Journal of Geoscience and Environment Protection, 2022, 10, 48-69
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Heavy Metal Dispersion in Stream Sediments in River Iyiudene, Abakaliki South-Eastern Nigeria: Source, Distribution Pattern, and Contamination Assessment

Emmanuel U. Nwazue[1], Erepamo J. Omietimi[2*], Eniye Mienye[3], Osayamen J. Imarhiagbe[4], Olumide A. Adeosun[5], Paulinus N. Nnabo[1]

[1]Department of Geology, Ebonyi State University, Abakaliki, Nigeria
[2]Department of Geology, University of Pretoria, Pretoria, South Africa
[3]Bayelsa state Polytechnic Aleibiri, Ekeremor, Nigeria
[4]Division of Earth Sciences and Geography, RWTH Aachen University, Aachen, Germany
[5]Department of Geology, University of Ibadan, Ibadan, Nigeria

Email: *u19390514@tuks.co.za

How to cite this paper: Nwazue, E. U., Omietimi, E. J., Mienye, E., Imarhiagbe, O. J., Adeosun, O. A., & Nnabo, P. N. (2022). Heavy Metal Dispersion in Stream Sediments in River Iyiudene, Abakaliki South-Eastern Nigeria: Source, Distribution Pattern, and Contamination Assessment. *Journal of Geoscience and Environment Protection, 10,* 48-69.
https://doi.org/10.4236/gep.2022.107004

Received: March 9, 2022
Accepted: July 10, 2022
Published: July 13, 2022

Abstract

River Iyiudene is a vital distributary resource in Abakaliki, southeastern Nigeria and conveys an abundant amount of sediments to provincial and residual ecosystems. Although the importance of the river cannot be overemphasized, the geochemistry of its stream sediments is less investigated. Twenty (20) stream sediment samples were taken at the centre of the river channels to represent the entire drainage area well and avoid collapsed bank materials. The stream sediment samples were used to determine the dispersion, contamination status and sources of heavy metal concentrations. Total elemental digestion accompanied this with the use of aqua regia, an admixture of Hydrochloric acid (HCl) and Nitric acid (HNO_3) in the ratio of 3:1 using the atomic absorption spectrometer (AAS). The heavy metal concentration levels in River Iyiudene were low compared with sediments from Imo River, Gulf of California, Upper continental crust, Average shale and surface horizons, excluding Cd, which showed high concentration levels than the other reference studies. The results delineated a wide contrast in the concentration levels of the heavy metals, with the mean contents in the order Zn > Cu > Pb > Cd > Ni > As. The pollution evaluation utilizing the Effect range low (ERL), Effect range median (ERM), single pollution index, and geo-accumulation index revealed Cd contamination. This study indicates that the heavy metals were sourced from the natural geological background of the river basin and possibly from agricultural runoff and atmospheric pollutants.

Keywords

Benue Trough, Heavy Metals, Contamination, Stream Sediments, Single Pollution Index, Correlation Matrix

1. Introduction

Rising levels of domestic wastes in urban communities as a result of rapid industrialization marked by huge developmental strides prompted the need to study heavy metal contamination levels in river sediments which have become a global worriment and have earned ample attention due to the lethal and persistent nature of heavy metals in marine and freshwater systems (Sun et al., 2019; Ali et al., 2019). Stream deposits store and transport considerable volumes of heavy metals (Guo et al., 2018; Li et al., 2020). Heavy metals are elements with a specific density of 5.0 or higher and are toxic to organisms and the environment when their concentration levels exceed the permissible limit. They are resistant bio-accumulative contaminants in the environment, and their toxicity is due to their metal structure (Patel et al., 2018). Heavy metals, similar to other metals in stream sediments, are sourced from the breakdown of bedrock, pesticides and fertilizers from agricultural runoff, combustion of fossil fuels, sewage disposal, irrigation of wastewater, industrial and municipal wastes, mining activities, ore smelting, emissions from vehicles and deposition from the atmosphere (Guo et al., 2018; Li et al. 2020).

Heavy metals pose a health threat to living organisms or human consumers once they enter the food chain (Strady et al., 2017; Raut et al., 2017; Xu et al., 2017; Patel et al., 2018). Thus, understanding their concentration levels in stream sediments is vital for assessing river system protection (Li et al., 2020). In terrestrial ecosystems, soils are the major recipient of heavy metals. In contrast, sediments are the primary sink for metals in the aquatic ecosystem; thus, various media are analysed to monitor, assess, and control metal pollution in the environment (Kruopiene, 2007). In the hydrological cycle, 99% of contaminants are stored in sediments, with just 1% dispersed in water (Paramasivam et al., 2015). The bulk of contaminants that are stored in sediments over time will sink and become major pollutants in the aquatic environment (Paramasivam et al., 2015; Nazneen & Patel, 2016; Patel et al., 2018). Hence the analysis of sedimentary deposits from the river system is of significant interest in aquatics system study. Sedimentary deposits indicate the present quality of the aquatic system and also provide relevant clues on the impact of contamination sources. River sediments studies have been performed internationally to comprehend the source, carrier and accretion of heavy metals in aquatic systems (Malvandi et al., 2017; Xu et al., 2017; Nawab et al., 2018; Vu et al., 2018; Patel et al., 2018; Chen et al., 2018; Omwene et al., 2018; Zhang et al., 2019; Li et al., 2020). Various tools have been advanced to appraise the potential risk to the environment and organisms as a result of the presence of heavy metals in stream deposits (Li et al., 2020), and these help in aquatic and environmental management (Vu et al., 2018; Patel et al., 2018; Ji et al., 2019).

Amudo Ezza is situated in Ezza South Local Government Area of Ebonyi province, southeastern Nigeria, within the Lower Benue Trough Basin **Figure 1**. The study area is known for Lead-Zinc mineralization and also the occurrence of Galena and Sphalerite (Igwe et al., 2015; Obiora et al., 2016); thus, this has led to the increase in artisanal mining accompanied by an associated rise in environmental and health challenges (Dondeyne et al., 2009; Huang et al., 2010; Dooyema et al., 2012; Plumlee et al., 2013; Bello et al., 2016; Yabe et al., 2018; Tabelin et al., al., 2020). Entrepreneurship, mining activities and small to large-scale farming are the primary sources of livelihood in the Ebonyi province of the eastern region of Nigeria (Obiora et al., 2016; Okolo & Oyedotun, 2018). Due to the poor management and regulation of the mining sector in Nigeria, most mining activities are prompted by artisanal and small-scale miners, who make up about 95% of miners in Nigeria (Lawal, 2002; Oramah et al., 2015). Oramah et al. (2015) reported that over 500,000 people are directly employed by artisanal and small-scale mining in Nigeria. Hitherto, the economic benefits that come from creating jobs, the risk that artisanal, open cast and small-scale mining poses are great due to the challenges tangled with the coordination and adequate monitoring of such enterprises (Twerefou, 2009; Ochieng et al., 2010; Oramah et

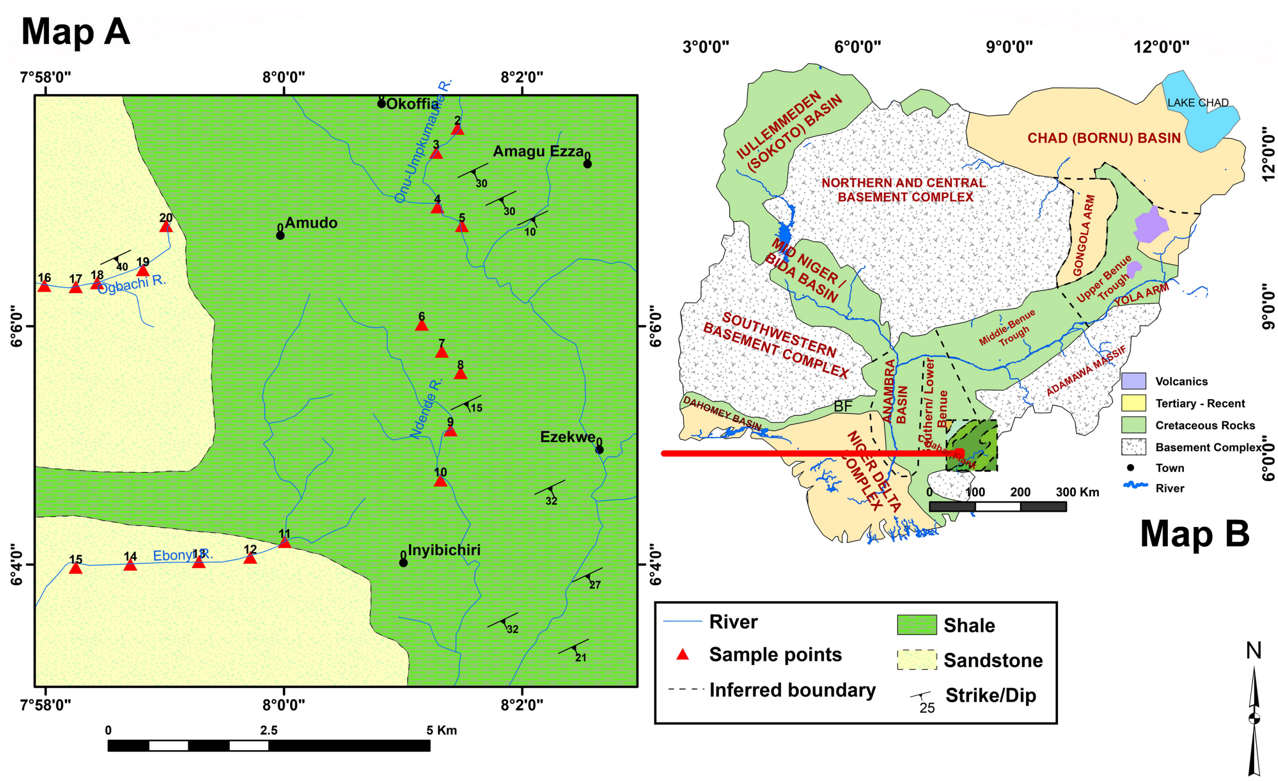

Figure 1. A. Geologic map of Amudo-Ezza and environ. B. Geologic map of Nigeria showing the study area (modified from Obaje, 2009).

al., 2015). Surface runoff can carry heavy metals associated with pesticides, fertilizers from agricultural activities and toxic metals associated with mining-related activities and deposit these poisonous metals into tributary and stream sediments. Therefore, this could lead to heavy metal contamination, affecting the ecosystem and human health in Ebonyi province (Okolo & Oyedotun, 2018).

