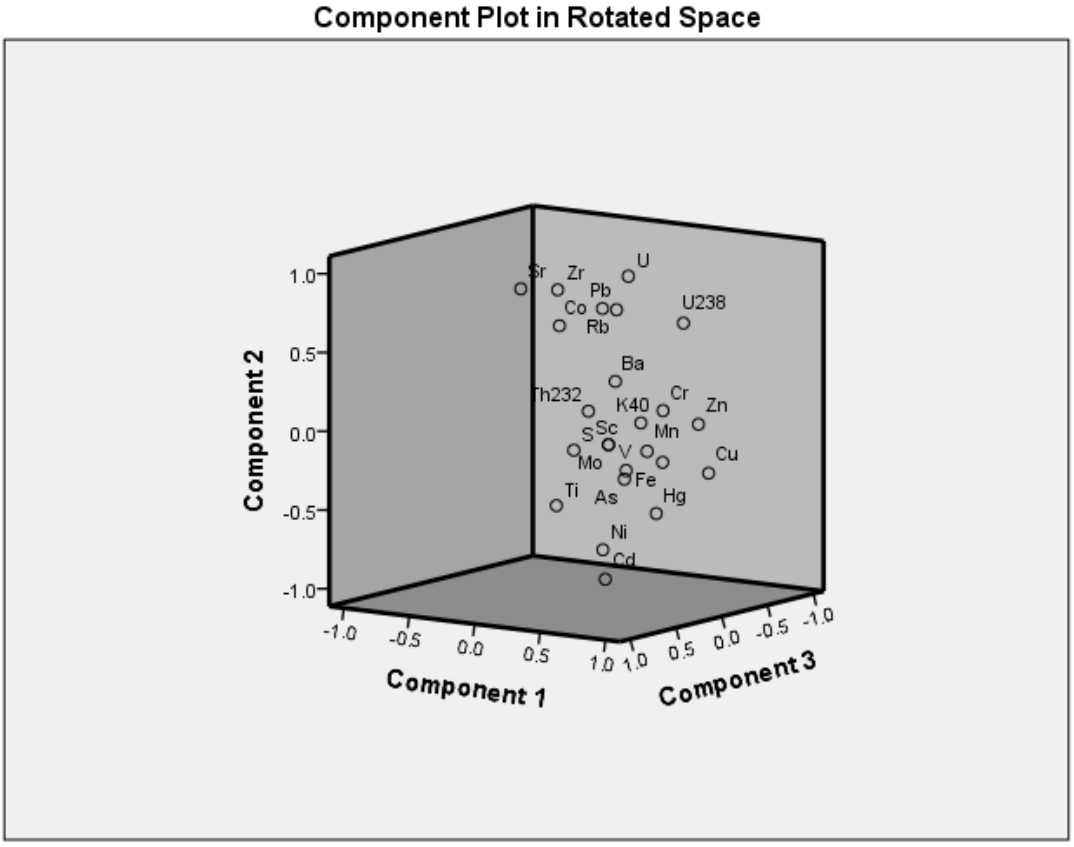


**Fig. 4. Component analysis for Bui dam**

**Radionuclide activity determinations**

Figure 5 illustrates the activity concentrations of naturally-occurring radionuclides ($^{238}$U, $^{232}$Th, and $^{40}$K), determined in the sediment samples from the reservoirs. In Lake Bosomtwe, activity concentration of $^{238}$U ranged from 5.27±0.43 Bq/kg in Abono to 10.40±0.58 Bq/kg in Detieso and the average activity of $^{238}$U in Lake Bosomtwe was 7.90±1.61 Bq/kg. On the other hand, activity of $^{232}$Th ranged from 5.38±0.75 Bq/kg in Abrodum to 13.80±1.87 Bq/kg also in Duase, recording an average value of 7.83±2.34 Bq/kg. The activity concentration of $^{40}$K ranged from 109±2.69 Bq/kg in Amakom to 205±4.71 Bq/kg in Adjamam with an average value of 169.73±31.81 Bq/kg. The activity concentration of $^{40}$K was higher than that of $^{238}$U and $^{232}$Th, combined in all the sediment samples from Lake Bosomtwe. The bedrock that contained hard crystalline minerals, consisting of aluminium silicates of potassium (Faanu et al., 2014), is likely to be the source of high activity concentrations of $^{40}$K, measured.

