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Mercury and lead pollution in rivers in Ghana: geo-accumulation index, contamination factor, and water quality index

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ABSTRACT

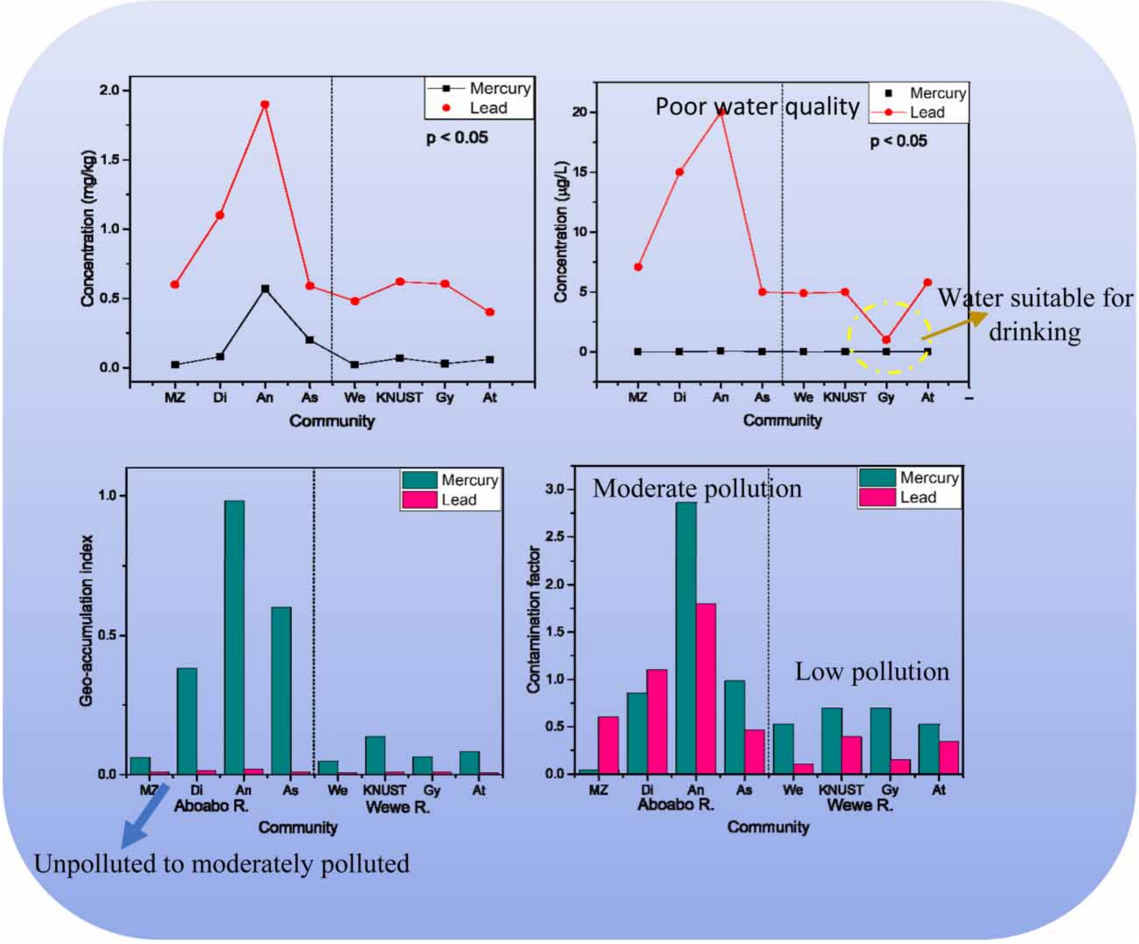
The main environmental problem in Kumasi is water pollution, but little is done about this. Neither water quality nor the degree of heavy metal contamination in Kumasi has been assessed. The degree of mercury and lead pollution in Kumasi was investigated in this study by determining the geo-accumulation index, the contamination factor, and the water quality index (WQI) of mercury and lead in selected rivers in Kumasi. Mercury and lead concentrations were the highest in the Aboabo River, particularly in the Anloga area. This was attributed largely to electronic waste dumping, collection, and processing in the area. The WQI of the rivers indicated that the water was unsuitable for drinking. It is also shown that the water should not be used for crop cultivation or animal rearing, which are among the anthropogenic activities that are both carried out along the rivers, to limit risk to human health.

Key words: contamination factor, geo-accumulation index, heavy metal, water pollution, water quality index

HIGHLIGHTS

- Mercury and lead concentrations in the Aboabo River exceed the WHO recommended maxima.
- The poor water quality limits the usability of the river water.
- Phytoremediation in the Gyinyase area contributed to the water quality of the Wewe River.
- Sustainable environmental policies and practices can reduce water pollution.

