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SEDIMENT QUALITY ASSESSMENT OF RIVERS ABESAN AND OWO IN PARTS OF LAGOS, NIGERIA

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ABSTRACT

The present study assessed the sediment quality of Rivers Abesan and Owo in parts of Lagos, Nigeria. Data employed for this study was obtained from twenty locations. The sediment samples were analyzed for ten heavy metals [Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Iron (Fe), Lead (Pb), Manganese (Mn), Mercury (Hg), Nickel (Ni), and Zinc (Zn)], using atomic absorption spectrophotometer. Descriptive and correlation statistics and indices were employed for data analysis. The results showed low contamination factors for Mn, Fe, Cr, Zn, Cd, As, and Ni. About 75% and 20% of the locations indicated very high and moderate contamination factors for Pb and Cu, respectively. The contamination factor for Hg showed very high contamination in all the sites. However, the pollution load index (PLI) revealed no pollution in all the areas. The geo-accumulation index (I-geo) for Mn, Fe, Cr, Zn, Cu, Cd, As, and Ni signified no contamination, while the I-geo index for Hg indicated that 35% of each site was heavily and extremely contaminated. Moreover, the I-geo for Pb provided evidence that 75% and 25% of the locations exhibited moderate to heavy contamination and moderate contamination, respectively. Also, the potential contamination index (PCI) for Mn, Fe, Cr, Zn, Cd, As, and Ni represented low contamination, while that of Cu and Hg/Pb indicated moderate and very severe contamination, respectively. The enrichment factor (EF) of Fe, Zn, and Cd indicated minor enrichment, while Cr and Cu showed moderate and moderately severe enrichment, respectively. In addition, Hg and Pb showed extremely severe enrichment. We observed a relationship between PLI and heavy metals in the study area. The heavy metals: Mn, Fe, Cd, and As have a significant impact on the sediment quality in the study area. The study recommended the monitoring of point source pollutants in the rivers catchment for sustainable environmental management.

Keywords: Contamination, Heavy metal, Rivers Abesan and Owo, Sediment quality indices.

INTRODUCTION

Sediments are free particles of soil found at the bottom of the aquatic environment in clay, sand, organic material, or silt. (Burton, 2002; Ingersoll *et al.,* 2002; Nowrouzi and Pourkhabbaz, 2014). They are essential elements of aquatic ecosystems because they support autotrophic and heterotrophic organisms (MacDonald *et al.,* 2003). The alarming population growth rate, uncontrolled urbanization, industrialization, and intensive agricultural activities, coupled with the discharge of untreated wastewater from point and non-point/diffused sources into the natural water bodies poses a significant environmental challenge to the ecosystems. These unsustainable activities pose a significant environmental challenge to the sediment quality of water bodies in developing countries (Moore *et al.,* 2009). The introduction of wide varieties of heavy metals into the receiving water bodies results in undesirable effects on the aquatic ecosystem (Ayoade and Nathaniel, 2018). Heavy metals are detected in the aquatic and terrestrial environment and are described in marine environments, from natural and anthropogenic sources. Examples of anthropogenic sources include mining, construction, industrial and agricultural activities, disposal of liquid effluents/wastewater, runoff from the urban road network, and leachates (Bakan and Özkoç, 2007; Taylor and Owens, 2009).

The alarming increase in heavy metals contamination in the aquatic environment pose a significant concern due to their persistent nature in the environment and the adverse effects on living organisms and humans through the food chain (Ntekim *et al.,* 1993; Sabo *et al.,* 2013). The significant impact of sediment contamination on the ecosystem is associated with contaminants that have direct effects on benthic communities and also on the upper trophic levels through food chain contamination (Foley *et al.,* 1988; Canfield *et al.,* 1994; Canfield *et al.,* 1996; Swartz *et al.,* 1994; Burton, 2002; Wei *et al.,* 2010). Contaminated sediment can cause lethal and sub-lethal effects on benthic and other sediment-associated organisms (Wei *et al.,* 2010). Polluted sediment can reduce or eliminate the recreational or ecological importance of rivers through direct effects on the food supply chain. The knowledge and understanding of sediment quality serve as a veritable tool for environmental pollution monitoring in the water column. It also allows for ecosystem protection and restoration of the health status of sediment for ecological risk assessments and management options (Batley, 1989; MacDonald *et al.,* 2003; Wakida *et al.,* 2008; Goorzadi *et al.,* 2009; Adel *et al.,* 2011; Aladesanmi *et al.,* 2016).

There is substantial literature on sediment quality assessment. The most common methods include the index of geo-accumulation (I-geo), pollution load index (PLI), contamination factor (Cf), enrichment factor (EF), (Adisa and Adekoya, 2016a), and potential contamination index (PCI) (Adel *et al.,* 2011). These techniques have been widely used to measure sediment contamination in the aquatic environment. These techniques are geared toward providing information on the overall level of heavy metal contamination in sediments for policy decisions (Singh *et al.,* 1997; Burton, 2002; Priju and Narayana, 2006; Adel *et al.,* 2011). The management and control of sediment contamination involve two main approaches: One approach is controlling and reducing sediment contaminants from point sources. This approach is one of the most effective sediment control methods in developed countries (Owens and Walling, 2003; Casper, 2008). The second approach is the removal of sediments within the river channels through dredging. This technique is expensive if the sediment is already contaminated (Taylor and Owens, 2009). Previous studies have focused mainly on surface water quality around rural areas with scanty literature on sediment quality assessment in the urban catchment of Lagos, Nigeria. This study, therefore, seeks to assess the sediment quality of Rivers Abesan and Owo in parts of Lagos, Nigeria, using sediment quality evaluation indices such as; contamination factor, enrichment factor, pollution load index, potential contamination index, and geo-accumulation index. The study is important because it provides baseline information on heavy metal toxicity and the ecological risk of anthropogenic impacts on bottom sediment.

MATERIALS AND METHODS

Study Area

River Abesan is located at Latitude 6°37' 0" N and Longitude 3°13' 60" E. River Owo is located at Latitude 8° 22' 59"' N and Longitude 3° 19' 59" E (Fig. 1). The two Rivers are important inland freshwater bodies and form part of the Ogun-Osun River Basin in Southwestern Nigeria (Agboola and Denloye 2011; Adegun *et al.* 2015). River Abesan has a maximum depth of about 3m and flows through the build-up areas into the Ologe Lagoon (Agboola and Denloye, 2011). The dominant human activity within the catchment is agriculture. Other activities include industrialization and urbanization. These anthropogenic activities have contributed immensely to the ecological degradation and consequently sediment quality deterioration in the river catchment. River Owo took its source from Ogun State in Southwestern Nigeria and discharged it into Ologe Lagoon. The river cut across Alimosho and Ojo Local Government Areas in parts of Lagos, Nigeria. River Owo is important because it serves as the primary source of Ishashi surface water abstraction for municipal water supply in Lagos State (Akoteyon *et al.,* 2011). The climate of the area is characterized by dry and wet seasons. The dry season spans between November and March, while the wet season covers April to October (Akoteyon, 2014). The mean temperature is 27°C, with an average rainfall of about 1.532 mm (Adedeji and Babatunde, 2010). The drainage system is comprised of Lagoons and waterways, barrier islands, and sandy beaches. The geology of the area is underlain by the Ilaro Formation, comprising marine and continental deposits of sedimentary rocks (Adegun *et al.,* 2015). The predominant vegetation is riparian forest (Adegun *et al.,* 2015).