The pollution and contamination of Pb, Cd, Zn, and Cu in soils around Enyigba have been studied, but there is a paucity of research on the stream sediments of Amudo-Ezza (Chukuma, 1994; Ezeh, 2007). Heavy metal pollution in Abakaliki Ebonyi province has led to persistent cardiovascular diseases in inhabitants around Lead-Zinc mineralization areas where mining activities are the primary source of livelihood (Okogbue & Ukpai, 2013). Contamination of water bodies by heavy metals in Enyigba, Abakaliki Ebonyi province has been reported by Ezeh & Anike, 2009; Nnabo, 2016; Igwe et al., 2015; Okolo & Oyedotun, 2018; Aloke et al., 2019; Obiora et al., 2019. Other researchers have observed higher than acceptable concentration limits of Pb, Cd and Ni in agricultural soils in the regions around the study area. At the same time, traces of heavy metals have also been observed in bouillon cubes and food condiments in some eastern states in Nigeria (Orisakwe et al., 2012, Obiora et al., 2016). Ogbodo (2011) accessed the soil fertility of the Iyiudene floodplain, Iyiokwu floodplain, Ebonyi river basin and upland areas in Abakaliki, eastern Nigeria. The research revealed low soil fertility for agricultural purposes. Also, Ali et al. (2019) posited that heavy metals could disturb metabolic processes and genetic makeup while also affecting foetal development, eventually leading to cancer and other developmental anomalies observed in some children. Hence there is a pertinent need to study the stream sediments in the study area owing to the fact the streams serve as a source of survival for residents of the area. Opencast mining is suggested to be the main contributor to heavy metal pollution in the eastern region of Nigeria (Okogbue & Ukpai, 2013; Okolo et al., 2015; Nnabo, 2016; Okolo & Oyedotun, 2018). Recently, Egbueri et al. (2020) reported heavy metal pollution of As, Cd, Co, Ni, Pb and Se in hand-dug wells and boreholes in Ameka district Ezza south local government area Ebonyi state. Onu-umpku ufie, Ndende, Onuebonyi and Ogbachi in Amudo-Ezza are vital tributaries in Ebonyi province in southeastern Nigeria and serve as the sources of surface water resources to over 150,000 people (NPC, 2007). These toxic metals that get attached to surface particles of the stream deposits can easily be released into the stream water and thus will be eventually ingested by the inhabitants who rely on surface water for domestic purposes and aquatic organisms. Therefore, there is a need to provide new insights into the contamination levels of stream sediments in the River Iyiudene Amudo-Ezza in southeastern Nigeria.

Based on a literature search of the present study area, no published work assessed the contamination status of stream sediments of River Iyiudene and the effects of these selected toxic metals on the ecosystem and humans. Therefore, in the present research, stream sediments were collected from Rivers Onu-umpku ufie, Ndende, Onuebonyi and Ogbachi in Amudo-Ezza, southeastern Nigeria and were analysed to (I) decipher the dispersion levels of heavy metals (lead, zinc, copper, cadmium, arsenic and nickel) (II), assess the contamination levels of the selected heavy metals using different techniques, Single pollution index (PI), Geo-accumulation index (Igeo), and Correlation matrix and (III) decipher the potential sources of the heavy metals in Amudo-Ezza stream deposits and how they affect the environment and its residents. Heavy metal assessment in River Iyiudene stream sediments would provide insights into the quality of the ecosystem.

2. Study Area Setting

The study area Amudo-Ezzai is situated in Ebonyi county, eastern Nigeria, which is bounded by coordinate readings 6˚03'N and 6˚08'N and Longitude 7˚58'E and 8˚03'E covering a total area of about 81 km^2 (**Figure 1**). Amudo-Ezza is within the Abakaliki Shale of the Asu River Group. Geologically the study area consists of Cretaceous deposits of the Asu river group belonging to the Benue Trough. The Benue Trough was developed due to the break-up of the South American continent from the African continent in the Early Cretaceous (Obaje et al., 2004). The Asu River group comprises shales, mudstones and sandstones.

The study area comprises shales, and mudstones, which appeared brown to dark grey, weathered, fissile and jointed. Also, the shales and mudrocks are embedded by the vein mineralization of lead-zinc and baked shales that are intrusive along veins (Nnabo et al., 2011). The lead-zinc vein mineralization is accommodated inside the grey to dark grey shales (Nnabo et al., 2011). The general trends of the beds were in the NE-SW direction, which corresponds to the significant trend in the Benue trough. The wet (i.e. rainy), and dry seasons are the two distinct seasonal intervals in the study area. The rainy season commences in early March and stops around October, while the dry season runs from October to February. The two seasons are controlled by the two prevalent winds, which blow over the nation in separate year periods (Odoh et al., 2012). The dry harmattan wind which blows from the Sahara Desert occurs in the dry seasonal period.

In contrast, during the rainy season, the significant wind is the marine wind which blows from the Atlantic Ocean (Odoh et al., 2012). The average temperatures during the dry seasonal period are between 20˚C to 38˚C, and during the rainy seasonal period is from 16˚C to 28˚C (Odoh et al., 2012). The normal monthly precipitation ranges from 3.1 mm in January and 270 mm in July. The average yearly precipitation varies from 1750 mm to 2250 mm (Aghamelu et al., 2011; Odoh et al., 2012).

Five main rivers (Onu-umpku ufie, Ndende, Onuebonyi, Ogbachi and Cross River) form the tributaries that drain the geological units and transport a large amount of sediments within the ecosystem in Ebonyi, eastern Nigeria. The geochemistry of stream sediments of Amudo-Ezza is less studied; thus, this research will provide new information on the heavy metal dispersion levels in eastern Nigeria.

3. Materials and Methods

Field Sampling

A topographic map was used to locate the various streams and river channels for the fieldwork and sample collection. A Global positioning system (GPS) was used to read the latitude and longitude coordinates of the sampling points. Also, a hand trowel, a scoop, and sample bags were used to collect the stream sediments. Stream sediment sampling was conducted during the dry season. The sampling interval was 400m along the stream channels. A total of 20 samples were taken from the centre of the river channel at separate points. To avoid surface contaminants, the samples were scooped from the 10 - 15 cm depth range. The stream sediments from the fieldwork and sampling were air-dried at room temperatures for a week. They were subsequently crushed and sieved through 177-µ sieve size fractions using nylon screens. Nitric acid (HNO3), Hydrochloric acid (HCl), deionised water, beakers and volumetric flasks were employed in the elemental decomposition (digestion) stage. Finally, an atomic absorption spectrophotometer (AAS) was used in the elemental analysis of six heavy metals: Pb, Zn, As, Cd, Cu and Ni.

4. Results

Heavy metal dispersion and concentration levels of the analyzed six heavy metals in the stream sediments are shown in **Table 1**. The concentration values are reported in mg/kg. The distribution pattern of the heavy metals shows wide variation pattern; the values in mg/kg are Pb: 1.3 - 9.4, Zn: 11.1 - 38.5, Cu 0.1 - 13.3, As: 0.1 - 0.6, Cd: 0.1 - 9.7 and Ni: 0.1 - 7.8 (**Figure 2**). Statistical data of the stream sediments is presented in **Table 2**. The mean contents of these heavy metals in the stream sediments took the order Zn > Cu > Pb > Cd > Ni > As, which is similar to the concentration levels reported in stream sediments of River Orle, Nigeria (Adepoju & Adekoya, 2014). The concentration levels of the heavy metals were low when correlated with sediments from Imo River, southeastern Nigeria (Ekwere et al., 2013), Gulf of California sediments (Brumsack, 1986), upper continental crust (UCC) (Taylor & McLennan, 1985), Average shale and surface horizons worldwide (Kabata-Pendias, 2010) and excluding Cd, which was available at higher concentration than in Imo river and UCC.

5. Discussion

5.1. Pollution Status of Stream Sediments

To characterize the stream sediment quality and to define acceptable concentrations of sediment contaminants in River Iyiudene, Sediment Quality Guidelines (SQGs) (Long et al., 1995, Zahra et al., 2014; Kiddon et al., 2003) were applied. This was in line with the approach described in the Mid-Atlantic Integrated Assessment (MAIA) for estuaries (1997-1998 concise report) and also United States' Environmental Protection Agency (USEPA, 1998) guidelines. In the

Table 1. Geochemical results of heavy metal concentrations in the stream sediment samples of the River Iyiudene in mg/kg.