The activity concentration of $^{238}$U in sediments from Bui Dam ranged between 6.31±0.49 Bq/kg in Jama and 8.97±0.55 Bq/kg in Old soldier, with the mean $^{238}$U activity in Bui being 7.56±1.05 Bq/kg. The recorded activity concentration of $^{232}$Th ranged from 6.12±0.85 Bq/kg in Jama to 9.89±1.35 Bq/kg in Donkokyina with a mean value of 8.11±1.45 Bq/kg, whereas the $^{40}$K activity ranged from 35.1±1.39 Bq/kg in Banda Nkwanta to 62.0±1.87 Bq/kg in Bator, with a mean value of 49.0±10.19 Bq/kg.

The average activity concentration of the three radionuclides in the sediments from both reservoirs were found to be lower than world average values (UNSCEAR, 2000) and those reported in similar environments for soils and sediments (Adukpo et al., 2014b; Agbalagba et al., 2013; Darko et al., 2015). However, the activities registered in these reservoirs were higher than those, reported for Assiut zone in Egypt (Uosif et al., 2013).

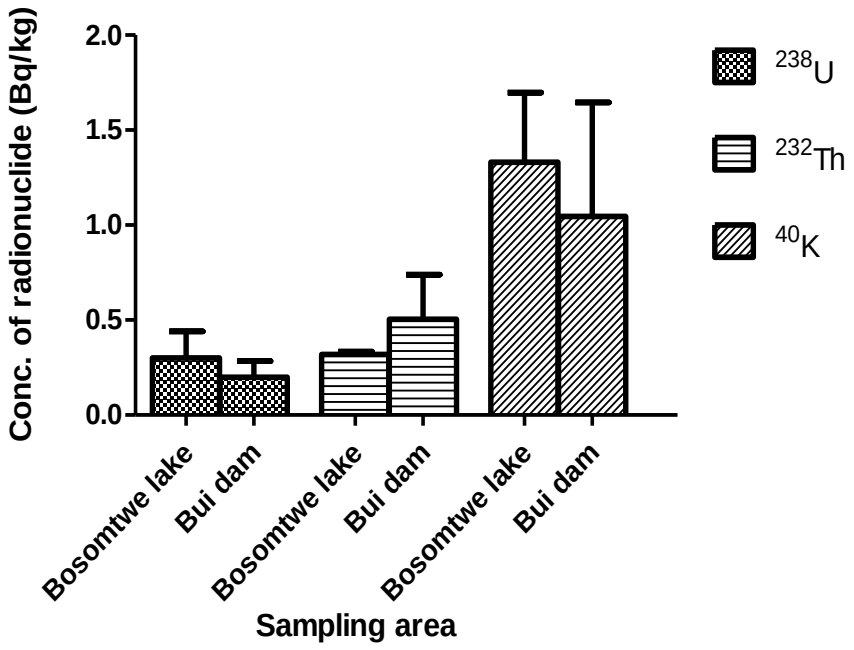


**Fig. 5. Average activity concentrations of natural occurring radionuclides in ($^{238}$U, $^{232}$Th, and $^{40}$K)**

The average absorbed dose rate in Lake Bosomtwe was found to be 15.45±2.00 nGy/h and 10.44±4.10 nGy/h for Bui Dam, both being lower than the acceptable international value of 59.00 nGy/h in sediments (UNSCEAR, 2000). The absorbed dose rate and annual effective dose, calculated, were also lower than those reported earlier for Lake Bosomtwe in Ghana (Darko et al., 2011) and the one reported in Egypt (Fahmi et al., 2010). The percentage contribution of the radionuclides to the absorbed dose rate were 46%, 30%, and 24% for $^{40}$K, $^{232}$Th and $^{238}$U, respectively. In Bui Dam, however, $^{232}$Th was the highest contributor (47%) followed by $^{238}$U (33%) and $^{40}$K (20%). The differences between the 2 reservoirs may be due to the different mineralogical and geochemical compositions of the soils and rocks that outcrop in both study areas.

Activity concentration of $^{238}$U in water from Lake Bosomtwe was from 0.20±0.07 Bq/L in Essase to 0.98±0.24 Bq/L in Abono. For $^{232}$Th, it ranged from 0.03±0.08 Bq/L in Adwafo to 0.82±0.13 Bq/L in Dompa, whereas that of $^{40}$K was from 0.02±0.67 Bq/L in Adjamam to 3.32±0.77 Bq/L in Abrodum. On the other hand, water samples from Bui Dam showed an activity concentration of $^{238}$U within the range of 0.13±0.08 Bq/L in Banda Nkwanta to 0.42±0.01 Bq/L in Jama, while $^{232}$Th activity ranged from 0.07±0.14 Bq/L in Donkokyina to 0.82±0.14 Bq/L in Bator and $^{40}$K activity was confined between 0.78±0.73 Bq/L in Old soldier and 2.42±0.75 Bq/L in Jama. These results were found to be lower than the ones from other sites, affected