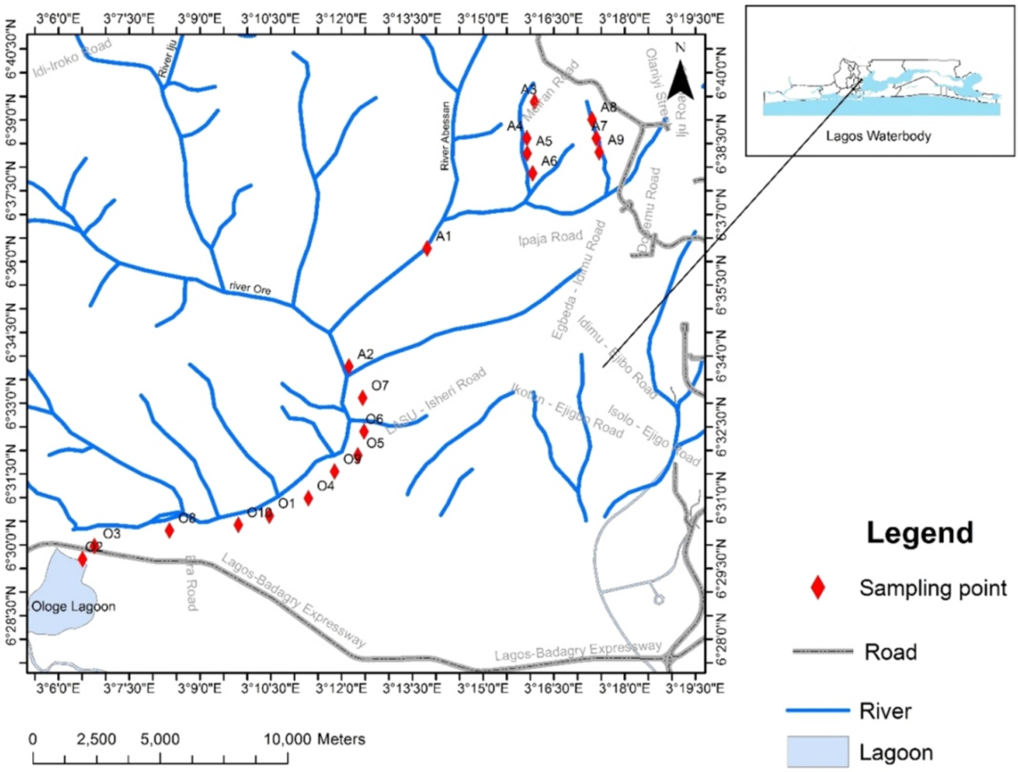

Figure 1: Study area.

Sample collection, procedure, and preparation

Single top sediment samples were collected at a depth of about 0-5 cm from 20 locations along Abesan and Owo Rivers banks within the urban catchment of Lagos, Nigeria, between June and July 2020. The coordinate of the sample locations was recorded using Global Positioning System (GPS) Garmin map, 76CSX model, and was mapped with ArcMap 10.3.1 version. The River sediments were sampled due to their importance for fishing and surface water abstraction. The samples were collected with a soil auger and kept inside a new polythene bag after treatment with nitric acidic of about 5% to avoid sticking the metals on the bag. This measure was taken to avoid the error of bias. The sediment samples were stored in an ice chest before transfer to the laboratory. Sediment samples were poured into porcelain crucibles and oven-dried at about 80 °C for 3 h. After that, 2 g of the sediment samples were weighed using the electronic balance model M 10001 digital machine (WINCOM, China). The sediments were crushed with a pestle and mortar and sieved using a 2 mm mesh. The samples were poured into a 100 mL volumetric flask and digested with 15.0 mL of HNO_3 and HCl acid in the ratio of 1:3 (aqua-regia). Ten heavy metals: Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Iron (Fe), Lead (Pb), Manganese (Mn), Mercury (Hg), Nickel (Ni), and Zinc (Zn) were analyzed using atomic absorption spectrometry (AAS) (AAS VGB 210 model). The corresponding measurable signal of each metal was taken at their specific wavelength, as described previously (Manoj and Padhy, 2014; Remeikaitė-Nikienė *et al.,* 2018). Both blank and standard solutions were analyzed at regular intervals. The quality assurance and control (QA/QC) protocol prescribed by the Standard Organisation of Nigeria (SON) for sediment reference materials was used for the examined heavy metals. The sample was analyzed at Emzor Pharmaceutical Laboratory, Ikeja, Lagos, Nigeria.

Data analysis

Descriptive and correlation statistical techniques were applied to examine the spread and association of the sediment parameters, respectively, using IBM Statistical Package for Social Sciences (version 22.0). In addition, five sediment quality indices were adopted for the sediment quality assessment. Due to the lack of background data on metals in sediments of the study area, the global Earth's shale values for metals, according to Turekian and Wedepohl (1961), were employed.

Sediment quality assessment

(a) Contamination factor (Cf)

The contamination factor determines the degree of anthropogenic heavy metal contamination or the enrichment of metals in sediments. The Cf of the sediment samples was obtained by dividing the concentration of each metal in the sediments by the background value (Hakanson, 1980; Bonnail *et al.,* 2016). The formula is stated in equation 1. According to Bonnail *et al.* (2016), Cf value can be classified into four as follows; low contamination (Cf < 1), moderate contamination (1 < Cf < 3), considerable contamination (3 < Cf < 6), and very high contamination.
(Cf > 6).

$$CF = Cs/Cref \quad \text{.........} \qquad \text{(Eq.1)}$$

Where Cs and Cref are concentrations of the element in the sediment sample and the background or pristine value of the element, respectively.

