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Quantifying the Ecological Risk Posed by Heavy Metals in Oil Spill Remediated Soil and Sediment in Parts of the Niger Delta

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Abstract
The metal pollution status of soil and sediment was assessed using ecological risk posed by trace heavy metals in oil spill remediated soil and sediment in parts of the Niger Delta. Remediated soil (0-15cm top and 15-30 cm bottom) and sediment samples collected between 2010-2018 were evaluated for Lead (Pb), Cadmium (Cd), Chromium (Cr), Nickel (Ni), Vanadium (V) Copper Cu, and Zinc (Zn) in line with the Department of Petroleum Resources guideline in Environmental Guideline and Standard for Petroleum Industries in Nigeria. Descriptive univariate analysis which preceded the single ecological risk index (*Ei*) and the potential ecological risk index (PERI) were used to evaluate the average concentration trends of heavy metals, trace heavy metal pollution status of the study area and the impact of the remedial measures on soil and sediment over years. With respect to their DPR target values, the result revealed reduction in the concentration of Cr, Cd, Ni, and Zn in the topsoil and upward trend in the average concentration levels of Cu and Pb. In the bottom soil and sediment, Zn showed an upward but its average values were much below the given target.Similarly, sediment samples from remediated sites showed downward trends in concentration levels of Cr, Pb, Cu, Cd and Ni Cd showed downward trend intop, bottom soil and sediment although with concentration values above the DPR target.70% and 73% of the remediated soil sites (topsoil and bottom) and sediment, respectively, had low ecological risk index. The general pollution status of the study area with respect to heavy metal pollution showed increasing improvement in soil and sediment qualities in recent years.

Keywords: *heavy metals; ecological risk; oil spill; remediated soil; sediment*

Introduction

Heavy metal concentration in the environment could be potential pollutant especially in soil and sediment. In the Niger Delta, one of the sources of these metals could be from oil spillage during oil and gas/related activities, sabotage of oil facilities, transportation and storage. Oil spillage in soil and sediment in the Niger Delta has caused immense damage because of its effect on human health and the environment (Ikporukpo, 1983; World Bank, 1995 NDES, 1997; Ikporukpo, 2004; Adeyemo, 2002; UNDP, 2006;; Zabbey, 2009; Ibaba and Olumati, 2009; UNEP, 2011; Achi, 2003, Bayode *et al.*, 2011; Akpomuvie, 2011; Elum *et al.* 2016; Wikipedia, 2019). Several literatures documented the extent, widespread and negative environmental impact of oil spillage in some parts of the Niger Delta (Ikporukpo, 1983; World Bank, 1995; NDES, 1997; Adeyemo, 2002; Ikporukpo, 2004; UNDP, 2006; Zabbey, 2009; Ibaba and Olumati, 2009; Aghalino and Eyinla, 2009; UNEP, 2011; Adekola et al, 2017; Osuagwu and Olaifa, 2018; Frank and Boisa, 2018; Alberta et al, 2018; Enegide and Chukwuma, 2018; Okon and Ogba, 2018). One of the consequences of this problem which is of distinctive ecological concern is the contamination of soil and sediment with several heavy metals of environmental and health importance (Meindinyo and Agbalagba (2012), Uzoukwu and Onomake, 2005; Onwuka and Uzoukwu, 2008), Ogboi (2012), Omubo-Pepple *et al.*, (2011), Fagbote and Olanipekun (2010), Iwuegbue 2007).

Heavy metals remain in soil and sediment for longer time due to their resistance to breakdown naturally. Although important for proper functioning of biological systems, certain heavy metals such as Zinc (Zn), Manganese (Mn), and Copper (Cu) which are essential could be toxic at concentrations above standard. And heavy metals such as Cadmium (Cd), lead (Pb), Arsenic (As) could cause damage to biological system even at low concentrations. While the Department of Petroleum Resources (DPR) in Nigeria have set values for metals in soil and sediment. These settarget values are used as guideline for carrying out remediation and to certify or verify remedial measures carried out on oil spill polluted soil and sediment. It is therefore important that regular follow-up and monitoring of remedial measures should be implemented to ensure effective removal or reduction of concentration level of heavy metals in soil and sediment.