Sample No	Pb	Zn	Cu	As	Cd	Ni
FCN/SS/1	1.4	12.5	13.3	0.1	5.2	0.1
FCN/SS/2	3.2	16.7	4.5	-	4.5	0.2
FCN/SS/3	6.4	38.5	5.5	-	1.4	-
FCN/SS/4	6.5	26.4	6.9	0.6	9.7	2.2
FCN/SS/5	5.0	31.2	9.9	0.1	6.2	0.8
FCN/SS/6	5.4	23.9	2.7	0.3	5.7	0.4
FCN/SS/7	3.6	17.4	-	-	1.9	0.8
FCN/SS/8	4.9	11.1	6.6	-	5.1	0.1
FCN/SS/9	9.4	12.8	2.3	0.2	8.4	-
FCN/SS/10	1.5	22.4	1.5	0.2	0.4	-
FCN/SS/11	2.0	12.5	4.7	0.3	0.3	-
FCN/SS/12	2.2	25.8	8.8	-	0.3	2.5
FCN/SS/13	1.9	11.1	7.5	0.1	0.5	1.4
FCN/SS/14	3.5	20.3	2.5	0.2	0.1	7.8
FCN/SS/15	1.3	15.8	0.1	0.4	0.2	-
FCN/SS/16	2.6	20.0	-	0.2	0.3	-
FCN/SS/17	4.7	15.8	0.7	0.2	0.2	-
FCN/SS/18	9.2	14.7	5.8	0.1	0.2	5.7
FCN/SS/19	4.7	30.4	6.1	-	0.2	1.1
FCN/SS/20	5.8	22.2	0.4	-	0.1	5.8

Table 2. Statistical summary of heavy metal concentrations in the stream sediments of the River Iyiudene and other selected rivers as reference studies.

River		Pb	Zn	Cu	As	Cd	Ni	Reference
Iyiudene	(range)	1.3 - 9.4	11.1 - 38.5	0.1 - 13.3	0.1 - 0.6	0.1 - 9.7	0.1 - 7.8	This Study
	Mean	4.26	20.08	4.49	0.15	2.55	1.445	
	SD	2.25	7.35	3.62	0.17	3.07	2.24	
Orle		2.0 - 162.3	5.0 - 57.0	2.3 - 24.3	0.5 - 4.8	<0.10 - 0.10	1.20 - 28.50	Adepoju and Adekoya (2014)
Imo		9.0 - 29.0	31.0 - 306.0	-	30.02 - 22.0	1.0 - 1.80	6.0 - 28.0	Ekwere et al. (2013)
Gulf of California		17	88	-	7	1	38	Brumsack (1986)
UCC		17	70	28	4.8	0.09	47	Rudnick and Gao (2003)
Average shale		20	95	50	10	1	68	Wedepohl (1971)
Surface horizons worldwide (K-P)		27	70	38.9	0.67	0.41	29	Kabata-Pendias (2010)

Continued

Uke stream	0.095	4.79	1.34	-	0.035	-	Opaluwa et al. (2012)
River Oyan	5 - 31	45 - 360	15 - 31	-	1 - 1.8	25 - 42	Oyebamiji et al. (2018)
Woji creek	11.58	52.15	12.4	6.9	0.06	10.17	Ibanga et al. (2019)
River Benin	1.10	6.38	1.75	-	-	0.75	Ogbeibu et al. (2014)
Ikorodu stream	9.73	95.21	9.99	0.99	0.18	3.30	Odukoya and Akande (2015)
Lagos Lagoon	0.12 - 0.18	14.23 - 21.21	14.88 - 20.8	1.27 - 2.62	2.95 - 6.69	12.68 - 19.76	Kafilat-Adebola et al. (2018)
Dakoto Sheha stream	0.4 - 7.8	7.0 - 110	0.8 - 38.3	0.3 - 39.5	0.5 - 3.8	1.2 - 41.4	Arhin et al. (2016)
Municipal Lake	317 - 496	34.6 - 872.1	0 - 385	-	1.14 - 18.3	12.04 - 63.49	Léopold et al. (2012)
Dakar coast	2.83 - 1308	7.14 - 88.5	12.9 - 121	-	0.18 - 1.63	1.16 - 27.6	Diop et al. (2015)
Koshi River	12.9 - 36.1	33.3 - 93.3	11.2 - 43.6	-	0.07 - 0.59	10.4 - 52.6	Li et al. (2020)
Liaohe River	10.57	50.24	17.82	9.88	1.20	17.73	Ke et al. (2017)
Unit-mg/kg							

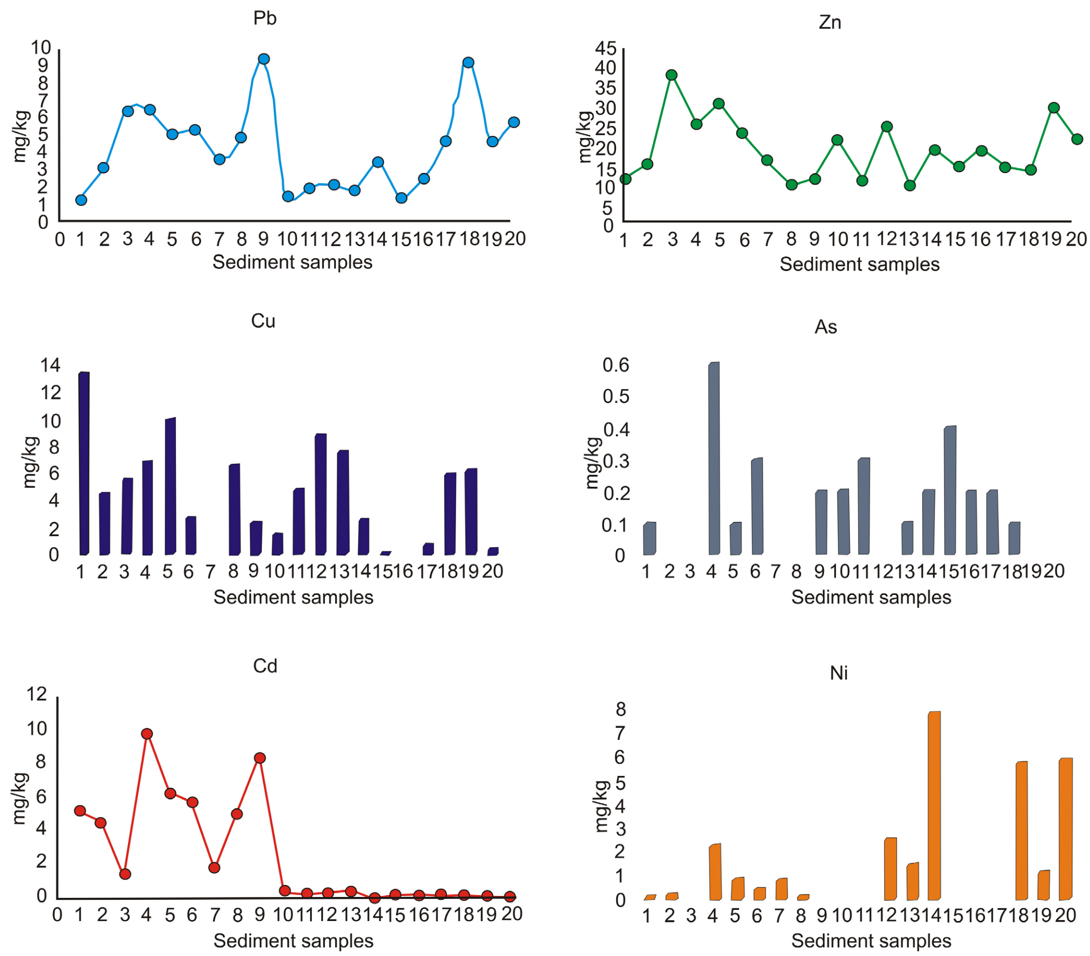

Figure 2. Concentration levels of heavy metals in the stream sediments.

SQGs, the effect range low (ERL) defines the number below which the concentration levels of heavy metals pose no adverse effect on the ecosystem. In contrast, the Effect range median (ERM) connotes the chemical volume at which adverse biological effects are predicted to occur (Long et al., 1995). Metal concentrations in sediments lower than ERL values are not expected to cause repugnant effects. Metal concentrations in sediments above ERM are probable to be toxic. **Table 3** shows the ERL and ERM limits for metal contaminants in sediments.

The concentration levels of Pb, Zn, Cu, As, and Ni in all the sampled locations are below the ERM and ERL limits; hence, their concentrations are below the toxic level. Thus, the stream sediments in River Iyiudene pose no threat to the ecosystem. The concentration of Pb in all sampled locations is below the ERM and ERL (47 mg/kg); thus, lead concentration is below the toxic level. The highest zinc concentration is 38.5 mg/kg, which is way below the toxic level. Cu attains a maximum concentration of 13.3 mg/kg, which is below the toxic level, thus poses no threat in the study area. The As concentration in all sampled locations is below the ERL limit. The maximum concentration for nickel in this study is 7.8 mg/kg; hence it is below the toxic level. ERM for cadmium is 9.6 mg/kg and its ERL value is set at 1.2 mg/kg. The maximum concentration of Cd is 9.7 mg/kg, found to be above the toxic level by 0.1 mg/kg. The Cd concentrations were above the ERL limits in Nine (9) sample locations (i.e. FCN/SS/1, 2, 3, 4, 5, 6, 7, 8, 9) and ERM limits in one (1) location, (FCN/SS/9). Thus, the Cd concentration in the study area poses a plausible biological threat to the ecosystem.