GRAPHICAL ABSTRACT



INTRODUCTION

Water pollution, any change in the state of water that results in adverse consequences on living organisms when consumed, is a major global issue (Akubugwo *et al.* 2013; Wirnkor *et al.* 2018; Hasan *et al.* 2019). Water can be polluted through anthropogenic or natural means (Shukla *et al.* 2010; Machiwal & Jha 2014; Singh *et al.* 2019; Bhardwaj *et al.* 2020). Anthropogenic sources of pollution include the discharge of partially treated/untreated wastewater, the use of synthetic fertilizers, and improper waste management (Akpoveta *et al.* 2011; Hussain *et al.* 2019; Anjum *et al.* 2021). The determinants of water pollution vary extensively depending on the population growth rate, techniques of waste management, and the local development level (Olajuyigbe *et al.* 2012). Akubugwo *et al.* (2013) and Seiyaboh *et al.* (2016) reported that countries with poor waste management systems and high population growth rates generate more waste compared to those with proper waste management systems and relatively low population growth rates, which can cause water pollution, when contaminants leach from waste dumpsites.

The exponential growth rate and rapid industrialization and urbanization over the past decade in major cities in Ghana have contributed significantly to river quality deterioration in the country's cities. Causes of water pollution in Ghana vary depending on the prevailing economic activities in the various regions. In Kumasi (Ghana's second largest city), major pollution causes include the leaching of synthetic fertilizers, pesticides, dyes, and heavy metals from farms, tanning industry sites, and industrial/electronic waste dumpsites (Agyarko *et al.* 2010; Oduro *et al.* 2012). Industrial/electronic waste contains trace amounts of heavy metals such as arsenic, cadmium, cobalt, nickel, mercury, and lead (Singh *et al.* 2011). In mining communities, the main cause of water pollution includes heavy metal leaching from mine sites (Boateng 2018; Duncan 2020). The presence of heavy metals in water sources (sediments and aqueous phase) increases fish mortality, reduces biodiversity, and can cause carcinogenic and neurotoxic effects in humans when the water is ingested (Wang *et al.* 2012; Ansah *et al.* 2018; Opoku *et al.* 2020). Public health may be at risk when heavy metals bioaccumulate in livestock that are later consumed by humans. Ingestion of contaminated water can also cause typhoid, polio, hepatitis, dysentery, diarrhea, and cholera in humans (Levallois & Villanueva 2019; Lin *et al.* 2022).

Several studies have been made in the levels of heavy metals and nutrients in major rivers – e.g., the Pra, Ankobra, Tano, and Densu Rivers – in Ghana (Oduro *et al.* 2012; Awuah 2016; Ansah *et al.* 2018; Duncan *et al.* 2018). Awuah (2016) assessed the levels of mercury, lead, and arsenic in the Tano and Ankobra rivers and concluded that the concentration of heavy metals was in the order of mercury > arsenic > lead. In Duncan *et al.* (2018), the concentrations of zinc, arsenic, iron, and manganese in the Pra River showed low geo-accumulation indices (I_{geo}), indicating low to moderate contamination with these species. Bessah *et al.* (2021) assessed surface waters and pollution impacts in southern Ghana, mainly focusing on 25 rivers in the Pra River Basin. They reported that the concentration of lead exceeded the WHO recommendation in about 30% of the rivers assessed, and that concentrations of iron, mercury, copper, and arsenic were above the permissible levels for farm irrigation, particularly, in mining communities along the river. They recommended that a more efficient and effective land-use policy be formulated to minimize water quality degradation in the basin. Ansah *et al.* (2018) established the concentrations of iron, manganese, cadmium, copper, nickel, zinc, and lead in the Weija Reservoir. Obiri-Yeboah *et al.* (2021) assessed the potential health effect of mercury and lead and the influence of artisanal mining activities in the Bonsa River in Tarkwa. A comparative assessment of heavy metals in drinking water sources in northern Ghana was evaluated by Cobbina *et al.* (2015). They reported that the concentrations of mercury, zinc, lead, cadmium, and arsenic in water sources in the Nangodi and Tinga areas far exceeded WHO's recommended maximum, and the local water sources were not suitable for drinking. In effect, they have the potential to cause significant health risks among the local people. Kpan *et al.* (2014) investigated heavy metal pollution in soil and water in towns in Dunkwa-on-Offin District, central Ghana, due to small-scale gold mining. They reported that heavy metal contamination levels have spread beyond control since the concentrations of lead, copper, and mercury all exceed the WHO recommendation. Asiedu *et al.* (2013) conducted a non-cancer, human health risk assessment from exposure to copper, mercury, lead, and cadmium in surface water and groundwater in Konongo-Odumasi Municipality, Ghana, and found that children and adults were at risk of non-cancer health diseases if they consumed groundwater in the area. However, surface water consumption does not expose them to such agents, because the hazard quotient (defined as the ratio of the average daily dose (ADD) of exposure to a substance to the reference dose (RfD) which is the daily dose that enables an exposed individual to sustain some degree of exposure over a certain period of time without experiencing significant harmful effects (Asiedu *et al.* 2013)) in the area's groundwater was greater than 1, whereas in the surface water it was below 1.