by gold mining in Ghana, like the Pra River (Adukpo et al., 2015) and the Chirano mine (Faanu et al., 2014). The values, measured in this study, were also lower than those registered in waters from the oil communities in Nigeria affected by mining and oil prospecting (Agbalagba et al., 2013), and in some floodplains' lakes of Nigeria, frequently polluted by oil and gas exploration activities (Agbalagba & Onoja 2011) as well as some lakes in Turkey (Akyil et al., 2009). However, the radionuclides' activities in waters from both reservoirs were higher than the activity concentration in drinking water from boreholes in Kumasi (Darko et al., 2014a) and food producing communities in the Tano district of Brong Ahafo (Darko et al., 2015).

The activities of the radionuclides in the reservoirs are within the WHO guidelines and world average values for drinking water: i.e. 10 Bq/l for $^{238}$U and 1 Bq/l for $^{232}$Th. The annual effective dose due to drinking water from Lake Bosomtwe was from 15.2 to 23.0 μSv with an average value of 18.9±2.5 μSv, while that of Bui Dam varied from 10.6 to 14.1 μSv with an average value of 12.8±5.0 μSv, which are within the International Commission for Radiological Protection safe limit, amounting to 100 μSv/year (ICRP, 2007). The committed effective dose due to drinking water from lake Bosomtwe had an average of 46.5±26.9 μSv/year and that of Bui dam was 127.10±56.68 μSv/year.

**Hazard assessment in sediment samples**

Hazard indices, associated with the activities of the naturally-occurring radionuclides, are summarised in Table 4. The average radium equivalent activity in the reservoirs was 32.17±4.37 Bq/kg for Lake Bosomtwe and 22.93±2.46 Bq/kg for Bui Dam. Radium equivalent activity correlates the external gamma dose from the terrestrial radionuclides as well as the internal dose due to radon and its decay products such as $^{210}$Pb and $^{210}$Po. The maximum value of $Ra_{eq}$, in construction materials must be less than 370 Bq/kg (OECD/NEA, 1979) for the material to be considered safe. The calculated external hazard index in sediment samples ranged from 0.07 (Abono) to 0.11 (Duase) for Lake Bosomtwe and from 0.05 to 0.07 for Bui Dam. Similarly, the internal hazard index for Lake Bosomtwe and Bui Dam were

0.11±0.02 and 0.08±0.01, respectively. The external and internal hazard indices must be less than one in order to keep the radiation hazard insignificant (Agyarko et al., 2014). All sediment samples had their Radium equivalent, external hazard indices, and internal hazard indices within the recommended limits, implying that the material could be used for building purposes, without posing any health hazard to the population.