(a) Enrichment factor (EF)

The enrichment factor is one of the universal methods used for assessing the environmental impact of metals and the pollution level in sediments. It is determined by calculating the ratio between uncontaminated background levels and contaminated sediment layers (Selvaraj *et al.,* 2010; Costa *et al.,* 2015; Zalewska *et al.,* 2015). The determination of EF is based on the normalization approach (Simex and Helz, 1981). Some frequently used metals for normalization include Al, Fe, total organic carbon, and grain size (Benhaddya and Hadjel, 2013). Iron was used as the normalization factor in this study because of its low human impact (Ho *et al.,* 2012; Selvaraj *et al.,* 2010). According to Ergin *et al.* (1991), the EF is indicated in equation 2.

$$EF = \left(\frac{M}{Fe}\right) Sample / \left(\frac{Me}{Fe}\right) Background \qquad \text{(Eq.2)}$$

Where (M/Fe) Sample is the ratio of metal and Fe concentrations in the sample, and (M/Fe) background is the ratio of metal and Fe concentrations in the background (Ergin *et al.,* 1991; Nowrouzi and Pourkhabbaz, 2014). The global Earth's shale values for the metals according to Turekian and Wedepohl (1961) employed are: (Mn= 850; Fe=47200; Hg=0.4; Pb = 20; Cu = 45; Cd = 0.3; Ni = 68; Cr = 90; Zn = 95; As =13 mg kg^{-1} dry weight. The classification scheme as described by Costa *et al.* (2015), and Zalewska *et al.* (2015) was used. The classification is given as: EF <1 (no enrichment), EF <3 (minor enrichment), EF (between 3 and 5 (moderate enrichment), EF between 5 and 10 (moderately severe enrichment), EF between 10 and 25 (severe enrichment), EF between 25 and 50 (very severe enrichment), EF > 50 (extremely severe enrichment) (Costa *et al.* 2015; Zalewska *et al.*, 2015).

(c) Pollution load index (PLI)

According to Adel *et al.* (2011), PLI is obtained as Cfs. They represent the quotient obtained by dividing the concentration of each metal. The index is computed based on the n-root from the n-CFs obtained from the heavy metals under investigation (Tomlinson *et al.,* 1980; Soares *et al.,* 1999; Adel *et al.,* 2011; Li *et al.,* 2013). The PLI is stated in equation 3. The PLI value is categorized into two according to Harikumar *et al.* (2009), namely, polluted (PLI > 1) and no pollution (PLI <1).

$$PLI = (Cf1\ x\ Cf2\ x\ Cf3\ x\ Cf4 \ldots\ldots Cfn)^{(1/n)} \text{……..(Eq.3)}$$

(d) Potential contamination index (PCI)

The PCI was determined using Hakanson's (1980) formula indicated in equation 4.

Cp = (Metal)Samplemaximum/
(Metal)Background (Eq.4)

Where (Metal) Sample maximum is the maximum concentration of a metal in sediment, and (Metal) Background is the average value of the same metal at a background level. The classification of Cp values was interpreted as described previously (Tomlinson *et al.,* 1980; Davaulter and Rognerud, 2001) i.e., Potential contamination index Cp < 1 (low contamination), 1 < Cp < 3 (moderate contamination) and Cp > 3 (severe or very severe contamination).

(e) Geo-accumulation index (I-geo)

The I-geo index is a quantitative measure of the degree of pollution in aquatic sediments, which can be applied to determine and define metal contamination in sediments by comparing current concentrations with pre-industrial levels (Muller, 1979). The I-geo was obtained using equation 5.

$$Igeo = Log2[\frac{Cn}{1.5Bn}] \qquad \text{(Eq.5)}$$

Where Cn is the measured concentration in the sediment for the metal n, Bn is the background value for the metal n), and 1.5 is a factor that represents the lithological variations of the background data (Turekian and Wedepohl, 1961). The I-geo for this study was calculated based on the global average shale data from Turekian and Wedepohl (1961). The I-geo index value was classified into seven factors: Igeo < 0 (uncontaminated), 0 ≤ Igeo < 1 (uncontaminated to moderately contaminated), 1 ≤ Igeo < 2 (moderately contaminated), 2 ≤ Igeo < 3 (moderately to heavily contaminated), 3 ≤ Igeo < 4 (heavily contaminated), 4 ≤ Igeo < 5 (heavily to extremely contaminated), 5 ≥ Igeo (extremely contaminated) (Müller, 1979; García *et al.,* 2008; Zalewska *et al.,* 2015).

RESULTS

The descriptive statistics of heavy metals in sediment are presented in Table 1. The result showed that Fe and As recorded the highest and lowest concentrations in the study area. The values for manganese ranged from 29.8-101.19 mg kg^{-1} with an average of 63.4 mg kg^{-1}. Iron varied between 1427.09-7453.44 mg kg^{-1} with an average of 4164.93 mg kg^{-1}. The values for mercury were 8.16-79.13 mg kg^{-1} with a mean value of 18.12 mg kg^{-1}. The measurement for chromium ranged between 17.11-78.14 mg kg^{-1} with an average of 32.95 mg kg-1. Also, the lead concentration was 84.16-204.11 mg kg^{-1}, with a mean value of 135.34 mg kg^{-1}. The concentration of Zn and Cu ranged from 8.74-54.17 and 14.01-58.63 mg kg^{-1}, with an average of 19.13mg kg^{-1} and 36.03 mg kg^{-1}, respectively. Also, the concentration for Cd, As, and Ni were 0.0-0.09, 0.09-0.29, and 0.0-4.61 mg kg^{-1}, with an average value of 0.04, 0.17 and 1.65 mg kg^{-1}, respectively. Nickel and Cd were not detected in locations 1 and 17, respectively.

Table 1: Descriptive statistics of heavy metals in sediment of the study area.

SN	Mn	Fe	Hg	Cr	Pb	Zn	Cu	Cd	As	Ni
1	67.19	4219.83	17.44	17.11	138.17	12.04	31.55	0.09	0.17	ND
2	89.22	6001.79	19.8	54.14	204.11	8.74	49.98	0.05	0.21	1.07
3	94.49	6544.07	21.16	38.4	89.07	15.18	38.99	0.05	0.21	2.34
4	101.19	7453.44	24.06	32.17	187.31	11.02	58.63	0.09	0.29	1.88
5	82.63	6314.17	20.86	49.44	179.04	8.88	42.17	0.02	0.12	1.19
6	74.87	5809.31	18.03	51.08	84.16	9.07	39.19	0.05	0.17	1.03
7	100.44	7361.39	79.13	78.14	84.56	17.19	14.01	0.04	0.19	1.11
8	71.84	5065.34	22.09	28.14	132.46	46.7	38.21	0.06	0.17	1.1
9	74.43	5593.09	19.11	32.72	144.81	54.17	37.93	0.06	0.17	1.73
10	88.7	5981.83	27.41	54.01	121.75	38.62	42.09	0.06	0.18	1.89
11	52.81	3014.16	10.24	22.57	146.13	18.01	42.18	0.04	0.24	4.61
12	44.73	2872.43	9.01	21.23	139.04	17.22	38.37	0.02	0.18	1.14
13	36.89	1784.74	8.83	20.24	127.41	13.19	30.81	0.02	0.09	ND
14	40.01	2434.50	9.44	20.97	129.33	22.17	32.26	0.01	0.11	1.18
15	38.17	1997.38	9.18	20.09	140.72	16.74	30.67	0.01	0.11	1.18
16	64.11	3480.62	11.03	35.38	164.14	19.09	39.31	0.04	0.28	4.32
17	29.8	1427.09	8.16	20.03	101.09	12.12	24.53	ND	0.09	1.18
18	33.41	1819.53	8.92	20.91	138.47	16.08	29.14	0.02	0.14	1.64
19	44.84	2574.66	9.89	22.41	142.63	16.39	37.46	0.02	0.18	2.69
20	38.28	1549.17	8.51	19.84	112.49	9.88	23.11	0.02	0.12	1.73
Mean	63.40	4164.927	18.115	32.951	135.34	19.13	36.03	0.04	0.17	1.65
Max	101.19	7453.44	79.13	78.14	204.11	54.17	58.63	0.09	0.29	4.61
Min	29.8	1427.09	8.16	17.11	84.16	8.74	14.01	nd	0.09	nd
Average shale value (Turekian and Wedepohl, 1961)	850	47200	0.4	90	20	95	45	0.3	13	68

NB: Max-maximum, min-minimum, ND- not detected.