The water quality of rivers in Kumasi has not been extensively investigated, and the collective impact of contaminants on river water quality there is not known. This makes it difficult to determine the extent to which the ingestion of contaminated water directly affects human health.

In this study, mercury and lead pollution in the Wiwi and Aboabo Rivers in Kumasi were evaluated through the determination of contamination factor (CF), I_{geo}, and water quality index (WQI). The Wiwi River was selected because of the prevalent use of synthetic fertilizers along it by farmers and its use to irrigate crops. Ahmad *et al.* (2019) and De Santiago-Martín *et al.* (2020) have reported that crops absorb contaminants from water used during irrigation, potentially posing risks to human health when consumed. The Aboabo River was selected because of the tanning and livestock farming activities carried out along its banks, as well as the electronic dumpsite about 10 m away from it. This study (1) determined the concentrations of mercury and lead in sediment and water in the rivers; (2) evaluated the CF and I_{geo} of those metals in the sediment; and (3) established the WQIs of the rivers with respect to lead and mercury concentrations.

MATERIALS AND METHODS

Study area

The study was carried out in Kumasi (latitude 6° 35′–6° 40′ N and longitude 1° 30′–1° 35′ W), the capital of Ashanti Region, Ghana. The city covers about 270 km^2 and is around 248.3 km North-West of Accra. Its population is approximately 2 million and the growth rate is about 5.4% (Appiah *et al.* 2020). The study area, which is Kumasi, is shown in Figure 1. The Aboabo and Wiwi Rivers (latitude 6° 40′ 32.9″–6° 41′ 30.1″ N and longitude 1° 33′ 74.4″–1° 34′ 20.9″ W) both pass through Kumasi (Amo *et al.* 2017; Akoto *et al.* 2021). The Aboabo River