5.2. Assessment of Heavy Metal Contamination

Single pollution index (PI), Geo-accumulation index (Igeo) and Correlation matrix (CM) were applied to precisely and effectively evaluated the heavy metal pollution state of the stream sediments. In this paper, we applied the average content of heavy metals in surface horizons worldwide (Kabata-Pendias, 2010) as background references. Using average heavy metal concentration in surface horizons is more suitable than UCC and average shale (Blaser et al., 2000).

Table 3. The ERL and ERM limits for metals (Long et al., 1995; Kiddon et al., 2003).

Metal	ERL values in Mg/Kg	ERM values in Mg/Kg
Lead (Pb)	47	220
Zinc (Zn)	150	410
Copper (Cu)	34	270
Cadmium (Cd)	1.2	9.6
Arsenic (As)	8.2	70
Nickel (Ni)	21	52

5.3. Single Pollution Index (PI)

PI is an indicator that is employed to decipher which heavy metal depicts the maximum risk to sediments in the environment (Kowalska et al., 2018)

$$PI = C_n / G_B \quad (1)$$

where C_n is the concentration of the analyzed heavy metals in the stream sediments and G_B is the geochemical background. PI divides the heavy metal pollution into five classes (Kowalska et al., 2018): Class 1 represents no pollution (PI < 1); Class 2 indicates low pollution (1 < PI < 2); Class 3 signifies moderate pollution (2 < PI < 3); Class 4 indicates strong pollution (3 < PI < 5); Class 5 stands for very strong pollution (PI > 5).

The studied heavy metals in this paper showed the following mean PI values: Pb (0.16), Zn (0.37), Cu (0.12), As (0.34), Ni (0.08), and Cd (6.17) **Table 4**. The calculated PI values for Pb, Zn, Cu, As, and Ni showed no pollution, whereas the PI values for Cd ranged from 0.24 to 23.66, indicating no pollution to strongly polluted. 35% of the stream samples in the study area are very strongly polluted with Cd. The computed PI numbers for all investigated metals excluding Cd fell into Class 1, Figure, indicating the absence of contamination from these heavy metals in the studied stream sediments. The PI values of Cd that fell into Class 1 no pollution (FCN/SS/10 - 12, 14 - 20: 50%), Class 2 low pollution (FCN/SS/13: 5%), Class 3 moderate pollution (FCN/SS/3: 5%), Class 4 strong pollution (FCN/SS/7: 5%) and Class 5 very strong pollution (FCN/SS/1 - 2, 4 - 6, 8 - 9: 35%), **Figure 3**.

5.4. Geo-Accumulation Index

The geo-accumulation index (Igeo) by Muller (1981) was applied to compute the heavy metal contamination of stream sediments caused by geological and anthropogenic processes. Igeo is ascertained by the formula:

$$Igeo = \log_2 Cn/1.5Bn \quad (2)$$

where Cn is the determined concentration of metals in the tested samples, while Bn is the geochemical background, factor 1.5 allows for fluctuation in the analysis due to natural and anthropogenic influences. Generally, Igeo divides the

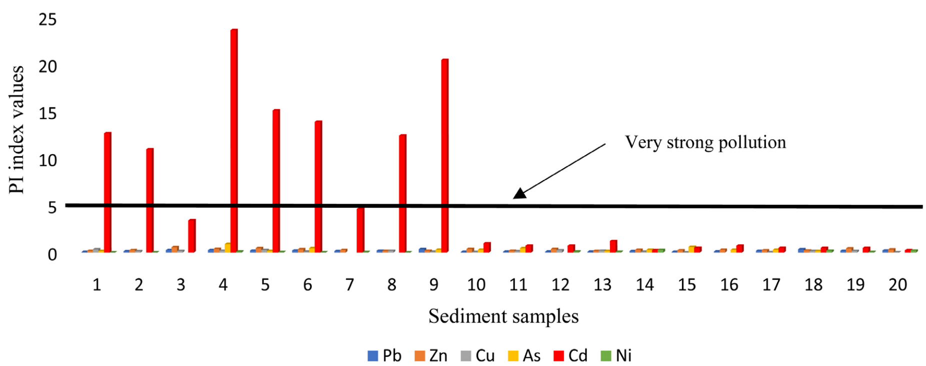

Figure 3. Single pollution index levels for the stream sediment samples.

Table 4. Geo-accumulation index values of analyzed metals in the stream sediments of the River Iyiudene and their classes.

	PI levels of the samples						PI Class					
Sample No.	Pb	Zn	Cu	As	Cd	Ni	Pb	Zn	Cu	As	Cd	Ni
FCN/SS/1	0.05	0.18	0.34	0.15	12.68	0.003	1	1	1	1	5	1
FCN/SS/2	0.12	1.24	0.12		10.97	0.006	1	1	1		5	1
FCN/SS/3	0.24	0.55	0.14		3.41		1	1	1		4	
FCN/SS/4	0.24	0.38	0.18	0.89	23.66	0.08	1	1	1	1	5	1
FCN/SS/5	0.19	0.45	0.25	0.15	15.12	0.03	1	1	1	1	5	1
FCN/SS/6	0.20	0.34	0.07	0.45	13.9	0.01	1	1	1	1	5	1
FCN/SS/7	0.13	0.25			4.63	0.03	1	1			4	1
FCN/SS/8	0.18	0.16	0.17		12.44	0.003	1	1	1		5	1
FCN/SS/9	0.35	0.18	0.06	0.29	20.48		1	1	1	1	5	
FCN/SS/10	0.05	0.37	0.04	0.29	0.97		1	1	1	1	1	
FCN/SS/11	0.07	0.18	0.12	0.45	0.73		1	1	1	1	1	
FCN/SS/12	0.08	0.37	0.23		0.73	0.08	1	1	1		1	1
FCN/SS/13	0.07	0.16	0.19	0.15	1.22	0.05	1	1	1	1	2	1
FCN/SS/14	0.13	0.29	0.06	0.29	0.24	0.27	1	1	1	1	1	1
FCN/SS/15	0.05	0.23	0.002	0.59	0.49		1	1	1	1	1	
FCN/SS/16	0.09	0.29		0.29	0.73		1	1		1	1	
FCN/SS/17	0.17	0.23	0.02	0.29	0.49		1	1	1	1	1	
FCN/SS/18	0.34	0.21	0.15	0.15	0.49	0.19	1	1	1	1	1	1
FCN/SS/19	0.17	0.43	0.16		0.49	0.04	1	1	1		1	1
FCN/SS/20	0.21	0.32	0.01		0.24	0.2	1	1	1		1	1
Mean	0.16	0.37	0.13	0.34	6.17	0.08						

contamination level caused by heavy metal concentration into seven classes (Muller, 1969, 1981; Nowrouzi & Pourhabbaz, 2014) **Table 5**.

The Igeo values determined by mathematical calculation for Pb, Zn, Cu, As, Ni and Cd varied from no pollution through moderate pollution to high pollution **Figure 4**. The heavy metals studied, Pb, Zn, Cu, As, and Ni, showed values less than 0 and fell into class 0, indicating no pollution (Kowalska et al., 2018) **Table 6**. Thus, there is no contamination by Pb, Zn, Cu, As, and Ni heavy metals. In contrast, the Igeo values for Cd vary between −1.62 to 3.98 (mean: 2.01), delineating no pollution through moderate pollution to highly polluted with Cd in the study area **Figure 4**. The tested heavy metals showed the following mean values: Pb (−3.49), Zn (−2.48), Cu (−4.2), As (−2.3), Ni (−5.43) and Cd (2.01) **Table 6**.

Table 5. Geo-accumulation index classes indicate sediment quality (Muller, 1969).

Class	Values of I_{geo}	Soil quality
0	$I \leq 0$	Unpolluted
1	0 - 1	unpolluted to moderate pollution
2	1 - 2	moderate pollution
3	2 - 3	moderate to high pollution
4	3 - 4	high pollution
5	4 - 5	high to extreme high pollution
6	5 - 6	extreme high pollution

Table 6. Geo-accumulation index values of analyzed metals in the stream sediments of the River Iyiudene and their classes.

	Igeo values of the samples						Igeo Class					
Sample No.	Pb	Zn	Cu	As	Cd	Ni	Pb	Zn	Cu	As	Cd	Ni
FCN/SS/1	−4.85	−3.07	−2.13	−3.35	3.08	−8.76	0	0	0	0	4	0
FCN/SS/2	−3.66	−2.65	−3.70		2.87	−7.76	0	0	0		3	0
FCN/SS/3	−2.66	−1.45	−3.41		1.19		0	0	0		2	
FCN/SS/4	−2.64	−1.99	−3.08	−0.74	3.98	−4.31	0	0	0	0	4	0
FCN/SS/5	−3.02	−1.75	−2.56	−3.33	3.33	−5.76	0	0	0	0	4	0
FCN/SS/6	−2.91	−2.14	−4.43	−1.74	3.21	−6.76	0	0	0	0	4	0
FCN/SS/7	−3.49	−2.59			1.63	−5.76	0	0			2	0
FCN/SS/8	−3.05	−3.24	−3.14		3.05	−8.76	0	0	0		4	0
FCN/SS/9	−2.11	−3.04	−4.67	−2.33	3.77		0	0	0	0	4	
FCN/SS/10	−4.75	−2.23	−5.28	−2.33	−0.62		0	0	0	0	0	
FCN/SS/11	−4.34	−3.09	−3.63	−1.74	−1.04		0	0	0	0	0	
FCN/SS/12	−4.20	−2.02	−2.73		−1.04	−4.12	0	0	0		0	0
FCN/SS/13	−4.41	−3.24	−2.96	−3.33	−0.30	−4.96	0	0	0	0	0	0
FCN/SS/14	−3.53	−2.37	−4.54	−2.33	−2.62	−2.48	0	0	0	0	0	0
FCN/SS/15	−4.96	−2.73	−9.19	−1.32	−1.62		0	0	0	0	0	
FCN/SS/16	−3.96	−2.39		−2.33	−1.04		0	0		0	0	
FCN/SS/17	−3.11	−2.73	−6.38	−2.33	−1.62		0	0	0	0	0	
FCN/SS/18	−2.14	−2.84	−3.33	−3.33	−1.62	−2.93	0	0	0	0	0	0
FCN/SS/19	−3.11	−1.79	−3.26		−1.62	−5.31	0	0	0		0	0
FCN/SS/20	−2.80	−2.24	−7.19		−1.62	−2.91	0	0	0		0	0
Mean	−3.49	−2.48	−4.2	−2.3	2.01	−5.43						