Also the annual effective dose was 1.89 x $10^{-11}$ mSv for sediment and 7.72 x $10^{-5}$ mSv for water from Lake Bosomtwe, while those of Bui Dam were 1.28 x $10^{-11}$ and 1.27 x $10^{-4}$ mSv respectively. This implies that the water and sediments from Lake Bosomtwe and Bui Dam do not pose radiological hazard to their users.

## Conclusion

The exposure of inhabitants to radioactivity and heavy metals (Cr, Cu, Co, Fe, Pb, Mn, Zn, Cd, As, Ti, Zr, V, Sc, U, Hg, and Ni) through the ingestion of water and fish in some reservoirs of Ghana (i.e. Lake Bosomtwe and Bui Dam) has been analyzed in this work. The mean concentrations of Cr, Cu, Co, Fe, Zn, Mn, Pb, Cd, As, Ti, Zr, V, U, Ni, and Hg in the water, sediment, and fish were generally below the world average (WHO, FAO, US-FDA and CEQG) and maximum permissible limits.

**Table 4. Absorbed dose rate, annual effective dose, $Ra_{eq}$, $H_{ex}$, and $H_{in}$ in sediment, and Hex, Hin and commited effective dose for water samples**

| Location | Absorbed dose rate (nGy/h) | Annual effective dose ( μSv ) | Radium equivalent activity (Bq/kg) | External hazard index for sediments | Internal hazard Index for sediments | External hazard index for water | Internal hazard Index for water | Committed effective dose for water (μSv/ year) |
|---|---|---|---|---|---|---|---|---|
| Bosomtwe | | | | | | | | |
| Essase | 17.24 | 21.14 | 35.61 | 0.10 | 0.12 | 0.001 | 0.002 | 46.5 |
| Abrodum | 12.92 | 15.84 | 26.48 | 0.07 | 0.09 | 0.003 | 0.004 | 57.9 |
| Amakom | 12.41 | 15.22 | 26.36 | 0.07 | 0.09 | 0.004 | 0.005 | 122.0 |
| Duase | 18.74 | 22.98 | 40.34 | 0.11 | 0.13 | 0.002 | 0.003 | 48.6 |
| Adjamam | 17.05 | 20.91 | 35.24 | 0.10 | 0.12 | 0.001 | 0.003 | 26.9 |
| Adwafo | 15.61 | 19.14 | 32.14 | 0.09 | 0.11 | 0.001 | 0.002 | 20.5 |
| Detieso | 17.24 | 21.14 | 35.61 | 0.10 | 0.12 | 0.002 | 0.003 | 47.5 |
| Anyinatiase | 15.61 | 19.12 | 32.14 | 0.09 | 0.11 | 0.004 | 0.006 | 155.0 |
| Dompa | 14.78 | 18.12 | 30.80 | 0.08 | 0.10 | 0.005 | 0.006 | 156.0 |
| Ankaase | 14.89 | 18.26 | 31.74 | 0.09 | 0.11 | 0.002 | 0.002 | 33.8 |
| Abono | 13.48 | 16.53 | 27.38 | 0.07 | 0.09 | 0.005 | 0.008 | 134.0 |
| Average | 15.45 | 18.95 | 32.17 | 0.09 | 0.11 | 0.003 | 0.004 | 46.5 |
| Standard deviation | 2.00 | 2.50 | 4.37 | 0.01 | 0.02 | 0.001 | 0.002 | 57.9 |
| Bui Dam | | | | | | | | |
| Banda Nkwanta | 10.61 | 13.02 | 23.59 | 0.06 | 0.09 | 0.004 | 0.004 | 146.00 |
| Bator | 10.39 | 12.74 | 22.56 | 0.06 | 0.08 | 0.005 | 0.006 | 156.00 |
| Donkokyina | 11.04 | 13.53 | 24.52 | 0.07 | 0.09 | 0.001 | 0.002 | 26.50 |
| Jama | 8.68 | 10.64 | 18.88 | 0.05 | 0.07 | 0.005 | 0.006 | 162.00 |
| Old soldier | 11.47 | 14.07 | 25.12 | 0.07 | 0.09 | 0.004 | 0.004 | 145.00 |
| Average | 10.44 | 12.80 | 22.93 | 0.06 | 0.08 | 0.004 | 0.004 | 127.10 |
| Standard deviation | 4.10 | 5.00 | 2.46 | 0.01 | 0.01 | 0.001 | 0.002 | 56.68 |