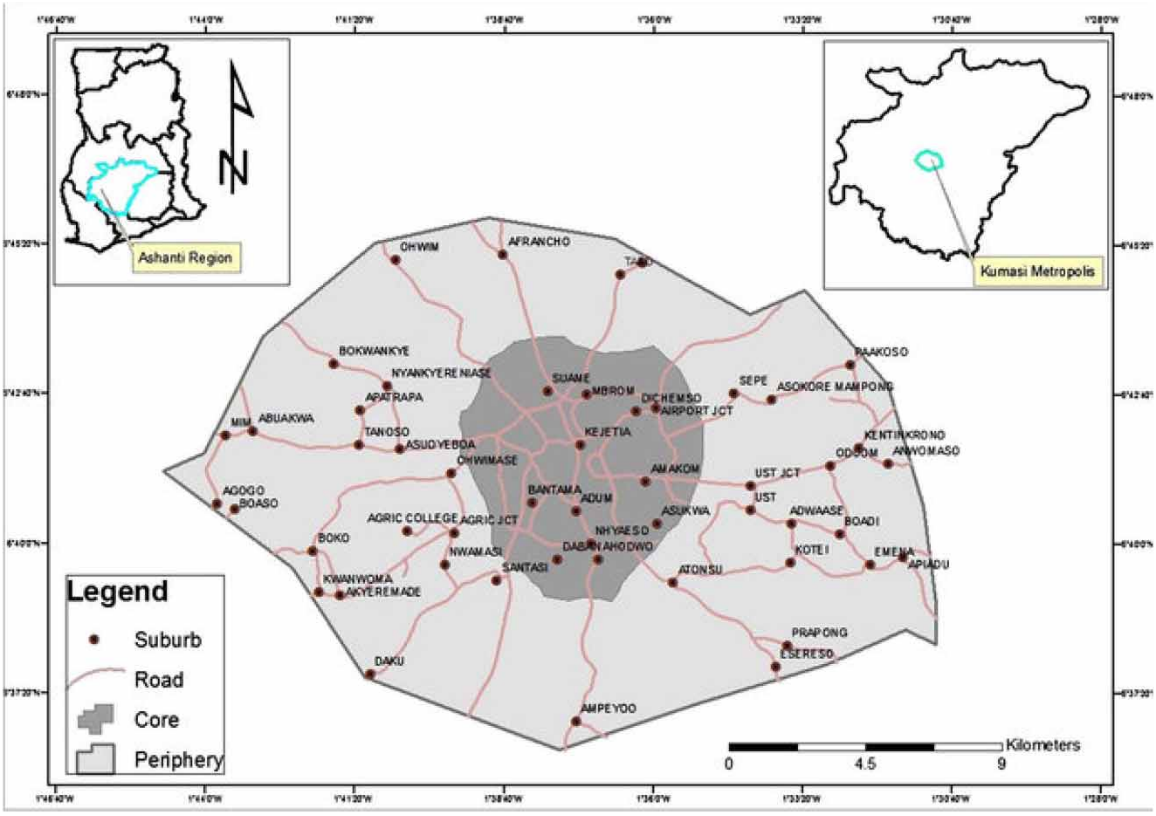


Figure 1 | The study area showing the Kumasi Metropolis (Adam & Amuquandoh 2013).

(average flowrate 0.87 m/s) rises in Tafo Pankrono in northern Kumasi and flows southward through Moshie Zongo, Dichemso, and Anloga Junctions to join the Sisan River at Asokwa (Boateng 2020) (Figure 2). The Wiwi River rises in Aboabo Nkwanta and flows southwest toward Abirim, Wiwiso, joining the Sisan River at Atonsu through KNUST or UST (Kwame Nkrumah University of Science and Technology) and Gyinyase (Figure 2).

Sampling

Water (500 mL) and sediment samples were taken from communities along the Aboabo – e.g., Moshie Zongo, Dichemso, Anloga, Asokwa – and Wiwi Rivers – e.g., Wiwiso, KNUST, Gyinyase, and Atonsu. In each community, four samples were taken (sampling sites within communities were 1 km apart), and the average lead and mercury concentrations were determined. All 32 samples were collected over 3 months (June to August 2019). The samples were labeled and transported on ice (4 °C) to the KNUST Chemistry Laboratory.

Analytical procedure

Both water and sediment samples were subjected to wet digestion before atomic absorption spectrometry (AAS) (SHIMADZU AA7000 Series, Japan) to determine lead concentrations. Water sample preparation for lead analysis involved adding 10 mL of HNO_3 (5 M) to 50 mL of each sample, swirling gently and heating for about 30 min before cooling to room temperature (25 °C) (Azanu & Voegborlo 2014).

Sediment samples were dried for 7 days, then ground and sieved before 1 mL of distilled water was added to 1 g of sample, followed by 4 mL of each HNO_3 (5 M) and $HClO_4$ (4 M). The mixture was homogenized, and 5 mL of H_2SO_4 (6 M) was added before boiling at 200 °C for about 45 min (Mwegoha 2008).

The sediment and water digestion supernatants were filtered (0.45 μm) into 50 mL flasks for AAS lead analysis. A hollow cathode lamp (Akoto *et al.* 2016) was used to determine Pb concentrations. AAS calibration depended on a linear five-point calibration curve for which the calibration co-efficient was higher than 0.999 (Amankwaa *et al.* 2020).