Contamination factor and pollution load index

The computed CFs are presented in Table 2. The result showed that the CFs for Mn, Fe, Hg, Cr, Pb, Zn, Cu, Cd, As and Ni ranged between 0.04-0.12, 0.03-0.16, 20.4-197.83, 0.19-0.87, 4.21-10.21, 0.09-0.57, 0.31-1.3, 0.0-0.3, 0.01-0.02, and 0.0-0.07, respectively. The CF of Cu indicated that 80% and 20% of the sites exhibited low and moderate contamination, respectively. As for CF for Pb, 25% of the locations showed considerable contamination from locations 3, 6, 7, 1, and 20, while the remaining 75% displayed very high contamination. Mercury recorded the highest CF, while Cd/Ni had the least value. On the PLI, it ranged from 0.25-0.61 with a mean value of 0.42. The PLI showed no pollution in all the sampling points (Figure 2).

Table 2: Contamination factor of sediment in the study area.

SN	CF_{Mn}	CF_{Fe}	CF_{Hg}	CF_{Cr}	CF_{Pb}	CF_{Zn}	CF_{Cu}	CF_{Cd}	CF_{As}	CF_{Ni}
1	0.08	0.09	43.6	0.19	6.91	0.13	0.7	0.3	0.01	0.0
2	0.11	0.13	49.5	0.6	10.21	0.09	1.11	0.17	0.02	0.02
3	0.11	0.14	52.9	0.43	4.45	0.16	0.87	0.17	0.02	0.03
4	0.12	0.16	60.15	0.33	9.37	0.12	1.3	0.3	0.02	0.03
5	0.09	0.13	52.15	0.55	8.95	0.09	0.94	0.07	0.01	0.02
6	0.09	0.12	45.08	0.57	4.21	0.09	0.87	0.17	0.01	0.02
7	0.12	0.16	197.83	0.87	4.23	0.18	0.31	0.13	0.02	0.02
8	0.09	0.11	55.23	0.31	6.62	0.49	0.85	0.2	0.01	0.02
9	0.09	0.12	47.78	0.36	7.24	0.57	0.84	0.2	0.01	0.03
10	0.1	0.13	68.53	0.6	6.09	0.41	0.94	0.2	0.01	0.03
11	0.06	0.06	25.6	0.25	7.31	0.19	0.94	0.13	0.02	0.07
12	0.05	0.06	22.53	0.24	6.95	0.18	0.85	0.07	0.01	0.02
13	0.04	0.04	22.08	0.23	6.37	0.14	0.69	0.07	0.01	0.0
14	0.05	0.05	23.6	0.23	6.47	0.23	0.72	0.03	0.01	0.02
15	0.05	0.04	22.95	0.22	7.05	0.18	0.68	0.03	0.01	0.02
16	0.08	0.07	27.58	0.39	8.21	0.2	0.87	0.13	0.02	0.06
17	0.04	0.03	20.4	0.22	5.06	0.13	0.55	0.0	0.01	0.02
18	0.04	0.04	22.3	0.23	6.92	0.17	0.65	0.07	0.01	0.02
19	0.05	0.06	24.73	0.23	7.13	0.17	0.83	0.07	0.01	0.04
20	0.05	0.03	21.28	0.22	5.63	0.1	0.51	0.07	0.01	0.03
Mean	0.07	0.09	45.29	0.36	6.77	0.20	0.80	0.13	0.01	0.03
Max	0.12	0.16	197.83	0.87	10.21	0.57	1.30	0.30	0.02	0.07
Min	0.04	0.03	20.40	0.19	4.21	0.09	0.31	0.00	0.01	0.00

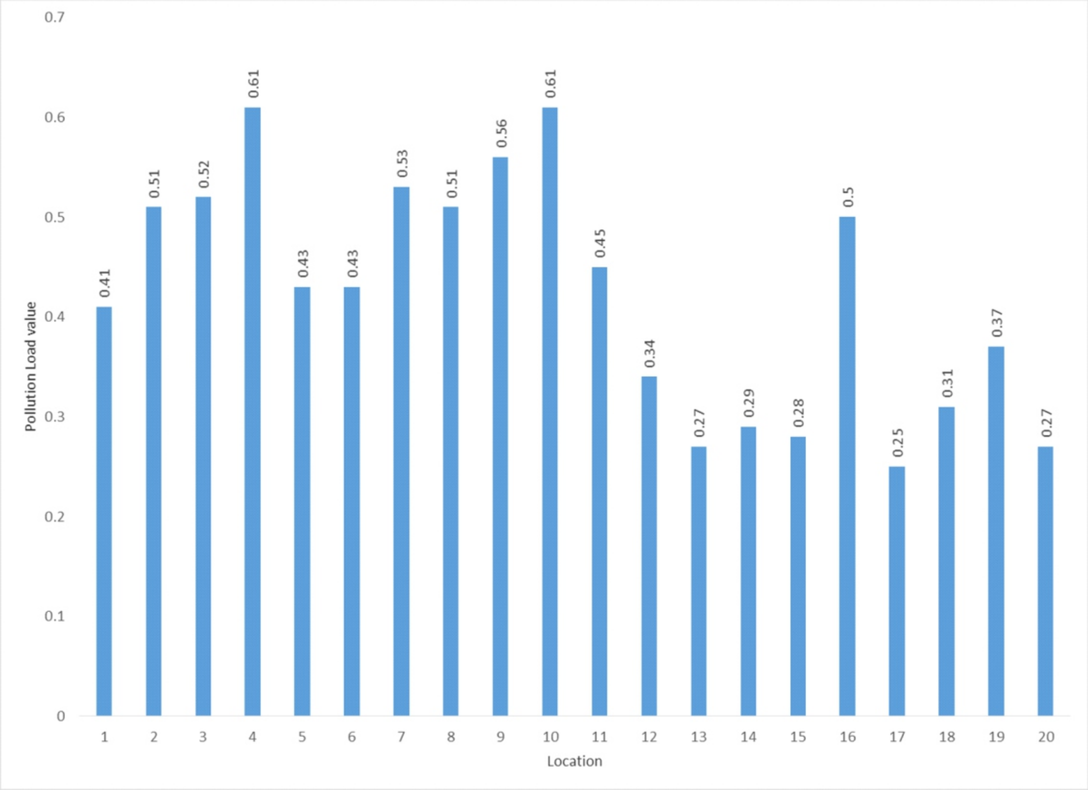

Figure 2: Pollution load index of sediment in the study area.