Evaluating the ecological significance of some heavy metals is relevant for sustainable environmental development.Although remedial measures have been implemented in some of the spill sites but there were concerns raised about the presence of pollutants especially heavy metals in past spill sites which were certified as remediated. With recent studies and evaluations carried out on these remediated sites, it implies that some of the remedial measures applied were unsatisfactory. And consequently, there are still residues of these metals which pose several ecological risks ranging from limited usability of soil and sediment to its impacts on human health and environment.

Oil spillage and crude oil related activities could deposit several heavy metals simultaneously on to soil and sediment thereby causing collective pollution. Methods developed to evaluate multiple element pollution of soil and sediment include the potential ecological risk index (PERI) by Hakanson (1980). Cheng et.al, 2007; Bhattacharya *et al.*, (2006), Soliman *et al.*, 2015; Ahmad et al, 2015; Mortuza and Al-Misned, 2017 applied this method to study the contamination of heavy metals in soil and sediment.

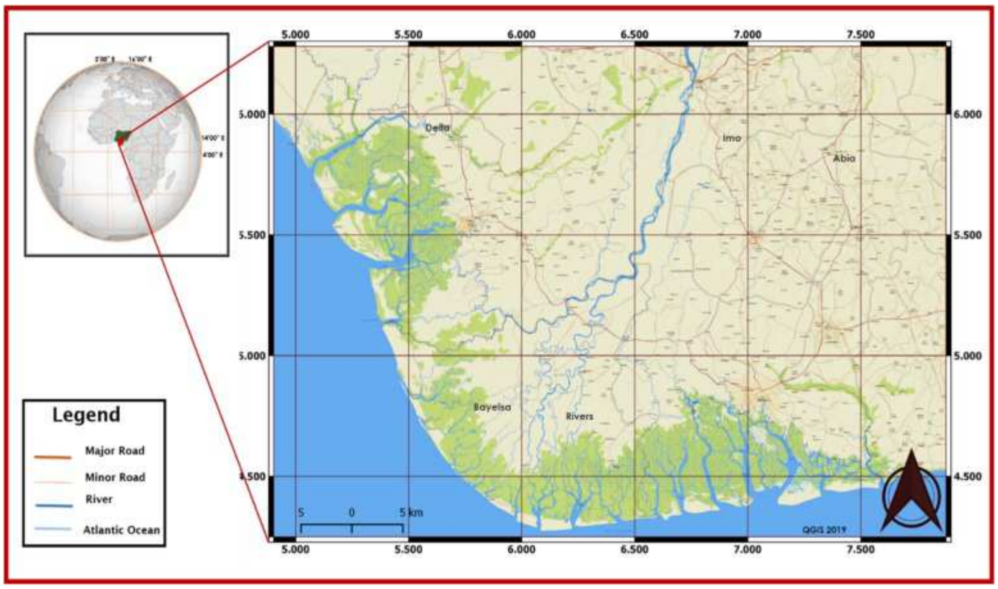
This research evaluates the present environmental quality of soil and sediment with respect to its heavy metal content after remedial measures have been applied and the achieved risk reduction. Consideration were given to the following heavy metals of Lead (Pb), Cadmium (Cd), Chromium (Cr), Nickel (Ni), Vanadium (V), Copper (Cu) and Zinc (Zn) due to their association with crude oil and its related activities.

This study aims to:
1. Evaluate, categorize and present the distribution of trace heavy metals of remediated oil polluted soil and sediment of study area in parts of the Niger Delta.
2. Evaluate the pollution status of the study area using the potential ecological risk index.
3. And present validation for the remedial measures applied on soil and sediment in the study area.

The Study Area, Location and Its Geology

The study area lies within the Niger Delta Sedimentary Basin. Located in the Niger Delta basin and covering five states (Imo, Abia, Delta, Rivers and Bayelsa states).