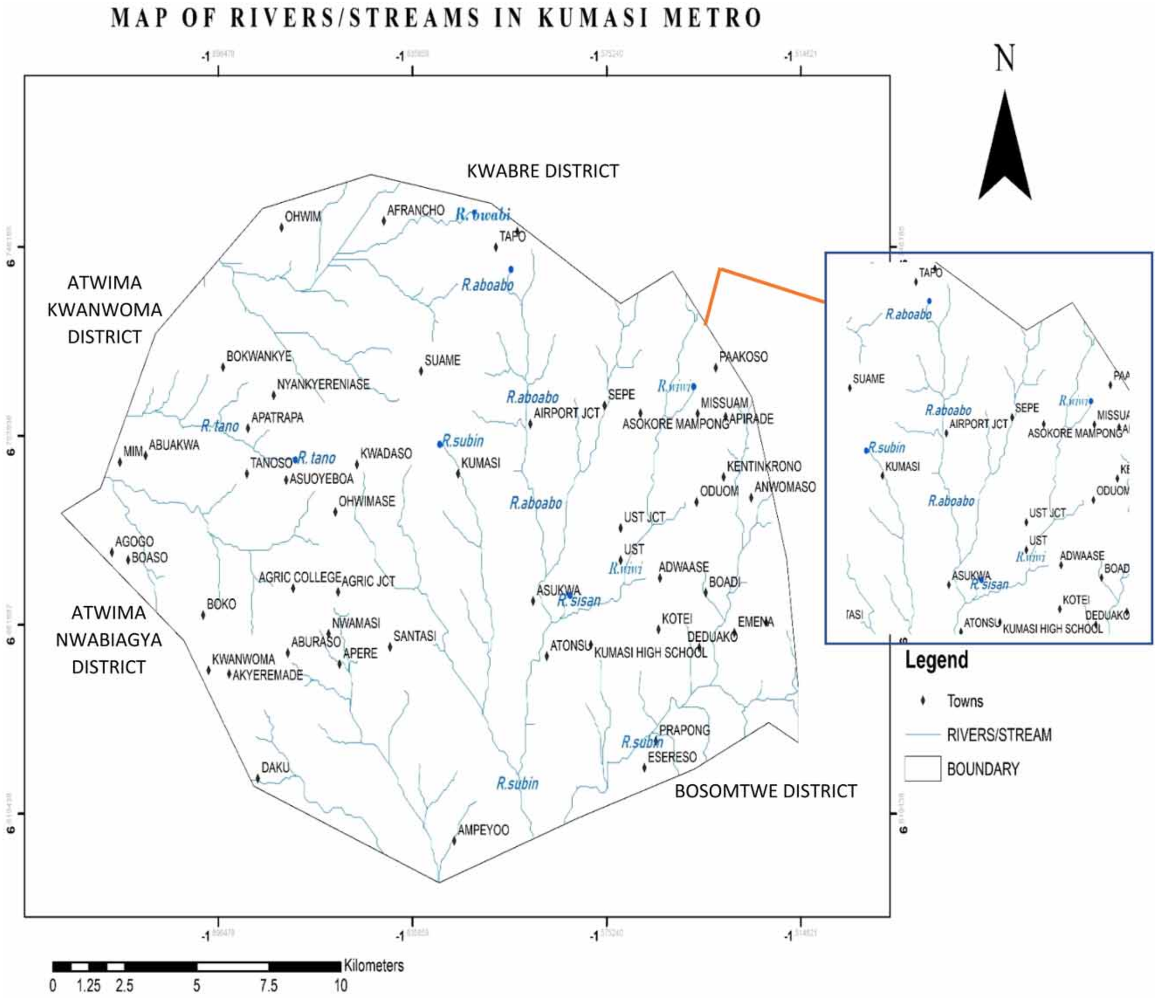


Figure 2 | The study area showing the Wiwi and Aboabo Rivers.

A cold vapor AAS/hydride generator (Pyro-915$^+$, Alumex, Canada) was used to determine sediment mercury concentrations; hence, the sediment samples for mercury analysis were not digested. The water samples for mercury analysis were digested, however, and determined by AAS. Wet digestion of the water samples for mercury analysis involved adding H_2SO_4 (5 mL, 6 M) and HNO_3 (2.5 mL, 5 M) to 50 mL of each sample in a 300 mL Erlenmeyer bottle, followed by 15 mL of $KMnO_4$ (4 M). The mixture was homogenized and allowed to stand for about 15 min (Azanu & Voegborlo 2014) before $K_2S_2O_8$ (8 mL, 5 M) was added and the mixture was heated for 2 h (95 °C) before cooling at ambient temperature. Excess $KMnO_4$ was removed by adding 5 mL of hydroxylamine. The water digestion supernatants were filtered (0.45 μm) into 50 mL flasks for AAS analysis. A blank solution was prepared for AAS analysis using the same process as wet digestion. For the sediment, the mercury concentration was determined using the hydride generator. Analyses were done in duplicate and the values were analyzed statistically.

Data analyses

The geo-accumulation index (I_{geo}) was calculated to determine the extent of heavy metal adsorption in the sediments. It was determined by comparing the sediment heavy metal and background concentrations – Equation (1) (Agyarko *et al.* 2010).

$$I_{\text{geo}} = \log_2(C_n/(1.5 \times B_n)) \quad (1)$$

where C_n is the measured concentration of the heavy metal in the sediment (mg/kg); B_n (determined by the composition of the underlying rock and weathering) is the background value of the heavy metal (mg/kg); and 1.5 is the background matrix correction factor (Agyarko *et al.* 2010). The I_{geo} classes proposed by Förstner *et al.* (1993) are shown in Table 1.

Table 1 | Classes of I_{geo} adopted to define the sediment quality

Value	Class	Description
<0	0	Unpolluted
0–1	1	From unpolluted to moderately polluted
1–2	2	Moderately polluted
2–3	3	From moderately polluted to strongly polluted
3–4	4	Strongly polluted
4–5	5	From strongly polluted to extremely polluted
>5	6	Extremely polluted

Adapted from Förstner *et al.* (1993).