Geo-accumulation index

Table 3 presents the computed I-geo for heavy metals. Mn, Fe, Hg, Cr, Pb, Zn, Cu, Cd, As, and Ni values ranged from -5.42 to -3.66, -5.63 to -3.25, 3.77 to 7.04, -2.98 to -0.79, 1.49 to 2.77, -2.27 to -0.20, -5.49 to 0.0, -7.76 to -6.07 and -6.63 to 0.0, respectively. The computed I-geo for Mn, Fe, Cr, Zn, Cu, Cd, As, and Ni indicated that the sediments are uncontaminated. The I-geo of Hg showed that 35% of the sites are heavily and extremely contaminated, while 30% indicated heavy to extreme contamination. The overall I-geo in the study area revealed that location 7 had the highest value, while locations 13 and 17 recorded the lowest. On the I-geo for Pb, 75% and 25% of the locations showed moderate to heavy contamination and moderate contamination, respectively.

Table 3: Geo-accumulation index of sediment in the study area.

SN	I_{geoMn}	I_{geoFe}	I_{geoHg}	I_{geoCr}	I_{geoPb}	I_{geoZn}	I_{geoCu}	I_{geoCd}	I_{geoAs}	I_{geoNi}
1	-4.25	-4.07	4.86	-2.98	2.2	-3.57	-1.09	-2.32	-6.84	0
2	-3.84	-3.56	5.04	-1.32	2.77	-4.03	-0.43	-3.17	-6.54	-6.58
3	-3.75	-3.44	5.14	-1.81	1.57	-3.23	-0.79	-3.17	-6.54	-5.45
4	-3.66	-3.25	5.33	-2.07	2.64	-3.69	-0.2	-2.32	-6.07	-5.76
5	-3.95	-3.49	5.12	-1.45	2.58	-4	-0.68	-4.49	-7.34	-6.42
6	-4.09	-3.61	4.91	-1.4	1.49	-3.97	-0.78	-3.17	-6.84	-6.63
7	-3.67	-3.27	7.04	-0.79	1.49	-3.05	-2.27	-3.49	-6.68	-6.52
8	-4.15	-3.81	5.2	-2.26	2.14	-1.61	-0.82	-2.91	-6.84	-6.54
9	-4.09	-3.66	4.99	-2.05	2.27	-1.39	-0.83	-2.91	-6.84	-5.88
10	-3.85	-3.567	5.51	-1.32	2.02	-1.88	-0.68	-2.91	-6.76	-5.75
11	-4.59	-4.55	4.09	-2.58	2.28	-2.98	-0.68	-3.49	-6.34	-4.47
12	-4.83	-4.62	3.91	-2.67	2.21	-3.049	-0.82	-4.49	-6.76	-6.48
13	-5.11	-5.31	3.88	-2.74	2.09	-3.43	-1.13	-4.49	-7.76	0.0
14	-4.99	-4.86	3.98	-2.69	2.12	-2.68	-1.07	-5.49	-7.47	-6.43
15	-5.06	-5.15	3.94	-2.75	2.23	-3.09	-1.14	-5.49	-7.47	-6.43
16	-4.31	-4.35	4.2	-1.93	2.45	-2.9	-0.78	-3.49	-6.12	-4.56
17	-5.42	-5.63	3.77	-2.75	1.75	-3.56	-1.46	0.0	-7.76	-6.43
18	-5.25	-5.28	3.89	-2.69	2.21	-3.15	-1.212	-4.49	-7.12	-5.96
19	-4.83	-4.78	4.043	-2.59	2.25	-3.12	-0.85	-4.49	-6.76	-5.25
20	-5.06	-5.51	3.83	-2.77	1.91	-3.8	-1.55	-4.49	-7.34	-5.88
Mean	-4.44	-4.29	4.63	-2.18	2.13	-3.11	-0.96	-3.56	-6.91	-5.37
Max	-3.66	-3.25	7.04	-0.79	2.77	-1.39	-0.20	0.00	-6.07	0.00
Min	-5.42	-5.63	3.77	-2.98	1.49	-4.03	-2.27	-5.49	-7.76	-6.63

Potential Contamination Index and Enrichment Factor

The PCI ranged from 0.02 to 197.83 with a mean value of 21.14. The degree PCI of sediment contamination showed low contamination for Mn, Fe, Cr, Zn, Cd, As, and Ni. In contrast, Cu and Hg/Pb indicated moderate and very severe contamination, respectively (Table 4). Mercury recorded the highest PCI, while As had the lowest value. The EF varied from 0.16-573.95, with an average value of 66.91. The EF value of Mn, As and Ni revealed no enrichment. Minor enrichment was observed for Fe, Zn, and Cd, while Cr and Cu showed moderate and moderately severe enrichment, respectively. The EF value of Hg and Pb indicated extremely severe enrichment. The highest and lowest EF value were recorded from Hg and Fe, respectively.

Table 4: Pollution contamination index and enrichment factor of sediment in the study area.

Parameters	Mn	Fe	Hg	Cr	Pb	Zn	Cu	Cd	As	Ni	Max	Min	Mean
PCI	0.12	0.17	197.83	0.87	10.21	0.57	1.3	0.3	0.02	0.07	197.83	0.02	21.14
EF	0.84	1.0	573.95	4.26	75.702	2.39	9.01	1.49	0.16	0.26	573.95	0.16	66.91

Relationship of PLI and heavy metal concentration in the study area

The relationship between PLI and heavy metal concentration in the study area was determined because PLI provides overall information about sediment contamination. There was a significantly high correlation between PLI and the following heavy metals: Mn (r=0.91), Fe(r=0.88); Cd (r=0.78), and As (r=0.75). The correlation between PLI and Hg/Cu and Cr indicated low and moderate values, respectively (Table 5).

Table 5: Correlation of PLI and heavy metal concentration in the study area.