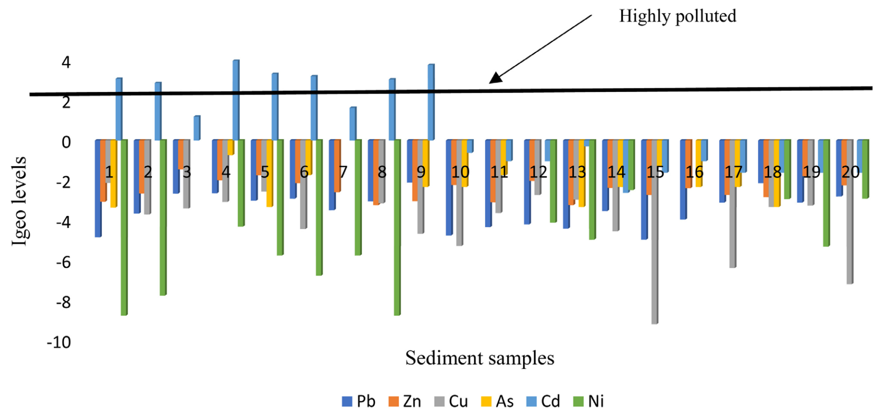

Figure 4. Geo-accumulation index concentration for the stream sediments.

5.5. General Evaluation of Heavy Metal Contamination

All the assessment techniques applied revealed no contamination to high contamination levels of heavy metal pollution in River Iyuidene sediment samples. There was no contamination in the stream sediments by heavy metals of Pb, Zn, Cu, As, and Ni, with low to high contamination levels by Cd as shown by high PI, Igeo and ERL values. This suggests that the geology of the river basin chiefly controls the dispersion and concentration of the studied six heavy metals in this paper, and the high Cd contamination levels are possibly sourced from agricultural runoff and mining activities in the study area (Sajn & Gosar, 2008; Wang et al., 2008; Nnabo, 2015). The high Cd concentrations in this study are adsorbed to the stream sediments and consequently discharged into the stream water which humans and aquatic organisms consume.

5.6. Comparison of Heavy Metal Concentrations in Stream Sediments with Other Regions

The concentration levels of heavy metals in stream sediments in this study is compared with data in literature cases of other regions within Nigeria and West Africa to determine the magnitude of the pollution; data from Koshi River sediment, Saint Louis estuary Senegal, and Liaohe River China were included in **Table 2**.

Data from the Uke stream in Northern Nigeria revealed moderate Pb, Zn, Cd, Cu, and Mn concentrations in stream sediments (Opaluwa et al., 2012). Results from this present study were slightly higher than the heavy metal concentrations level of River Uke Nasarawa province in northern Nigeria (Opaluwa et al., 2012). Compared with our present study, stream sediments of River Oyan, Abuja, and Central Nigeria showed similar concentrations except for Zn, which was enriched and revealed moderate contamination levels in River Oyan sediments (Oyebamiji et al., 2018). Oyebamiji et al., 2018 found a strong correlation between Pb and Zn, Ni and Cu. In contrast, Cd moderately correlates with Ni, Cd, Fe, and Zn (Oyebamiji et al., 2018).

The results from the heavy metal evaluation of River Orle, southern Nigeria, showed similar concentration levels to results from this present study, except for moderate to high pollution of Cr and Pb, respectively (Adepoju & Adekoya, 2014). Anthropogenic and natural sources were considered possible sources of high Pb pollution (Adepoju & Adekoya, 2014). Ogbeibu et al. (2014) used pollution load index (PLI) and Geo-accumulation index (Igeo) to study heavy metal pollution levels in stream sediments of River Benin, Southern Nigeria and revealed that the sediments are not polluted with heavy metals such as Cr, Zn, Cu, Mn, Pb, Ni, and Fe and, thus shows lower values when compared to results from this present study. Data from a heavy metal evaluation of the sediments of Woji creek and River Bonny in Rivers province, Niger Delta, southern Nigeria, shows similar values compared to the present study (Ibanga et al., 2019). Heavy metals, Cu, Ni, Co, Pb, Zn, As, Cr, Mn, Fe and Cd showed low contamination levels in Woji creek and Bonny River and thus, signifying low contamination from anthropogenic and natural background sources (Ibanga et al., 2019).

The concentration levels of heavy metals in Ikorodu stream sediments in Lagos state, southwestern Nigeria, showed similar concentration levels to this study except for Zn (95.21) and Cd (0.18), which recorded higher and lower values, respectively (Odukoya & Akande, 2015). Their study revealed slightly contamination of Cu, moderate contamination of Pb, and substantial contamination of Cr, Zn and Cd in stream deposits of Owode Onirin, Igbonla, Ikosi Ado, Owode Elede, Ogun river, and Ise stream sediments Ikorodu southwestern Nigeria (Odukoya & Akande, 2015). Kafilat-Adebola et al. (2018) evaluated heavy metals in stream sediments of Lagos Lagoon, southwestern Nigeria and showed similar concentration levels to our present study. Data from the Lagos lagoon revealed extreme Cd pollution with Igeo > 5 in the sediments (Kafilat-Adebola et al., 2018).

Results from the present study is similar to the results of Arhin et al. (2016) on stream sediments in Dakoto Sheha, Northern Ghana; Léopold et al. (2012) on stream sediments of Municipal Lake of Yaounde, Cameroon; Diop et al. (2015) sediments from Dakar coast and Saint Louis estuary in Senegal, all in West Africa recorded high pollution of Cd in stream sediments and thus indicating the pollution status of the aquatic ecosystem. Koshi River sediments and sediments from the Liaohe River in China (Ke et al., 2017; Li et al., 2020) are reported to be enriched with Cd in the stream sediments and are comparable with the present study.

5.7. Correlation Matrix

Correlation analysis was performed on selected heavy metallic concentration levels of the stream sediments to recognize significant inter-relationship. The correlation matrix of the six heavy metals in the stream deposit samples from River Iyiudene (**Table 7**) shows, a moderate positive (+) correlation exists between Zn and Pb alone. Among all other heavy metals, the correlation matrix was generally weak (i.e. (<±0.5).

Table 7. Correlation matrix of six heavy metals in the stream sediment samples.

	Pb	Zn	Cu	Cd	Ni	As
Pb	1					
Zn	0.547665	1				
Cu	−0.162551	−0.361191	1			
Cd	−0.043869	0.300717	−0.545404	1		
Ni	0.173631	−0.057279	0.566508	−0.352250	1	
As	−0.113648	−0.146662	−0.263423	0.230830	−0.065518	1

5.8. Implication of the Cd Contamination

This research has shown Cd pollution in the studied area, and it needs to be correctly monitored over a long period to deduce the harmful effects of Cd on the ecosystem and humans. Cd is a toxic heavy metal that is very carcinogenic and poses a threat even in minor concentrations (Khan et al., 2015, 2017). Cd enrichment in stream sediments is sourced from both the natural geological background and anthropogenic processes, and it is considered a threat to the ecosystem (Pan et al., 2016a). The natural sources involve weathering of geologic materials. In contrast, agricultural runoff, vehicular emissions, and waste disposals are possible anthropogenic sources contributing to Cd enrichment levels in stream sediments (Nawab et al., 2016; Pan et al., 2016b). Extreme Cd levels can have lethal side effects on organisms and shift into the vegetative cover, which can eventually get into the food chain (Nawab et al., 2016; Li et al., 2016). High intake of Cd contaminated food by humans can result in severe damage to essential organs in the body such as; the lungs, kidneys and liver and can cause cancer also (Bernard, 2008; Sarkar et al., 2013; Khan et al., 2017; Moynihan et al., 2017).

6. Conclusion

Several authors have argued that the increasing spate of cardiovascular diseases in eastern Nigeria can be blamed on the open-cast mining practices in the region; hence the need to assess the heavy metal concentration in sediments recovered from the study area was the main motivator for this research. Stream sediments were sampled from the River Iyiudene, Abakaliki, south-eastern Nigeria, and assessed to determine the concentration and contamination levels of six heavy metals, including Pb, Zn, Cu, As, Cd and Ni. The results delineated a wide contrast in the concentration levels of the heavy metals, with the mean contents in the order Zn > Cu > Pb > Cd > Ni > As. The heavy metal concentration levels in River Iyiudene were low compared with sediments from Imo River, Gulf of California, Upper continental crust, Average shale and surface horizons, excluding Cd, which showed high concentration levels than the other reference studies. The concentration of Pb, Zn, Cu, As and Ni in all the sampled locations was below the ERM and ERL limits; thus, their concentration levels are below the toxic limit and pose no threat to the ecosystem. In contrast, the Cd concentration in Nine (9) sample locations was above the ERL limits, and one sample location was above the ERM limits. Therefore, the Cd concentration in this study poses a plausible biological risk to the ecosystem.