The geology of the Niger Delta has been described extensively by Reyment (1965), Short and Stauble (1967), Allen (1965), Etu-Efeotor and Akpokodje (1990). During the Paleocene time, the build-up of fine grained sediments eroded and transported by the River Niger and its tributaries formed the formations of the Niger Delta. The three major depositional environments typical of most deltaic environments are observable in the Niger Delta (marine, mixed and continental) and are represented in respective orders by the Akata, Agbada and Benin Formations (Short and Stauble, 1967). Its geographic location is within latitudes 5.000 to 7.5000 and longitudes 4.500 to 6.000. Geomorphologically, it comprises of dry deltaic plain with rare freshwater swamps, extensive freshwater swamps flood plains and meander belt, saltwater mangrove swamps, estuaries, creeks and lagoon, including abandoned and active coastal islands and beaches (Etu-Efeotor and Akpokodje, 1990) .It is relatively flat terrain, predominantly made up of dense network of rivers, lakes, creeks, swamps, marshy lands, dry land, the low relief (less than 500m) and gentle slope morphology which impacts on drainage. The geology and geomorphology influence the soil types in the study area which range from sand to clay but predominantly clayey and silty loamy of fluvial origin.



The geomorphology of the study area influences traditional economic activities of the communities. These activities fall into two main categories; Land based type which includes farming, collecting and processing palm fruits, as well as hunting, and water-based type of economy including fishing and related activities and trading. It is important to note that the underlying geology of the study area and past geologic processes which prevailed were a major contributing factor to the presence and abundance of hydrocarbon resource which led to the extensive oil and gas development. The implication of this development is that most of these local economic activities have been interrupted by oil spill, with consequences such as contamination of these environment leading to the disruption of economic activities. Agricultural land in particular has been rendered unproductive and there is limited space for farming due to the high density of oil and gas installations. This is because most of the spillages occurred on land, while lesser percentage occurred on swamp, inland waters, offshore and some were not specified based on location.

Table 1 summarizes major Geologic units of the Niger Delta.

Table 1: Geologic Units of the Niger delta Sedimentary Basin (Etu-Efeotor and Akpokodje, 1990).

GEOLOGIC UNIT	LITHOLOGY	AGE
Alluvium (General)	Gravel, sand, clay, silt	Quaternary
Freshwater Back Swamp, Meander Belt	Sand, clay, some silt, gravel	
Mangrove and Saltwater/Back Swamps	Medium – fine sands	
Active / Abandoned Beach Ridges	Sand, clay, and some silt	
Sombreiro-Warri Deltaic Ridges	Sand	
Benin Formation (Coastal Plain Sands)	Coarse to medium sand with subordinate silt and clay lenses	Eocene
Agbada Formation	Mixture of sand, clay and silt	Eocene
Akata Formation	Clay	Paleocene

Materials and Methods

Sampling and Data Pre-Treatment

Methods adopted to achieve the research aim and objectives explored relevant literatures and collection of field samples of soil and sediment collected from oil spill remediated sites. The data set utilized for this study include soil and sediment quality physicochemical data obtained from 2010, 2011, 2012, 2017 and 2018. The data were acquired from post clean-up investigation and environmental evaluation review and compliance monitoring exercise of remediated spill sites. Soil samples were one thousand two hundred and thirty-three and a thousand and sixty-seven top and bottom sampled points, respectively (1233 and 1067). Thirty-eight (38) sediment samples were collected between 2011, 2017, and 2018 (figure 2 and 3).

All precautions were reported to be observed during sample collection, transportation and storage in preparation for laboratory analysis. The samples collected were analyzed for heavy metals (Lead (Pb), Cadmium (Cd), Chromium (Cr), Nickel (Ni), Vanadium (V) Copper Cu, and Zinc Zn) using Atomic Absorption Spectroscopy (Varian Spectra AA 220FS) in line with the Department of Petroleum Resources guideline in Environmental Guideline and Standard for Petroleum Industries in Nigeria (EGASPIN, 2002).