		PLI	Mn	Fe	Hg	Cr	Pb	Zn	Cu	Cd	As	Ni
PLI	r	1										
	p-value											
Mn	r	.906**	1									
	p-value	.000										
Fe	r	.877**	.985**	1								
	p-value	.000	.000									
Hg	r	.532*	.677**	.679**	1							
	p-value	.016	.001	.001								
Cr	r	.629**	.780**	.782**	.815**	1						
	p-value	.003	.000	.000	.000							
Pb	r	.224	.133	.106	-.270	-.100	1					
	p-value	.343	.578	.655	.250	.675						
Zn	r	.416	.139	.165	.105	.022	-.052	1				
	p-value	.068	.558	.486	.661	.925	.828					
Cu	r	.549*	.441	.437	-.265	.042	.676**	.053	1			
	p-value	.012	.051	.054	.259	.860	.001	.825				
Cd	r	.783**	.724**	.692**	.314	.261	.203	.257	.502*	1		
	p-value	.000	.000	.001	.177	.267	.391	.275	.024			
As	r	.750**	.601**	.532*	.233	.289	.353	.040	.600**	.644**	1	
	p-value	.000	.005	.016	.324	.216	.127	.867	.005	.002		
Ni	r	.212	-.016	-.078	-.168	-.084	.180	.017	.244	-.044	.608**	1
	p-value	.368	.947	.743	.480	.726	.447	.944	.299	.853	.004	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

DISCUSSION

The study showed that the high concentrations of heavy metals in the study could be attributed to high anthropogenic activities such as local boat transportation and poor solid waste disposal. Our observation is similar to the reports of Stephen *et al.* (2001), Akan *et al.* (2010), Egbe and Ahunanya (2016), Ayoade and Nathaniel (2018), and Remeikaitė-Nikienė *et al.* (2018) on high heavy metal contamination in the bottom sediments of rivers in Southwestern Nigeria and Lithuania above the prescribed regulatory guideline. The high accumulation of heavy metals in benthic organisms can disrupt the food chain leading to enhanced levels in the liver and muscle problems with severe environmental and health problems. Also, the low values of CFs for Mn, Fe, Cr, Zn, Cd, As, and Ni observed in this study are related to the findings of Puyate *et al.* (2007), Seshan *et al.* (2010) and Devanesan *et al.* (2017) in Agbor, Nigeria and Tamilnadu, India. Also, the CF for Hg is similar to the report of Adel *et al.* (2011), while the findings regarding the CFs of Ni, Cr, and Cd are consistent with the views of Forstner (1980), Ntekim *et al.* (1993). The implications of these results showed that heavy metal contamination in the study area can be linked to the natural weathering process (Achi *et al.,* 2021).

The result of the PLI revealed no pollution in the study area which is consistent with the previous findings by Adisa and Adekoya (2016a), while the I-geo value for most of the heavy metals in the current study corroborates the findings of Adisa and Adekoya (2016a) in Southwestern Nigeria. However, the I-geo of Hg and Pb of the current study is at variance with the study conducted by Adisa and Adekoya (2016a). This could be attributed to the prevailing land uses and the dominant processes (Achi *et al.*, 2021). On the degree of enrichment, the findings indicated moderate to moderately severe enrichment of Cr and Cu. This observation poses significant lethal and sub-lethal effects on benthic and other sediment-associated organisms which can result in the reduction or elimination of the ecological importance of the river. A previous study by Adisa and Adekoya (2016a) reported moderate EF due to the concentration of Cu, Cr, Mn, and Pb in the Oyi River. The computed EF for Hg, Cr, Pb, Zn, and Cu in the study area indicated anthropogenic origins, while Mn, Fe, Cd, As and Ni can be attributed to crustal or natural processes with a significant impact on the sediment quality (Zhang and Liu, 2002; Nobi *et al.,* 2010; Ghrefat *et al.,* 2011). The results of the computed PCI of Hg and the EF of Pb corroborate the findings of Bakan and Özkoç (2007), Nowrouzi and Pourkhabbaz (2014), Alyazichi *et al.* (2015), Al-Mur *et al.* (2017) and Remeikaitė-Nikienė *et al.* (2018). Also, the high positive correlation between PLI and Mn, Fe, Cd, and As suggests they are from the same source. Unlike the relationship between PLI and Hg/Cu and Cr, it showed that the metals come from different sources based on their low correlation coefficients (Akpan and Thompson, 2013). The result supports the findings of Nowrouzi and Pourkhabbaz (2014), Adisa and Adekoya (2016b), and Remeikaitė-Nikienė *et al.* (2018).

CONCLUSION

The present study assessed sediment quality using sediment quality evaluation indices. The findings revealed that about 75% of the locations showed very high contamination factors for Pb and Hg, while 35% of each site based on I-geo value exhibited heavy and extreme contamination. The PCI for Cu and Hg/Pb indicated moderate and very severe contamination, respectively, while the EF for Cu showed moderately severe enrichment. The study concluded that Mn, Fe, Cd, and As are the major heavy metals with a significant impact on the sediment quality in the study area. The study provides baseline information for policymakers in planning and monitoring point source pollutants.

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REFERENCES

Achi, C. G., Omoniyi, A. M., Coker, A. O., and Sridhar, M. K. C. 2021. Multivariate analysis of sediment quality in River Ogbere, Ibadan, South-West Nigeria. *H_2Open Journal*, 4(1): 1-11.

Adedeji, A. and Babatunde, A. 2010. Quality of Hand-dug Wells in Selected Locations in Lagos Coastal Aquifer, Nigeria. *Report and Opinion*, 2 (3): 51-54.

Adegun, O., Odunuga, S. and Ajayi, O. S. 2015. Climate, runoff and land use trends in the Owo \River Catchment in Nigeria. *Proceedings of the International Association of Hydrological Sciences*, 371: 137-142.

Adel, M.R., Al-Fatlawy, Y.F., Abd-Al-Husain N.A and Mustafa, N. 2011. Using Pollution Load Index (PLI) and Geoaccumulation Index (I-Geo) for the Assessment of Heavy Metals Pollution in Tigris River Sediment in Baghdad Region. *Journal of Al-Nahrain University*, 14 (4): 108-114.

Adisa, A. L. and Adekoya, J. A. 2016a. Assessment of pollution by heavy metals in sediments of River Oyi and its tributary, Southwestern Nigeria. *Ife Journal of Science*, 18(4): 871-886.

Adisa, A. L. and Adekoya, J. A. 2016b. Statistical analysis of stream sediment geochemical data from Oyi drainage System, Western Nigeria. *Ife Journal of Science*, 18(1): 1-16.

Agboola, J. I. and Denloye, A. A. B. 2011. Preliminary assessment of anthropogenic impact on some ecological components of Abesan River, Lagos, Nigeria. *Journal of Water Resource and Protection*, 3(2): 98-104.

Akan, J.C., Abdulrahman, F. I. Sodipo, O. A. Ochanya A. E. and Askira, Y. K. 2010. Heavy metals in sediments from River Ngada, Maiduguri Metropolis, Borno State, Nigeria. *Journal of Environmental Chemistry and Ecotoxicology*, 2(9): 131-140.

Akoteyon, I.S., Omotayo, A.O., Soladoye, O. and Olaoye, H.O. 2011. Determination of water quality index and suitability of urban river for municipal water supply in Lagos-Nigeria. *European Journal of Scientific Research*, 54 (2): 263-271.

Akoteyon, I.S. 2014. Seasonal variations of shallow well water quality in Amuwo-Odofin and Ojo LGA's of Lagos, Nigeria. *Environmental Research, Engineering and Management*, 2(68): 5-14.