Multiple approaches were applied to determine the heavy metallic contamination of the stream sediments. The single pollution index showed no pollution from heavy metals of Pb, Zn, Cu, As, and Ni, whereas Cd revealed no pollution to strongly polluted sediments. The geo-accumulation index revealed no pollution from Pb, Zn, Cu, As, and Ni. In contrast, the Igeo values for Cd indicate no pollution through moderate to high pollution. Correlation analysis showed a moderate positive correlation exists between Zn and Pb alone. Our findings revealed Cd pollution in the study area, which needs to be monitored due to the toxic effect of Cd on the ecosystem and Humans. High Cd concentration in the stream sediments of River Iyiudene is sourced from the geological background of the river basin and anthropogenic processes. It is noteworthy that there are other avenues through which pollution can occur, including hydrophobic organic contaminants; hence we recommend that other works be designed to investigate this and other contaminants present in the sediments.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Adepoju, M. O., & Adekoya, J. A. (2014). Heavy Metal Distribution and Assessment in Stream Sediments of River Orle, Southwestern Nigeria. *Arabian Journal of Geosciences, 7,* 743-756. https://doi.org/10.1007/s12517-013-0845-1

Aghamelu, O. P., Nnabo, P. N., & Ezeh, H. N. (2011). Geotechnical and Environmental Problems Related to Shales in the Abakaliki Area, Southeastern Nigeria. *African Journal of Environmental Science and Technology, 5,* 80-88.

Ali, H., Khan, E., & Ilahi, I. (2019). Environmental Chemistry and Ecotoxicology of Hazardous Heavy Metals: Environmental Persistence, Toxicity, and Bioaccumulation. *Journal of Chemistry, 2019,* Article ID: 6730305. https://doi.org/10.1155/2019/6730305

Aloke, C., Uzuegbu, I. E., Ogbu, P. N., Ugwuja, E. I., Orinya, O. F., & Obasi, I. O. (2019). Comparative Assessment of Heavy Metals in Drinking Water Sources from Enyigba Community in Abakaliki Local Government Area, Ebonyi State, Nigeria. *African Journal of Environmental Science and Technology, 13,* 149-154. https://doi.org/10.5897/AJEST2018.2517

Arhin, E., Boansi, A. O., & Zango, M. S. (2016). Trace Elements Distributions at Datoko-Shega Artisanal Mining Site, Northern Ghana. *Environmental Geochemistry and Health, 38,* 203-218. https://doi.org/10.1007/s10653-015-9705-0

Bello, O., Naidu, R., Rahman, M. M., Liu, Y., & Dong, Z. (2016). Lead Concentration in the Blood of the General Population Living Near a Lead-Zinc Mine Site, Nigeria: Exposure Pathways. *Science of the Total Environment, 542,* 908-914. https://doi.org/10.1016/j.scitotenv.2015.10.143

Bernard, A. (2008). Cadmium & Its Adverse Effects on Human Health. *Indian Journal of Medical Research, 128,* 557-564.

Blaser, P., Zimmermann, S., Luster, J., & Shotyk, W. (2000). Critical Examination of Trace Element Enrichments and Depletions in Soils: As, Cr, Cu, Ni, Pb, and Zn in Swiss Forest Soils. *Science of the Total Environment, 249,* 257-280. https://doi.org/10.1016/S0048-9697(99)00522-7

Brumsack, H. J. (1986). The Inorganic Geochemistry of Cretaceous Black Shales (DSDP Leg 41) in Comparison to Modern Upwelling Sediments from the Gulf of California. *Geological Society, London, Special Publications, 21,* 447-462. https://doi.org/10.1144/GSL.SP.1986.021.01.30

Chen, L., Zhou, S., Shi, Y., Wang, C., Li, B., Li, Y., & Wu, S. (2018). Heavy Metals in Food Crops, Soil, and Water in the Lihe River Watershed of the Taihu Region and Their Potential Health Risks When Ingested. *Science of the Total Environment, 615,* 141-149. https://doi.org/10.1016/j.scitotenv.2017.09.230

Chukwuma, C. (1994). Evaluating Baseline Data for Trace Elements, pH, Organic Matter Content, and Bulk Density in Agricultural Soils in Nigeria. *Water, Air, and Soil Pollution, 86,* 13-34. https://doi.org/10.1007/BF00279143

Diop, C., Dewaelé, D., Cazier, F., Diouf, A., & Ouddane, B. (2015). Assessment of Trace Metals Contamination Level, Bioavailability and Toxicity in Sediments from Dakar Coast and Saint Louis Estuary in Senegal, West Africa. *Chemosphere, 138,* 980-987. https://doi.org/10.1016/j.chemosphere.2014.12.041

Dondeyne, S., Ndunguru, E., Rafael, P., & Bannerman, J. (2009). Artisanal Mining in Central Mozambique: Policy and Environmental Issues of Concern. *Resources Policy, 34,* 45-50. https://doi.org/10.1016/j.resourpol.2008.11.001

Dooyema, C. A., Neri, A., Lo, Y. C., Durant, J., Dargan, P. I., Swarthout, T., Biya, O., Gidado, S. O., Haladu, S., Sani-Gwarzo, N., & Nguku, P. M. (2012). Outbreak of Fatal Childhood Lead Poisoning Related to Artisanal Gold Mining in Northwestern Nigeria, 2010. *Environmental Health Perspectives, 120,* 601-607. https://doi.org/10.1289/ehp.1103965

Egbueri, J. C., & Enyigwe, M. T. (2020). Pollution and Ecological Risk Assessment of Potentially Toxic Elements in Natural Waters from the Ameka Metallogenic District in Southeastern Nigeria. *Analytical Letters, 53,* 2812-2839. https://doi.org/10.1080/00032719.2020.1759616

Ekwere, A., Ekwere, S., & Obim, V. (2013). Heavy Metal Geochemistry of Stream Sediments from Parts of the Eastern Niger Delta Basin, South-Eastern Nigeria. *RMG-M & G, 60,* 205-210.

Ezeh, H. N. (2007). *Environmental Significance of Heavy Metals Distribution in the Ebonyi River Drainage System, Abakaliki and Ohaozara Areas, South Eastern Nigeria* (p. 214). Doctoral Dissertation, Nnamdi Azikiwe University.

Ezeh, H. N., & Anike, O. L. (2009). The Preliminary Assessment of the Pollution Status of Streams and Artificial Lakes Created by Mining in the Mining District of Enyigba, South Eastern Nigeria, and Their Consequences. *Global Journal of Environmental Sciences, 8,* 41-48. https://doi.org/10.4314/gjes.v8i1.50823

Guo, B., Liu, Y., Zhang, F., Hou, J., Zhang, H., & Li, C. (2018). Heavy Metals in the Surface Sediments of Lakes on the Tibetan Plateau, China. *Environmental Science and Pollu-*

tion Research, 25, 3695-3707. https://doi.org/10.1007/s11356-017-0680-0

Huang, X., Sillanpää, M., Gjessing, E. T., Peräniemi, S., & Vogt, R. D. (2010). Environmental Impact of Mining Activities on the Surface Water Quality in Tibet: Gyama Valley. *Sci. of the Total Environ, 408,* 4177-4184. https://doi.org/10.1016/j.scitotenv.2010.05.015

Ibanga, L. B., Nkwoji, J. A., Usese, A. I., Onyema, I. C., & Chukwu, L. O. (2019). Hydrochemistry and Heavy Metals Concentrations in Sediment of Woji Creek and Bonny Estuary, Niger Delta, Nigeria. *Regional Studies in Marine Science, 25,* Article ID: 100436. https://doi.org/10.1016/j.rsma.2018.10.004

Igwe, O., Adepehin, E. J., & Adepehin, J. O. (2015). Integrated Geochemical and Microbiological Approach to Water Quality Assessment: Case Study of the Enyigba Metallogenic Province, South-Eastern Nigeria. *Environmental Earth Sciences, 74,* 3251-3262. https://doi.org/10.1007/s12665-015-4363-1

Ji, Z., Zhang, H., Zhang, Y., Chen, T., Long, Z., Li, M., & Pei, Y. (2019). Distribution, Ecological Risk and Source Identification of Heavy Metals in Sediments from the Baiyangdian Lake, Northern China. *Chemosphere, 237,* Article ID: 124425. https://doi.org/10.1016/j.chemosphere.2019.124425

Kabata-Pendias, A. (2010). *Trace Elements of Soils and Plants* (4th ed., p. 548). CRC Press. https://doi.org/10.1201/b10158

Kafilat-Adebola, B. A., Joseph Kayode, S., & Adebayo Akeem, O. (2018). Integrated Assessment of the Heavy Metal Pollution Status and Potential Ecological Risk in the Lagos Lagoon, South West, Nigeria. *Human and Ecological Risk Assessment: An International Journal, 24,* 377-397. https://doi.org/10.1080/10807039.2017.1384694

Ke, X., Gui, S., Huang, H., Zhang, H., Wang, C., & Guo, W. (2017). Ecological Risk Assessment and Source Identification for Heavy Metals in Surface Sediment from the Liaohe River Protected Area, China. *Chemosphere, 175,* 473-481. https://doi.org/10.1016/j.chemosphere.2017.02.029