The CF was calculated to determine the extent of contamination (Brown & Margolis 2012). The CF is expressed in Equation (2).

$$\text{CF} = C_{\text{metal}}/C_{\text{background}} \tag{2}$$

where C_{metal} is the concentration of heavy metal in the sediment (mg/kg), and $C_{\text{background}}$ is its background value (mg/kg) (Mmolawa *et al.* 2011) – see Table 2.

$$K = 1/\left(\frac{\sum 1}{S_n}\right) \tag{3}$$

$$W_n = K/S_n \tag{4}$$

$$Q_n = \frac{V_n}{S_n} * 100 \tag{5}$$

$$\text{WQI} = Q_n W_n \tag{6}$$

Table 2 | Categories of CF to determine the sediment quality

Value	Class	Description
<1	0	Low contamination
$1 \leq \text{CF} < 3$	1	Moderate contamination
$3 \leq \text{CF} < 6$	2	Considerable contamination
> 6	3	Very high contamination

Adapted from Mmolawa *et al.* (2011).

where K is the constant of proportionality (Equation (3)), S_n is the standard of the heavy metal (Equations (3) and (4)), W_n is the weight of the heavy metal (Equations (4) and (6)), Q_n is the quality rating scale (Equations (5) and (6)), and V_n is the estimated value of the nth water quality parameter (Equation (5)) (Yidana *et al.* 2008).

The water quality classification based on the WQI values is shown in Table 3 (Yidana *et al.* 2008).

The validity of the results was obtained by replicating the *treatments* two times in order to obtain similar results. The mean of the replicated results was calculated in order to facilitate the interpretation of the results and comparison with the literature.

Table 3 | Ranges for water quality classification based on WQI values

WQI	Description	Class
<50	Excellent water	I
50–100	Good water	II
100–200	Poor water	III
200–300	Very poor water	IV
>300	Water unsuitable for drinking	V

Fatoki *et al.* (2002).

RESULTS AND DISCUSSION

Concentrations of mercury and lead in the sediment

The mean concentrations of mercury and lead in the sediment are presented in Figure 3. It is obvious that the mercury and lead concentrations in the Aboabo River were higher than those in the Wiwi River. The mercury concentration in the Aboabo River ranged from 0.02 to 0.57 mg/kg, and in the Wiwi River, from 0.02 to 0.07 mg/kg. The lead concentration in the Aboabo River ranged from 0.59 to 1.9 mg/kg, and in the Wiwi River from 0.40 to 0.62 mg/kg (the variations in the mean concentrations were significant since the *p*-value was less than 0.05 ($p < 0.05$)). Specifically, the mercury concentration in the Anloga area (0.57 mg/kg) exceeded the WHO-recommended maximum (RM) in the sediment (0.2 mg/kg). The lead concentration in both rivers exceeded the WHO RM in the sediment (0.3 mg/kg). Lead concentration (1.9 mg/kg) was the highest in the Anloga area, and this is attributable to the dumping, processing, and collection of electronic waste in the area.

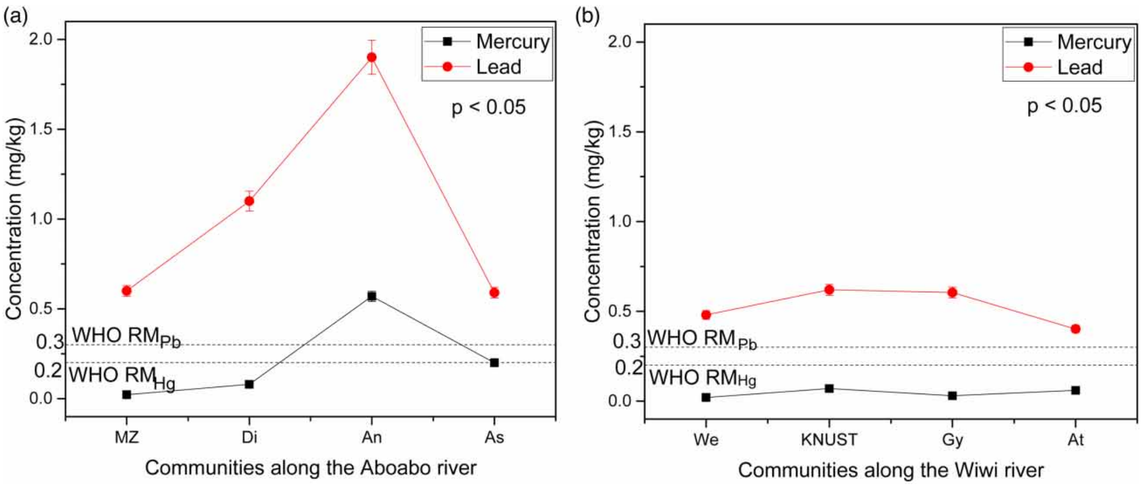


Figure 3 | Concentrations of mercury and lead in the sediment found in (a) the Aboabo and (b) Wiwi Rivers (notations: MZ, Moshie Zongo; Di, Dichemso; An, Anloga; As, Asokwa; We, Wiwiso; KNUST, Kwame Nkrumah University of Science and Technology; Gy, Gyinyase; At, Atonsu).