Hazard indices determined for sediments suggest that they are unpolluted with heavy metals, and the biota sediment accumulation factor determined for fish samples were indicative of bioaccumulation of metals by fish. Thus, the relatively low hazard indices recorded suggest that the population is not at any imminent health risk, due to heavy metals. Activity concentrations of $^{238}U$, $^{232}Th$, and $^{40}K$ in the reservoirs' samples were below the WHO and ICRP limits, thus posing no radiological health risks to people who have access to the reservoirs.

It can be concluded that Lake Bosomtwe and Bui Dam pose no health risks to the public for water and fish ingestion, as well as the use of sediments for building purposes. The results obtained in this work are a first approach, and we hope it to be useful for further studies in other parts of Ghana to assess the doses of radioactivity and heavy metal concentrations, which would help formulating local regulations for permissible radioactivity levels.

## References

Adu, S., Darko, E.O., Awudu, A.R., Adukpo, O.K., Obeng, M., Otoo, F. and Faanu, A. (2011). Preliminary Study of Natural Radioactivity in the Lake Bosumtwi Basin. Environ. Earth Sci. 3, 463-468.

Adukpo, O.K., Faanu, A., Lawluvi, H., Darko, E.O., Kansaana, C., Kpeglo, D.O. and Awudu, A.R. (2015). Distribution and assessment of radionuclides in sediments, soil and water from the lower basin of river Pra in the Central and Western Regions of Ghana. J. Radioanal. Nucl. Chem. 303, 1679-1685. doi:10.1007/s10967-014-3637-5.

Adukpo, O.K., Faanu, A., Lawluvi, H., Darko, E.O., Kansaana, C., Kpeglo, D.O. and Awudu, A.R. (2014a). Distribution and assessment of radionuclides in sediments, soil and water from the lower basin of river Pra in the Central and Western Regions of Ghana. Radioanal. Nucl. Chem. 302. doi:10.1007/s10967-014-3637-5.

Adukpo, O.K., Faanu, A., Lawluvi, H., Tettey-Larbi, L., Emi-Reynolds, G., Darko, E.O., Kansaana, C., Kpeglo, D.O., Awudu, A.R., Glover, E.T., Amoah, P.A., Efa, A.O., Agyemang, L.A., Agyeman, B.K., Kpordzro, R. and Doe, A.I. (2014b). Distribution and assessment of radionuclides in sediments, soil and water from the lower basin of river Pra in the Central and Western Regions of Ghana. J. Radioanal. Nucl. Chem. 303, 1679–1685. doi:10.1007/s10967-014-3637-5.

Agbalagba, E., Avwiri, G. and Chadumoren, Y. (2013). Gross α and β Activity Concentration and Estimation of Adults and Infants Dose intake in Surface and Ground Water of Ten Oil Fields Environment in Western Niger Delta of Nigeria. J. Appl. Sci. Environ. Manag. 17, 267-277. doi:10.4314/jasem.v17i2.10.