Akpan, I. O. and Thompson, E. A. 2013. Assessment of heavy metal contamination of sediments along the Cross-River channel in Cross River State, Nigeria. *Journal of Environmental Science, Toxicology and Food Technology*, 2 (5): 20-30.

Aladesanmi, O.T., Agboola, F.K. and Adeniyi, I.F. 2016. Distribution of heavy metals in surface sediments from streams and their associated fishponds in Osun State, Nigeria. *Journal of Health & Pollution*, 6(11): 34-46.

Al-Mur, B.A., Andrew N. Quicksall, A.N. and Al-Ansari, A.M.A. 2017. Spatial and temporal distribution of heavy metals in coastal core sediments from the Red Sea, Saudi Arabia. *Oceanologia*, 59(3): 262-270.

Alyazichi, Y. M., Jones, B. G. & McLean, E. 2015. Source identification and assessment of sediment contamination of trace metals in Kogarah Bay, NSW, Australia. *Environmental Monitoring and Assessment*, 187 (2): 1-10.

Ayoade, A. A. and Nathaniel, O. G. 2018. Assessment of heavy metals contamination of surface water and sediment of a tropical manmade Lake Southwestern Nigeria. *International Journal of Environment and Pollution Research*, 6 (3): 1-16.

Bakan, G. and Özkoç, H. B. 2007. An ecological risk assessment of the impact of heavy metals in surface sediments on biota from the mid-Black Sea coast of Turkey. *International Journal of Environmental Studies*, 64(1): 45-57.

Batley, G.E. 1989. Trace metal speciation: analytical methods and problems. CRC Press, Boca Raton, Florida.

Benhaddya, M.L. and Hadjel, M. 2013. Spatial distribution and contamination assessment of heavy metals in surface soils of Hassi Messaoud, Algeria. *Environmental Earth Sciences*, 71*(*3): 1473-1486.

Bonnail, E., Sarmiento, A.M., Del Valls, T.A., Nieto, J.M. and Riba, I. 2016. Assessment of metal contamination, bioavailability, toxicity and bioaccumulation in extreme metallic environments (Iberian Pyrite Belt) using Corbicula fluminea. *Science of the Total Environment,* 544: 1031-1044.

Burton, G.A. Jr. 2002. Sediment quality criteria in use around the world. *Limnology*, 3(2): 65-75.

Canfield, T. J., Kemble, N. E., Brumbaugh, W. G., Dwyer, F. J., Ingersoll, C. G. and Fairchild, J. F. 1994. Use of benthic invertebrate community structure and the sediment quality triad to evaluate metal-contaminated sediment in the upper Clark Fork River, Montana. *Environmental Toxicology and Chemistry: An International Journal*, 13(12): 1999-2012.

Canfield, T. J., Dwyer, F. J., Fairchild, J. F., Haverland, P. S., Ingersoll, C. G., Kemble, N. E. and Swift, M. C. 1996. Assessing contamination in Great Lakes sediments using benthic invertebrate communities and the sediment quality triad approach. *Journal of Great Lakes Research*, 22(3): 565-583.

Casper, S.T. 2008. Regulatory frameworks for sediment management. In: Owens PN (ed) Sustainable management of sediment resources: sediment management at the river basin scale. Elsevier, Amsterdam 4: 55-81.

Costa, E.S., Grilo, C.F., Wolff, G.A., Thompson, A., Figueira, R.C.L. and Neto, R.R. 2015. Evaluation of metals and hydrocarbons in sediments from a tropical tidal flat estuary of Southern Brazil. *Marine Pollution Bulletin*, 92 (1-2): 259-268.

Davaulter, V. and Rognerud, S. 2001. Heavy metal pollution in sediments of the Pasvik River drainage. *Chemosphere* 42(1): 9-18.

Devanesan, E., Gandhi, M.S., Selvapandiyanm, M., Senthilkumar, G., R. and Ravisankar, R. 2017. Heavy metal and potential ecological risk assessment in sediments collected from Poombuhar to Karaikal Coast of Tamilnadu using Energy dispersive X-ray fluorescence (EDXRF) technique. *Beni-Suef University Journal of Basic and Applied Sciences*, 6: 285-292.

Egbe, N.E.L. and Ahunanya, K.C. 2016. Assessment of Heavy Metal Contamination of River Gora Kaduna, Nigeria. *Journal of Natural Sciences Research*, 6 (8): 138-142.

Ergin, M., Saydam, C., Basturk, O., Erdem, E. and Yoruk, R. 1991. Metal concentrations in surface sediments from the two coastal inlets (Golden Horn Estuary and Izmit Bay) of the northeastern Sea of Marmara. *Chemical Geology,* 91(3): 269-285.

Foley, R. E., Jackling, S. J., Sloan, R. J. and Brown, M. K. 1988. Organochlorine and mercury residues in wild mink and otter: comparison with fish. *Environmental Toxicology and Chemistry*: *An International Journal*, 7(5): 363-374.

Forstner, U. 1980. Cadmium in polluted sediments. In: JO Nriagu (Ed), Cadmium in the environment, New York: *Wiley Interscience* 1: 305-363.

García, E.M., Cruz-Motta, J.J., Farina, O. and Bastidas, C. 2008. Anthropogenic influences on heavy metals across marine habitats in the western coast of Venezuela. *Continental Shelf Research*, 28 (20): 2757-2766.

Ghrefat, H. A., Abu-Rukah, Y. and Rosen, M. A. 2011. Application of geo-accumulation index and enrichment factor for assessing metal contamination in the sediments of Kafrain Dam, Jordan. *Environmental Monitoring and Assessment*, 178 (1-4): 95-109.

Goorzadi, A., Vahabzadeh, G. and Carbassi, A. R. 2009. Assessment of heavy metals pollution in Tilehbon River sediments. *Iran Journal of Applied Science*, 9 (6): 1190-1193.

Håkanson, L. 1980. Ecological risk index for aquatic pollution control. A sedimentological approach. *Water Research*, 14(8): 975-1001.

Harikumar, P.S., Nasir, U.P. and Rahman, M.P.M. 2009. Distribution of Heavy Metals in the Core Sediments of a Tropical Wetland System. *International Journal of Environmental Science and Technology*, 6(2): 225-232.

Ho, H.H., Swennen, R., Cappuyns, V., Vassilieva, E. and Van Tran, T. 2012. Necessity of normalization to aluminium to assess the contamination by heavy metals and arsenic in sediments near Haiphong Harbor, Vietnam. *Journal of Asian Earth Sciences*, 56: 229-239.

Ingersoll, C.G., Christopher, G. and Wenning, R.J. 2002. Use of sediment quality guidelines and related tools for the assessment of contaminated sediments: Executive Summary of a SETAC Pellston Workshop". *Society of Environmental Toxicology and Chemistry*

Li, G., Hu, B., Bi, J., Leng, Q., Xiao, C. and Yang, Z. 2013 Heavy metals distribution and contamination in surface sediments of the coastal Shandong Peninsula (Yellow Sea). *Marine Pollution Bulletin*, 76 (1-2): 420-426.