Concentrations of mercury and lead in water

Figure 4 presents the concentrations of mercury and lead in water sampled from the two rivers. It is evident that the soluble mercury concentration in the rivers was well below the WHO RM for drinking water (2 μg-Hg/L). The mercury concentrations determined at the sampling sites along the Aboabo River were 0.011 μg/L (Moshie Zongo), 0.01 μg/L (Dichemso), 0.06 μg/L (Anloga), and 0.03 μg/L (Asokwa). Additionally, the concentrations of mercury in the Wiwi River were found to be 0.013 μg/L (Wiwiso), 0.017 μg/L (KNUST), 0.02 μg/L (Gyinyase), and 0.016 μg/L (Atonsu). The concentration of soluble lead was higher than that of mercury in both rivers. Comparing the lead concentrations in the rivers, the soluble lead concentration was higher in the Aboabo than that in the Wiwi. Again, the lead concentration was the highest at the Anloga area (20 μg/L) as compared to the other communities along the Aboabo River (7.1 μg/L – Moshie Zongo; 15 μg/L – Dichemso; 5 μg/L – Asokwa). In the

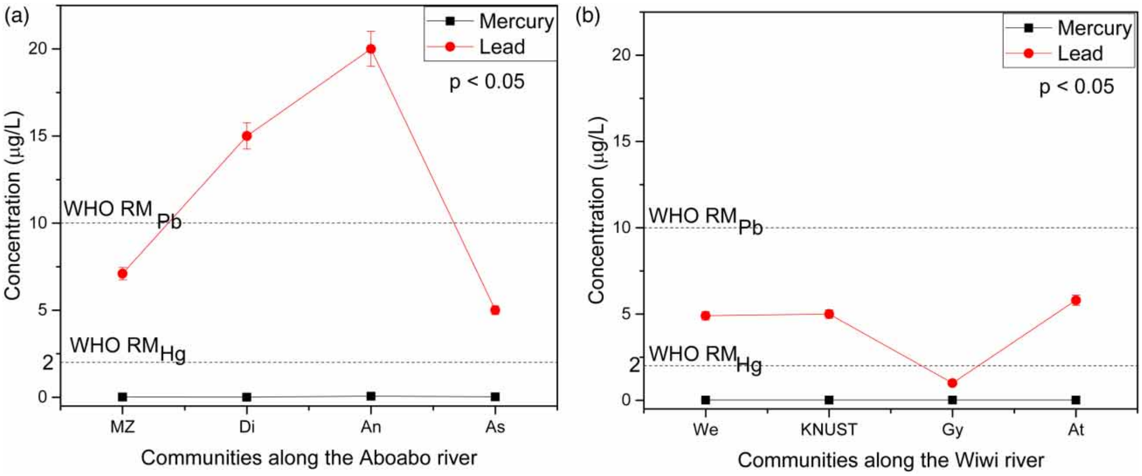


Figure 4 | Concentrations of mercury and lead in water found in (a) Aboabo and (b) Wiwi Rivers (notations: MZ, Moshie Zongo; Di, Dichemso; An, Anloga; As, Asokwa; We, Wiwiso; KNUST, Kwame Nkrumah University of Science and Technology; Gy, Gyinyase; At, Atonsu).

Wiwi River, the concentration of lead in the Gyinyase area was markedly low (1 µg/L) compared to other communities along the river. This could be due to the absence of activities, which could cause lead discharge or runoff into the Wiwi River.

The higher concentration of mercury in the sediment found in the Aboabo River compared to that in water sampled from it could be attributed to adsorption (Akoto *et al.* 2021), and this is thought to be likely in relation to both rivers.