Agbalagba, E.O. and Onoja, R.A. (2011). Evaluation of natural radioactivity in soil, sediment and water samples of Niger Delta (Biseni) flood plain lakes, Nigeria. J. Environ. Radioact. 102, 667-71. doi:10.1016/j.jenvrad.2011.03.002.

Agyarko, K., Dartey, E., Kuffour, R. and Sarkodie, P. (2014). Assessment of trace elements levels in sediment and water in some artisanal and small-scale mining (ASM) localities in Ghana. Curr. World Environ. J. 9, 7-16. doi:10.12944/CWE.9.1.02.

Akan, J.C., Mohmoud, S., Yikala, B.S. and Ogugbuaja, V.O. (2012). Bioaccumulation of some heavy metals in fish samples from River Benue in Vinikilang, Adamawa State, Nigeria. Am. J. Anal. Chem. 3, 727-736. doi:10.4236/ajac.2012.311097.

Akoto, O., Darko, G., Nkansah, M.A. (2011). Chemical Composition of Rainwater over a Mining Area in Ghana. Int. J. Enviromental Res. 5, 847-854.

Akoto, O., Bruce, T.N. and Darko, G. (2008). Heavy metals pollution profiles in streams serving the Owabi reservoir. African J. Environ. Sci. Technol. 2, 354-359.

Akyil, S., Aytas, S., Turkozu, D.A., Aslani, M.A.A., Yusan, S. (Doyurum) and Eral, M. (2009). Radioactivity levels in surface water of lakes around Izmir/Turkey. Radiat. Meas. 44, 390-395. doi:10.1016/j.radmeas.2009.04.013.

Asante, F., Agbeko, E., Addae, G. and Quainoo, A.K. (2011). Bioaccumulation of heavy metals in water, sediments and tissues of some selected fishes from the Red Volta, Nangodi in the Upper East Region of Ghana. Br. J. Appl. Sci. Technol. 4, 594-603.

Avwiri, G.O., Tchokossa, P. and Mokobia, C.E. (2007). Natural radionuclides in borehole water in Port Harcourt, Rivers State, Nigeria. Radiat. Prot. Dosimetry 123, 509-514. doi:10.1093/rpd/ncl526.

Banu, Z., Chowdhury, S.A., Hossain, M.D. and Nakagami, K. (2013). Contamination and ecological risk assessment of heavy metal in the sediment of Turag River, Bangladesh: An index analysis approach. J. Water Resour. Prot. 5, 239-248. doi:10.4236/jwarp.2013.52024.

Bonotto, D.M., Bueno, T.O., Tessari, B.W. and Silva, A. (2009). The natural radioactivity in water by gross alpha and beta measurements. Radiat. Meas. 44, 92-101. doi:10.1016/j.radmeas.2008.10.015.

Boszke, L., Sobczyński, T., Głosińska, G., Kowalski, A. and Siepak, J. (2004). Distribution of mercury and other heavy metals in bottom sediments of the middle Odra River (Germany/Poland). Polish J. Environ. Stud. 13, 495-502. doi:10.1023/B:WATE.0000049171.22781.bd.

Cai, Y. (2000). Speciation and analysis of mercury, arsenic, and selenium by atomic fluorescence spectrometry. TrAC Trends Anal. Chem. 19, 62-66. doi:10.1016/S0165-9936(99)00180-6.

Carr, C.J.R.G.M. (2009). Development and sensitivity analysis of a global drinking water quality index, 73-90. doi:10.1007/s10661-008-0464-6.

Darko, E.O., Adu, S., Awudu, A.R., Adukpo, O.K., Emi-Reynolds, G., Faanu, A. and Obeng, M.K. (2011). Preliminary study of natural radioactivity in the lake Bosumtwi Basin. Res. J. Environ. Earth Sci. 3, 463-468.