Khan, A., Khan, S., Khan, M. A., Qamar, Z., & Waqas, M. (2015). The Uptake and Bioaccumulation of Heavy Metals by Food Plants, Their Effects on Plants Nutrients, and Associated Health Risk: A Review. *Environmental Science and Pollution Research, 22,* 13772-13799. https://doi.org/10.1007/s11356-015-4881-0

Khan, M. A., Khan, S., Khan, A., & Alam, M. (2017). Soil Contamination with Cadmium, Consequences and Remediation Using Organic Amendments. *Science of the Total Environment, 601-602,* 1591-1605. https://doi.org/10.1016/j.scitotenv.2017.06.030

Kiddon, J. A., Paul, J. F., Buffum, H. W., Strobel, C. S., Hale, S. S., Cobb, D., & Brown, B. S. (2003). Ecological Condition of US Mid-Atlantic Estuaries, 1997-1998. *Marine Pollution Bulletin, 46,* 1224-1244. https://doi.org/10.1016/S0025-326X(03)00322-9

Kowalska, J. B., Mazurek, R., Gąsiorek, M., & Zaleski, T. (2018). Pollution Indices as Useful Tools for the Comprehensive Evaluation of the Degree of Soil Contamination—A Review. *Environmental Geochemistry and Health, 40,* 2395-2420. https://doi.org/10.1007/s10653-018-0106-z

Kruopiene, J. (2007). Distribution of Heavy Metals in Sediments of the Nemunas River (Lithuania). *Polish Journal of Environmental Studies, 16,* 715-722.

Lawal, M. (2002). Constraints to Small-Scale Mining in Nigeria: Policies and Strategies for Development. In *CEPMLP Annual Review—The Dundee Yearbook of International Natural Resources and Energy Law and Policy* (p. 17). Centre for Energy Petroleum Minerals Law and Policy, University of Dundee. https://www.dundee.ac.uk/cepmlp

Léopold, E. N., Baussand, P., & Emmanuel, E. G. (2012). Heavy Metals Accumulation in Sediment Cores of the Municipal Lake of Yaounde, Cameroon. *Global Journal of En-*

vironmental Research, 6, 100-110.

Li, M., Zhang, Q., Sun, X., Karki, K., Zeng, C., Pandey, A., Rawat, B., & Zhang, F. (2020). Heavy Metals in Surface Sediments in the Trans-Himalayan Koshi River Catchment: Distribution, Source Identification and Pollution Assessment. *Chemosphere, 244,* Article ID: 125410. https://doi.org/10.1016/j.chemosphere.2019.125410

Li, Y., Tang, H., Hu, Y., Wang, X., Ai, X., Tang, L., Matthew, C., Cavanagh, J., & Qiu, J. (2016). Enrofloxacin at Environmentally Relevant Concentrations Enhances Uptake and Toxicity of Cadmium in the Earthworm Eisenia Fetida in Farm Soils. *Journal of Hazardous Materials, 308,* 312-320. https://doi.org/10.1016/j.jhazmat.2016.01.057

Long, E. R., MacDonald, D. D., Smith, S. L., & Calder, F. D. (1995). Incidence of Adverse Biological Effects within Ranges of Chemical Concentrations in Marine and Estuarine Sediments. *Environmental Management, 19,* 81-97. https://doi.org/10.1007/BF02472006

Malvandi, H. (2017). Preliminary Evaluation of Heavy Metal Contamination in the Zarrin-Gol River Sediments, Iran. *Marine Pollution Bulletin, 117,* 547-553. https://doi.org/10.1016/j.marpolbul.2017.02.035

Moynihan, M., Peterson, K. E., Cantoral, A., Song, P. X., Jones, A., Solano-González, M., Meeker, J. D., Basu, N., & Téllez-Rojo, M. M. (2017). Dietary Predictors of Urinary Cadmium among Pregnant Women and Children. *Science of the Total Environment, 575,* 1255-1262. https://doi.org/10.1016/j.scitotenv.2016.09.204

Muller G. (1981). The Heavy Metal Pollution of the Sediments of the Neckars and Its Tributaries: An Inventory. *Chemiker-Zeitung, 105,* 157-164.

Muller, G. (1969). Index of Geoaccumulation in Sediments of the Rhine River. *GeoJournal, 2,* 108-118.

National Population Commission (NPC) (2007). Report of Nigeria's National Population Commission on the 2006 Census. *Population and Development Review, 33,* 206-210.

Nawab, J., Khan, S., & Wang, X. (2018). Ecological and Health Risk Assessment of Potentially Toxic Elements in the Major Rivers of Pakistan: General Population vs. Fishermen. *Chemosphere, 202,* 154-164. https://doi.org/10.1016/j.chemosphere.2018.03.082

Nawab, J., Khan, S., Aamir, M., Shamshad, I., Qamar, Z., Din, I., & Huang, Q. (2016). Organic Amendments Impact the Availability of Heavy Metal (Loid) S in Mine-Impacted Soil and Their Phytoremediation by *Penisitum americanum* and *Sorghum bicolor*. *Environmental Science and Pollution Research, 23,* 2381-2390. https://doi.org/10.1007/s11356-015-5458-7

Nazneen, S., & Patel, P. (2016). Distribution and Fractionation of Heavy Metals in Surface Sediments of Chilika Lagoon, East Coast of India. *Journal of Environmental Science, Toxicology and Food Technology, 10,* 63-71.

Nnabo, P. N. (2015). Heavy Metal Distribution and Contamination in Soils Around Enyigba Pb-Zn Mines District, South Eastern Nigeria. *Journal of Environment and Earth Science, 5,* 38-53.

Nnabo, P. N. (2016). Surface Water Contamination by Heavy Metals from Enyigba Pb-Zn Mine District, Southeastern Nigeria Using Metal Enrichment and Pollution Indices. *International Journal of Science and Technology, 5,* 8-16.

Nnabo, P. N., Orazulike, D. M., & Offor, O. C. (2011). The Preliminary Assessment of the Level of Heavy Elements Contaminations in Stream Bed Sediments of Enyigba and Environs, South Eastern Nigeria. *Journal of Basic Physical Research, 2,* 43-52.

Nowrouzi, M., & Pourkhabbaz, A. (2014). Application of Geoaccumulation Index and Enrichment Factor for Assessing Metal Contamination in the Sediments of Hara Biosphere Reserve, Iran. *Chemical Speciation & Bioavailability, 26,* 99-105. https://doi.org/10.3184/095422914X13951584546986

Obaje, N. G. (2009). Geology and Mineral Resources of Nigeria. Springer-Verlag. https://doi.org/10.1007/978-3-540-92685-6

Obaje, N. G., Wehner, H., Hamza, H., & Scheeder, G. (2004). New Geochemical Data from the Nigerian Sector of the Chad Basin: Implications on Hydrocarbon Prospectivity. *Journal of African Earth Sciences, 38,* 477-487. https://doi.org/10.1016/j.jafrearsci.2004.03.003

Obiora, S. C., Chukwu, A., & Davies, T. C. (2016). Heavy Metals and Health Risk Assessment of Arable Soils and Food Crops around Pb-Zn Mining Localities in Enyigba, Southeastern Nigeria. *Journal of African Earth Sciences, 116,* 182-189. https://doi.org/10.1016/j.jafrearsci.2015.12.025

Obiora, S. C., Chukwu, A., & Davies, T. C. (2019). Contamination of the Potable Water Supply in the Lead—Zinc Mining Communities of Enyigba, Southeastern Nigeria. *Mine Water and the Environment, 38,* 148-157. https://doi.org/10.1007/s10230-018-0550-0

Ochieng, G. M., Seanego, E. S., & Nkwonta, O. I. (2010). Impacts of Mining on Water Resources in South Africa: A Review. *Scientific Research and Essays, 5,* 3351-3357.

Odoh, B. I., Utom, A. U., Ezeh, H. N., & Egboka, B. C. (2012). Hydrogeochemical Properties of Groundwater in Parts of Abakaliki City, Southeastern Nigeria. *Environmental Geosciences, 19,* 53-61. https://doi.org/10.1306/eg.10051111006

Odukoya, A. M., & Akande, O. (2015). Metal Contamination Assessment in the Urban Stream Sediments and Tributaries of Coastal Area Southwest Nigeria. *Chinese Journal of Geochemistry, 34,* 431-446. https://doi.org/10.1007/s11631-014-0027-1

Ogbeibu, A. E., Omoigberale, M. O., Ezenwa, I. M., Eziza, J. O., & Igwe, J. O. (2014). Using Pollution Load Index and Geoaccumulation Index for the Assessment of Heavy Metal Pollution and Sediment Quality of the Benin River, Nigeria. *Natural Environment, 2,* 1-9.

Ogbodo, E. N. (2011). Assessment of Some Soil Fertility Characteristics of Abakaliki Urban Flood Plains of South-East Nigeria, for Sustainable Crop Production. *World Journal of Agricultural Sciences, 7,* 489-495.

Okogbue, C. O., & Ukpai, S. N. (2013). Geochemical Evaluation of Groundwater Quality in Abakaliki Area, Southeast Nigeria. *The Jordan Journal of Earth and Environmental Sciences, 5,* 1-8.