Geo-accumulation index and contamination factor

The accumulation of mercury and lead in the sediments of both rivers was investigated with the I_{geo} formula (see Figure 5(a)). The I_{geo} values for both mercury and lead were less than 1, indicating that mercury–lead accumulation in the sediment of both rivers fell within Class I and that the sediments were unpolluted to moderately polluted (Fatoki *et al.* 2002; Nowrouzi & Pourkhabbaz 2014). The mercury CF in the Aboabo River along Anloga and Asokwa was higher than 1 (Figure 5(b)), denoting moderate contamination (Mmolawa *et al.* 2011). Similarly, the lead CF in the Aboabo River along Anloga and Dichemso showed moderate contamination compared to the other communities, which had low contamination. The I_{geo} and CF values show that leaching from the electronic waste around the Aboabo area significantly impacts its contamination (from mid-stream to downstream) compared to the agro-chemical leaching from farms along the Wiwi River.

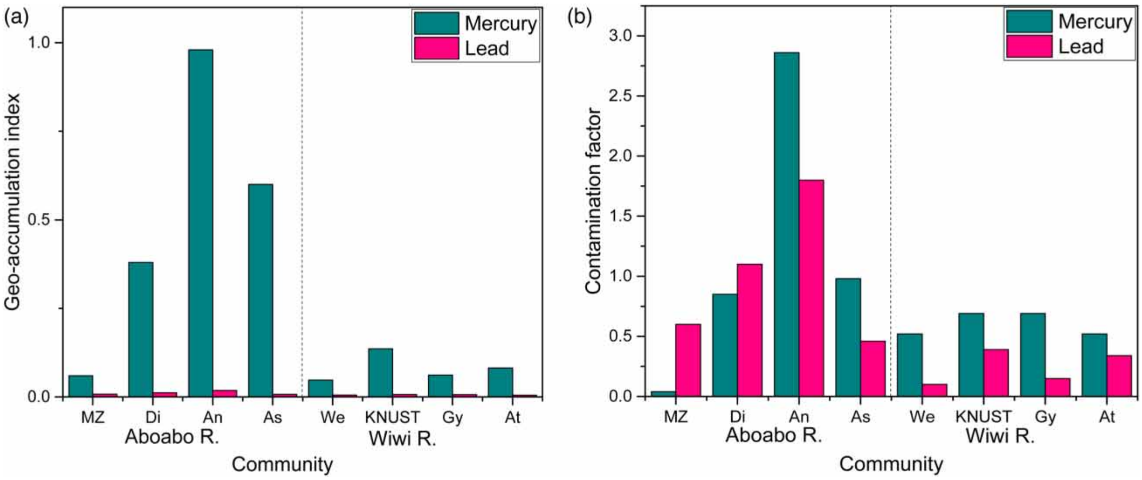


Figure 5 | I_{geo} (a) and CF (b) of mercury and lead in the sediment (notations: MZ, Moshie Zongo; Di, Dichemso; An, Anloga; As, Asokwa; We, Wiwiso; KNUST, Kwame Nkrumah University of Science and Technology; Gy, Gyinyase; At, Atonsu).

Water quality index

The calculated WQI values that depict the potability of the rivers are shown in Table 4. The water quality in the Gyinyase area can be attributed to the presence of water hyacinth in the Wiwi River in that area. The water hyacinth, in this case, serves as phytoremediation, absorbing the heavy metal content (Mwegoha 2008).

Table 4 | Classification of the WQI for the selected rivers

S/N	WQI	Description	Class
MZ	473.5	Water unsuitable for drinking	V
Di	1,000.1	Water unsuitable for drinking	V
An	1,333.4	Water unsuitable for drinking	V
As	333.8	Water unsuitable for drinking	V
We	326.8	Water unsuitable for drinking	V
KNUST	333.6	Water unsuitable for drinking	V
Gy	67.0	Good water	II
At	386.9	Water unsuitable for drinking	V

CONCLUSIONS

The degree of mercury and lead pollution in two major rivers in Kumasi was evaluated in this study. The evaluation was done by determining the mean concentrations of mercury and lead in water and sediment in the rivers. The I_{geo}, CF, and WQI were also determined to further investigate the extent of pollution of the rivers by mercury and lead. The mean concentrations of mercury were found to be low in both rivers as compared to lead. The assessment of the I_{geo} showed that mercury was more accumulated in the sediment samples as compared to lead. Moreover, the geo-accumulation of mercury was highest in the Aboabo River in the Anloga and Asokwa areas. The CFs of mercury and lead were also high in the Aboabo River, particularly, in the Anloga area. It was therefore concluded that the anthropogenic activities (especially dumping, collection, and processing of electronic waste) carried out along the Aboabo River largely contribute to its pollution. Overall, the Wiwi River was also found to be unsuitable for drinking with the exception of the water in the Gyinyase area (in terms of the heavy metals assessed) due to the presence of water hyacinth. However, it is indisputable that further assessment of water in the Gyinyase area in terms of biological components could show otherwise.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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