Darko, G., Faanu, A., Akoto, O., Acheampong, A., Goode, E.J. and Gyamfi, O. (2015). Distribution of natural and artificial radioactivity in soils, water and tuber crops. Environ. Monit. Assess. 187, 1-11. doi:10.1007/s10661-015-4580-9.

Darko, G., Faanu, A., Akoto, O., Atta-Agyeman, F., Aikins, M.A., Agyemang, B. and Ibrahim, A. (2014a). Assessment of the activity of radionuclides and radiological impacts of consuming underground water in Kumasi, Ghana. Environ. Earth Sci. 73, 399-404. doi:10.1007/s12665-014-3433-0.

Darko, G., Faanu, A., Akoto, O., Atta-Agyeman, F., Aikins, M.A., Agyemang, B. and Ibrahim, A. (2014b). Assessment of the activity of radionuclides and radiological impacts of consuming underground water in Kumasi, Ghana. Environ. Earth Sci. doi:10.1007/s12665-014-3433-0.

Degerlier, M. and, Karahan, G. (2010). Natural radioactivity in various surface waters in Adana, Turkey. Desalination 261, 126-130. doi:10.1016/j.desal.2010.05.020.

Dragovic, S., Mihailovic, N. and Gajic, B. (2008). Heavy metals in soils: Distribution, relationship with soil characteristics and radionuclides and multivariate assessment of contamination sources. Chemosphere 72, 491-495. doi:10.1016/j.chemosphere.2008.02.063.

El-Mageed, A.I.A., El-Kamel, A.E., Abbady, A.E., Harb, S., Saleh, I.I., Ibrahim, A. and Issa, I. (2011). Natural radioactivity of ground and hot spring water in some areas in Yemen. Desalination 321, 28-31. doi:10.1016/j.desal.2011.11.022.

Faanu, A., Lawluvi, H., Kpeglo, D.O., Darko, E.O., Awudu, A.R. and Adukpo, O.K. (2014). Assessment of natural and anthropogenic radioactivity levels In soils, rocks and water in the vicinity of Chirano Gold Mine in Ghana. Radiat. Prot. Dosimetry 158, 87-99. doi:10.1093/rpd/nct197.

Faanu, A., Kpeglo, D.O., Sackey, M., Darko, E.O., Lawluvi, H., Awudu, R. and Adukpo, O.K. (2013). Natural and artificial radioactivity distribution in soil, rock and water of the Central Ashanti Gold Mine, Ghana. Environ. Earth Sci. doi:10.1007/s12665-013-2244-z.

Faanu, A., Darko, E.O. and Ephraim, J.H. (2006). Determination of natural radioactivity and hazard in soil and rock samples in a mining area in Ghana. West African J. Appl. Ecol. 11, 1-11.

Fahmi, N.M., El-Khatib, A., El-Salam, Y.M.A., Shalaby, M.H., El-Gally, M.M. and Naim, M.A. (2010). Study of the environmental impacts of the natural radioactivity presents in beach sand and Lake Sediment samples Idku, Behara, Egypt, in: Proceedings of the 10th Radiation Physics & Protection Conference. Cairo, Egypt, 27-30.

Franco-Uría, A., López-Mateo, C., Roca, E. and Fernández-Marcos, M.L. (2009). Source identification of heavy metals in pastureland by multivariate analysis in NW Spain. J. Hazard. Mater. 165, 1008–1015. doi:10.1016/j.jhazmat.2008.10.118.

Gjoka, F., Felix-Henningsen, P., Wegener, H.R., Salillari, I. and Beqiraj, A. (2011). Heavy metals in soils from Tirana (Albania). Environ. Monit. Assess. 172, 517-527. doi:10.1007/s10661-010-1351-5

Gorchev, H.G. and Ozolins, G. (1984). WHO guidelines for drinking-water quality. WHO Chron. 38, 104-108. doi:10.1016/S1462-0758(00)00006-6.