Okolo, C. C., & Oyedotun, T. D. T. (2018). Open Cast Mining: Threat to Water Quality in Rural Community of Enyigba in South-Eastern Nigeria. *Applied Water Science, 8,* Article No. 204. https://doi.org/10.1007/s13201-018-0849-9

Okolo, C. C., Ezeaku, P. I., Nwite, J. N., Nwite, J. C., Ezeudo, V. C., Ene, J., Ukaegbu, E. P., Udegbunam, O. N., & Eze, N. C. (2015). Impact of Open Cast Mine Land Use on Soil Physical Properties in Enyigba, South-Eastern Nigeria and the Implication for Sustainable Land Use Management. *Nigerian Journal of Soil Science, 25,* 95-101.

Omwene, P. I., Öncel, M. S., Çelen, M., & Kobya, M. (2018). Heavy Metal Pollution and Spatial Distribution in Surface Sediments of Mustafakemalpaşa Stream Located in the World's Largest Borate Basin (Turkey). *Chemosphere, 208,* 782-792. https://doi.org/10.1016/j.chemosphere.2018.06.031

Opaluwa, O. D., Aremu, M. O., Logbo, L., Imagaji, J., & EOdiba, I. (2012). Assessment of Heavy Metals in Water, Fish and Sediments from UKE Stream, Nasarawa State, Nigeria. *Current World Environment, 7,* 213-220. https://doi.org/10.12944/CWE.7.2.04

Oramah, I. T., Richards, J. P., Summers, R., Garvin, T., & McGee, T. (2015). Artisanal and Small-Scale Mining in Nigeria: Experiences from Niger, Nasarawa and Plateau States. *The Extractive Industries and Society, 2,* 694-703. https://doi.org/10.1016/j.exis.2015.08.009

Orisakwe, O. E., Nduka, J. K., Amadi, C. N., Dike, D. O., & Bede, O. (2012). Heavy Metals Health Risk Assessment for Population via Consumption of Food Crops and Fruits in Owerri, South Eastern, Nigeria. *Chemistry Central Journal, 6,* Article No. 77. https://doi.org/10.1186/1752-153X-6-77

Oyebamiji, A., Odebunmi, A., Ruizhong, H., & Rasool, A. (2018). Assessment of Trace Metals Contamination in Stream Sediments and Soils in Abuja Leather Mining, Southwestern Nigeria. *Acta Geochimica, 37,* 592-613. https://doi.org/10.1007/s11631-017-0256-1

Pan, L. B., Ma, J., Wang, X. L., & Hou, H. (2016a). Heavy Metals in Soils from a Typical County in Shanxi Province, China: Levels, Sources and Spatial Distribution. *Chemosphere, 148,* 248-254. https://doi.org/10.1016/j.chemosphere.2015.12.049

Pan, L., Ma, J., Hu, Y., Su, B., Fang, G., Wang, Y., Wang, Z., Wang, L., & Xiang, B. (2016b). Assessments of Levels, Potential Ecological Risk, and Human Health Risk of Heavy Metals in the Soils from a Typical County in Shanxi Province, China. *Environmental Science and Pollution Research, 23,* 19330-19340. https://doi.org/10.1007/s11356-016-7044-z

Paramasivam, K., Ramasamy, V., & Suresh, G. (2015). Impact of Sediment Characteristics on the Heavy Metal Concentration and Their Ecological Risk Level of Surface Sediments of Vaigai River, Tamilnadu, India. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 137,* 397-407. https://doi.org/10.1016/j.saa.2014.08.056

Patel, P., Raju, N. J., Reddy, B. S. R., Suresh, U., Sankar, D. B., & Reddy, T. V. K. (2018). Heavy Metal Contamination in River Water and Sediments of the Swarnamukhi River Basin, India: Risk Assessment and Environmental Implications. *Environmental Geochemistry and Health, 40,* 609-623. https://doi.org/10.1007/s10653-017-0006-7

Plumlee, G. S., Durant, J. T., Morman, S. A., Neri, A., Wolf, R. E., Dooyema, C. A., Hageman, P. L., Lowers, H. A., Fernette, G. L., Meeker, G. P., & Benzel, W. M. (2013). Linking Geological and Health Sciences to Assess Childhood Lead Poisoning from Artisanal Gold Mining in Nigeria. *Environmental Health Perspectives, 121,* 744-750. https://doi.org/10.1289/ehp.1206051

Raut, R., Bajracharya, R. M., Sharma, S., Sharma, C. M., Kang, S., Zhang, Q., Tripathee, L., Chen, P., Rupakheti, D., Guo, J., & Dongol, B. S. (2017). Potentially Toxic Trace Metals in Water and Lake-Bed Sediment of Panchpokhari, an Alpine Lake Series in the Central Himalayan Region of Nepal. *Water, Air, & Soil Pollution, 228,* Article No. 303. https://doi.org/10.1007/s11270-017-3467-5

Rudnick, R. L., & Gao, S. (2003). Composition of the Continental Crust. *The Crust, 3,* 1-64. https://doi.org/10.1016/B0-08-043751-6/03016-4

Sajn, R., & Gosar, M. (2008). Pollution in Slovenia Owing to Mining and Metallurgy. *Brichte Der Geologischen Bundesanstalt, 77,* 22-23.

Sarkar, A., Ravindran, G., & Krishnamurthy, V. (2013). A Brief Review on the Effect of Cadmium Toxicity: from Cellular to Organ Level. *International Journal of Bio-Technology and Research, 3,* 17-36.

Strady, E., Dinh, Q. T., Némery, J., Nguyen, T. N., Guédron, S., Nguyen, N. S., Denis, H., & Nguyen, P. D. (2017). Spatial Variation and Risk Assessment of Trace Metals in Water and Sediment of the Mekong Delta. *Chemosphere, 179,* 367-378. https://doi.org/10.1016/j.chemosphere.2017.03.105

Sun, C., Zhang, Z., Cao, H., Xu, M., & Xu, L. (2019). Concentrations, Speciation, and Ecological Risk of Heavy Metals in the Sediment of the Songhua River in an Urban Area with Petrochemical Industries. *Chemosphere, 219,* 538-545. https://doi.org/10.1016/j.chemosphere.2018.12.040

Tabelin, C. B., Silwamba, M., Paglinawan, F. C., Mondejar, A. J. S., Duc, H. G., Resabal, V. J., Opiso, E. M., Igarashi, T., Tomiyama, S., Ito, M., & Hiroyoshi, N. (2020). Solid-Phase Partitioning and Release-Retention Mechanisms of Copper, Lead, Zinc and Arsenic in Soils Impacted by Artisanal and Small-Scale Gold Mining (ASGM) Activities. *Chemosphere, 260,* Article ID: 127574. https://doi.org/10.1016/j.chemosphere.2020.127574

Taylor, S. R., & McLennan, S. M. (1985). *Continental Crust: Its Composition and Evolution. An Examination of the Geochemical Record Preserved in Sedimentary Rocks*. Blackwell Scientific Publications.

Twerefou, D. K. (2009). *Mineral Exploitation, Environmental Sustainability and Sustainable Development in EAC, SADC and ECOWAS Regions* (ATPC Work in Progress No. 79). Economic Commission for Africa.

USEPA (1998). *Condition of the Mid-Atlantic Estuaries* (EPA/600/R98/147). US Environmental Protection Agency, Office of Research and Development.

Vu, C. T., Lin, C., Nguyen, K. A., Shern, C. C., & Kuo, Y. M. (2018). Ecological Risk Assessment of Heavy Metals Sampled in Sediments and Water of the Houjing River, Taiwan. *Environmental Earth Sciences, 77,* Article No. 388. https://doi.org/10.1007/s12665-018-7573-5

Wang, L., Guo, Z., Xiao, X., Chen, T., Liao, X., Song, J., & Wu, B. (2008). Heavy Metal Pollution of Soils and Vegetables in the Midstream and Downstream of the Xiangjiang River, Hunan Province. *Journal of Geographic Science, 18,* 353-362. https://doi.org/10.1007/s11442-008-0353-5

Wedepohl, K. H. (1971). Environmental Influences on Chemical Composition of Shales and Clays. *Physics and Chemistry of the Earth, 8,* 307-333. https://doi.org/10.1016/0079-1946(71)90020-6

Xu, F., Liu, Z., Cao, Y., Qiu, L., Feng, J., Xu, F., & Tian, X. (2017). Assessment of Heavy Metal Contamination in Urban River Sediments in the Jiaozhou Bay Catchment, Qingdao, China. *CATENA, 150,* 9-16. https://doi.org/10.1016/j.catena.2016.11.004

Yabe, J., Nakayama, S. M., Ikenaka, Y., Yohannes, Y. B., Bortey-Sam, N., Kabalo, A. N., Ntapisha, J., Mizukawa, H., Umemura, T., & Ishizuka, M. (2018). Lead and Cadmium Excretion in Feces and Urine of Children from Polluted Townships Near a Lead-Zinc Mine in Kabwe, Zambia. *Chemosphere, 202,* 48-55. https://doi.org/10.1016/j.chemosphere.2018.03.079

Zahra, A., Hashmi, M. Z., Malik, R. N., & Ahmed, Z. (2014). Enrichment and Geo-Accumulation of Heavy Metals and Risk Assessment of Sediments of the Kurang Nallah—Feeding Tributary of the Rawal Lake Reservoir, Pakistan. *Science of the Total Environment, 470-471,* 925-933. https://doi.org/10.1016/j.scitotenv.2013.10.017

Zhang, M., He, P., Qiao, G., Huang, J., Yuan, X., & Li, Q. (2019). Heavy Metal Contamination Assessment of Surface Sediments of the Subei Shoal, China: Spatial Distribution, Source Apportionment and Ecological Risk. *Chemosphere, 223,* 211-222. https://doi.org/10.1016/j.chemosphere.2019.02.058