MacDonald, D.D., Ingersoll, C.G., Smorong, D.E., Lindskoog, R.A., Sloane, G. and Biernacki, T. 2003. Development and evaluation of numerical sediment quality assessment guidelines for florida inland waters. Florida Department of Environmental Protection, Tallahassee, Florida, 1-13.

Manoj, K and Padhy, P.K. 2014. Distribution, enrichment and ecological risk assessment of six elements in bed sediments of a Tropical River, Chottanagpur Plateau: A spatial and temporal appraisal. *Journal of Environmental Protection*, 5: 1419-1434.

Moore, F., Forghani, G. and Qishlaqi, A. 2009. Assessment of heavy metal contamination in water and surface sediments of the Maharlu saline Lake, SW Iran. *Iranian Journal of Science &* Technology*, Transaction A*, 33(1): 43-55.

Muller, G. 1979. Heavy Metals in the Sediment of the Rhine-Changes Seity. *Umschau in Wissenschaft und Technik*, 79(24): 778-783.

Nobi, E. P., Dilipan, E., Thangaradjou, T., Sivakumar, K. and Kannan, L. 2010. Geochemical and geo-statistical assessment of heavy metal concentration in the sediments of different coastal ecosystems of Andaman Islands, India. *Estuarine, Coastal and Shelf Science,* 87 (2): 253-264.

Nowrouzi, M. and Pourkhabbaz, A. 2014. Application of geo-accumulation index and enrichment factor for assessing metal contamination in the sediments of Hara Biosphere Reserve, Iran. *Chemical Speciation & Bioavailability*, 26(2): 99-105.

Ntekim, E.E.U., Ekwere, S.J and Ukpong, E.E. 1993. Heavy metal distribution in sediments from Calabar River, Southeastern Nigeria. *Environmental Geology,* 21(4): 237-241.

Owens, P.N. and Walling, D.E. 2003. Temporal changes in the metal and phosphorus content of suspended sediment transported by Yorkshire rivers, U.K., over the last 100 years, as recorded by overbank floodplain deposits. *Hydrobiologia,* 494: 185-191.

Priju, C.P. and Narayana, A.C. 2006. Spatial and temporal variability of trace element concentrations in a Tropical Lagoon, Southwest Coast of India: *Environmental Implications. Journal of Coastal Research,* 39: 1053-1057.

Puyate, Y.T., Rim-Rukeh, A. and Awatefe, J.K. 2007. Metal Pollution Assessment and Particle Size Distribution of Bottom Sediment of Orogodo River, Agbor, Delta State, Nigeria. *Journal of Applied Sciences Research,* 3 (2): 2056-2061.

Remeikaitė-Nikienė, N., Garnaga-Budrė, G., Lujanienė, G., Jokšas, K., Stankevičius, A., Malejevas, V. and Barisevičiūtė, R. 2018. Distribution of metals and extent of contamination in sediments from the south-eastern Baltic Sea (Lithuanian zone). *Oceanologia*, 60(2): 193-206.

Sabo, A., Gani, A. M. and Ibrahim, A. Q. 2013. Pollution Status of Heavy Metals in Water and Bottom Sediment of River Delimi in Jos, Nigeria. *American Journal of Environmental Protection,* 1 (3): 47-53.

Selvaraj, K., Parthiban, G., Chen, C.T.A. and Lou, J.Y. 2010. Anthropogenic effects on sediment quality offshore southwestern Taiwan: assessing the sediment core geochemical record. *Continental Shelf Research*, 30 (10-11): 1200-1210.

Seshan, B.R.R., Natesan, U. and Deepthi, K. 2010. Geochemical and statistical approach for evaluation of heavy metal pollution in core sediments in southeast coast of India. *International Journal of Environmental Science and Technology*, 7 (2): 291-306.

Simex, S.A. and Helz, G.R. 1981. Regional geochemistry of trace elements in Checapeake Bay. *Environmental Geology,* 3(6): 315-323.

Singh, M., Ansari, A.A., Muller, G. and Singh, I.B. 1997. Heavy metals in freshly deposited sediments of the Gomati river a tributary of the Ganga River: Effects of human activities. *Environmental Geology*, 29(3): 246-252.

Soares, H. M., Boaventura, R. A. R. and Esteves da Silva, J. 1999. Sediments as Monitors of Heavy Metal Contamination in the Ave River Basin (Portugal): Multivariate Analysis of Data. *Environmental Pollution,* 105(3): 311-323.

Stephen, S.R, Alloway, B.J, Carter, J.E. and Parker, E. 2001. Towards the characterization of heavy metals in dredged canal sediments and an appreciation of availability. *Environmental Pollution*, 113(2): 395-401.

Swartz, R.C, Cole, F.A., Lamberson, J.O., Ferraro, S.P., Schults, D.W., DeBen, W.A., Lee, H II, and Ozretich, R.J. 1994. Sediment toxicity, contamination and amphipod abundance at a DDT- and dieldrin-contaminated site in San Francisco Bay. *Environmental Toxicology and Chemistry: An International Journal*, 13(6): 949-962.

Taylor, K. G. and Owens, P.N. 2009. Sediments in urban river basins: a review of sediment–contaminant dynamics in an environmental system conditioned by human activities. *J Soils Sediments,* 9(4): 281-303.

Tomlinson, D. L., Wilson, J. G., Harris, C. R. and Jeffrey, D. W. 1980. Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgoländer Meeresuntersuchungen,* 33(1-4): 566-575.

Turekian, K.K. and Wedepohl, K.H. 1961. Distribution of the elements in Some Major Units of the Earth's Crust. *Geological Society of American Bulletin*, 72(2): 175-192.

Wakida, F. T. D., Lara-Ruiz, E. J. and Temores, P. 2008. Heavy metals in sediments of the Tecate River, Mexico. *Environmental Geology,* 54(3): 637-642.

Wei, B.G., Jiang, F.Q., Li, X.M & Mu, S.Y. 2010. Heavy metal induced ecological risk in the city of Urumqi, NW China. *Environmental Monitoring and Assessment*, 160: 33-45.

Yahaya, M.I., Jacob, A. G., Agbendeh, Z. M., Akpan, G. P. and Kwasara, A. A. 2012. Seasonal potential toxic metals contents of Yauri river bottom sediments: North western Nigeria. *Journal of Environmental Chemistry and Ecotoxicology,* 4(12): 212-221.

Zalewska, T., Woroń, J., Danowska, B. and Suplińska, M. 2015. Temporal changes in Hg, Pb, Cd and Zn environmental concentrations in the southern Baltic Sea sediments dated with ^{210}Pb method. *Oceanologia,* 57 (1): 32-43.

Zhang, J. and Liu, C. L. 2002. Riverine composition and estuarine geochemistry of particulate metals in China-weathering features, anthropogenic impact and chemical fluxes. *Estuarine, Coastal and Shelf Science*, 54(6): 1051-1070.