IAEA (1996). International Basic Safety standards for Protection against Ionizing radiation and for the Safety of Radiation Sources, Safety series. Vienna, Austria.

ICRP (2007). Recommendations of the International Commission on Radiological Protection, ICRP Publication 103, Annals of the International Commission for Radiological Protection. Pergamon Press, Oxford.

Khayet, M. and Matsuura, T. (2013). Radioactive decontamination of water. Desalination 321, 1–2. doi:10.1016/j.desal.2013.05.004.

Kishe, M.A. and Machiwa, J.F. (2000). Distribution of heavy metals in sediments of Mwanza Gulf of Lake Victoria, Tanzania. Environ. Int. 28, 619-625.

Liang, L.N., Jiang, G.B., Liu, J.F. and Hu, J.T. (2003). Speciation analysis of mercury in seafood

by using high-performance liquid chromatography on-line coupled with cold-vapor atomic fluorescence spectrometry via a post column microwave digestion. Anal. Chim. Acta 477, 131-137. doi:10.1016/S0003-2670(02)01412-5.

Liu, C.W., Lin, K.H. and Kuo, Y.M. (2003). Application of factor analysis in the assessment of groundwater quality in a black foot disease area in Taiwan. Sci. Total Environ. 313, 77-89.

Lu, A., Wang, J., Qin, X., Wang, K., Han, P. and Zhang, S. (2012). Multivariate and geostatistical analyses of the spatial distribution and origin of heavy metals in the agricultural soils in Shunyi, Beijing, China. Sci. Total Environ. 425, 66-74. doi:10.1016/j.scitotenv.2012.03.003.

OECD/NEA (1979). Exposure to radiation from natural radioactivity in building materials, report by NEA Group of Experts, Nuclear Energy Agency. OECD. Paris.

Ogoyi, D.O., Mwita, C.J., Nguu, E.K. and Shiundu, P.M. (2011). Determination of heavy metal content in water, sediment and microalgae from Lake Victoria, East Africa. The open Environmental Engineering Journal. 4, 156-161.

Pakade, V.E., Cukrowska, E.M., Darkwa, J., Darko, G., Torto, N. and Chimuka, L. (2012). Simple and efficient ion imprinted polymer for recovery of uranium from environmental samples. Water Sci. Technol. 65, 728-736. doi:10.2166/wst.2012.911.

UNSCEAR (2000). Annex B: Exposures from natural radiation sources, UNSCEAR 2000 Report: Sources and Effects of Ionizing Radiation. New York.

Uosif, M.A.M., Mostafa, A.M.A., Elsaman, R. and Moustafa, E. (2014). Natural radioactivity levels and radiological hazards indices of chemical fertilizers commonly used in Upper Egypt. J. Radiat. Res. Appl. Sci. 7, 430-437. doi:10.1016/j.jrras.2014.07.006.

Uosif, M., Abuel-Fadl, K., Issa, S.M., Mostafa, A. and Taha, M.M. (2013). The status of natural radioactivity and heavy metals pollution on soil at Assiut Zone in Central Upper-Egypt. Radiat. Prot. Environ. 36, 20–26. doi:10.4103/0972-0464.121819.

US-EPA (2012). 2012 Edition of the Drinking Water Standards and Health Advisories. EPA 822-S-12-001. Washington DC.

US-EPA (2007). Field portable x-ray fluorescence spectrometry for the determination of elemental concentrations in soil and sediment. Method 6200 [WWW Document]. URL http://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/3dc283e6c5d6056f88257426007417a2/e599199dc919b049882576a300616943/$file/attachment 1.pdf#_ga=1.260838029.1899728909.1418825614.

Welz, B. and Melcher, M. (1985). Decomposition of marine biological tissues for determination of arsenic, selenium, and mercury using hydride-generation and cold-vapor atomic absorption spectrometries. Anal. Chem. 57, 427-431. doi:10.1021/ac50001a024.

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