The data was quality checked, sorted and organized in matrix of rows and columns. Codes were assigned to each top soil sample (0-15 cm) with its corresponding bottom (15-30 cm) having same code. Univariate descriptive statistical techniques were employed to extract the general trend of heavy metals parameters under study and pollution indices were used for evaluation of heavy metal loads of the individual remediated sites. All statistical analysis were carried out using Microsoft Excel 2013 and Minitab 17. Results from analysis of pollution index were used to produce thematic based models of the study area for enhanced visualization using Surfer 15 software. The produced models aided the interpretation of spatial and temporal pattern depicting status of remediated sites in the study area. Key research questions which guided the realization of the aim and objectives of the study were the evaluation of general pattern of environmental quality of soil and sediment in compliance with provided reference standards/guideline or interim values. Secondly, the research evaluated the general heavy metal pollution status of the study area over years after application of remediation techniques.

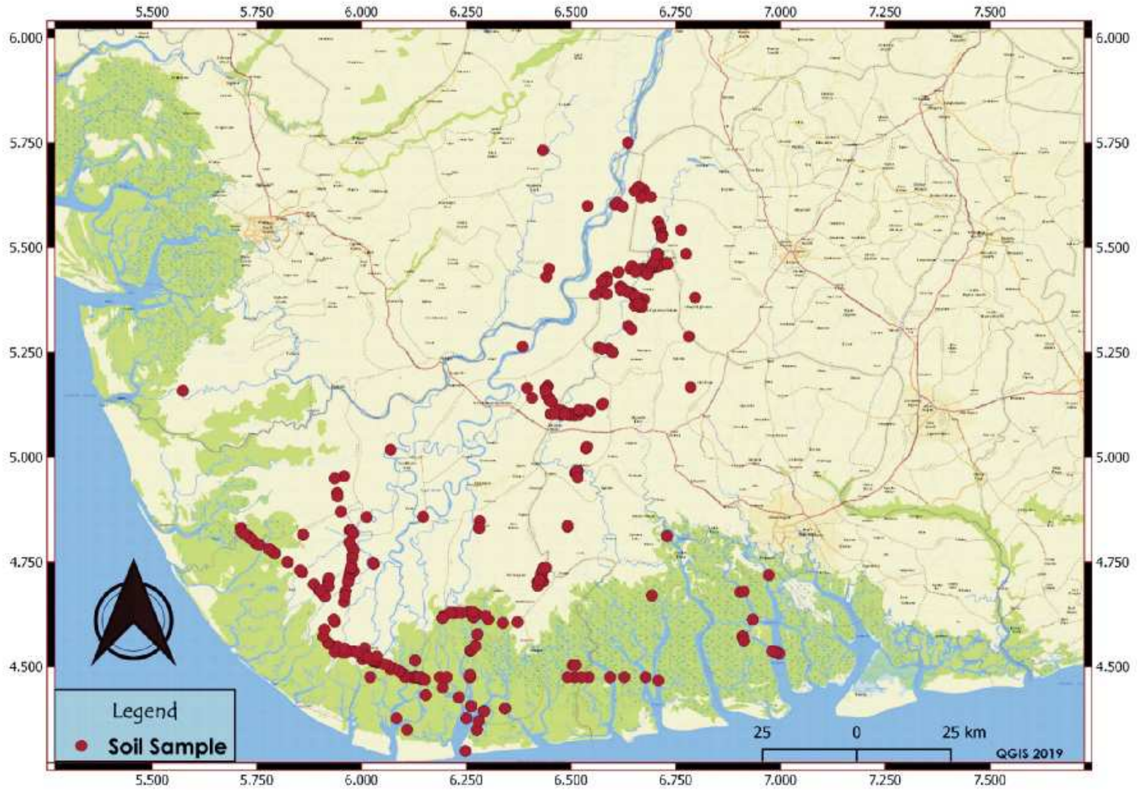


Fig. 2: Location of soil sample points

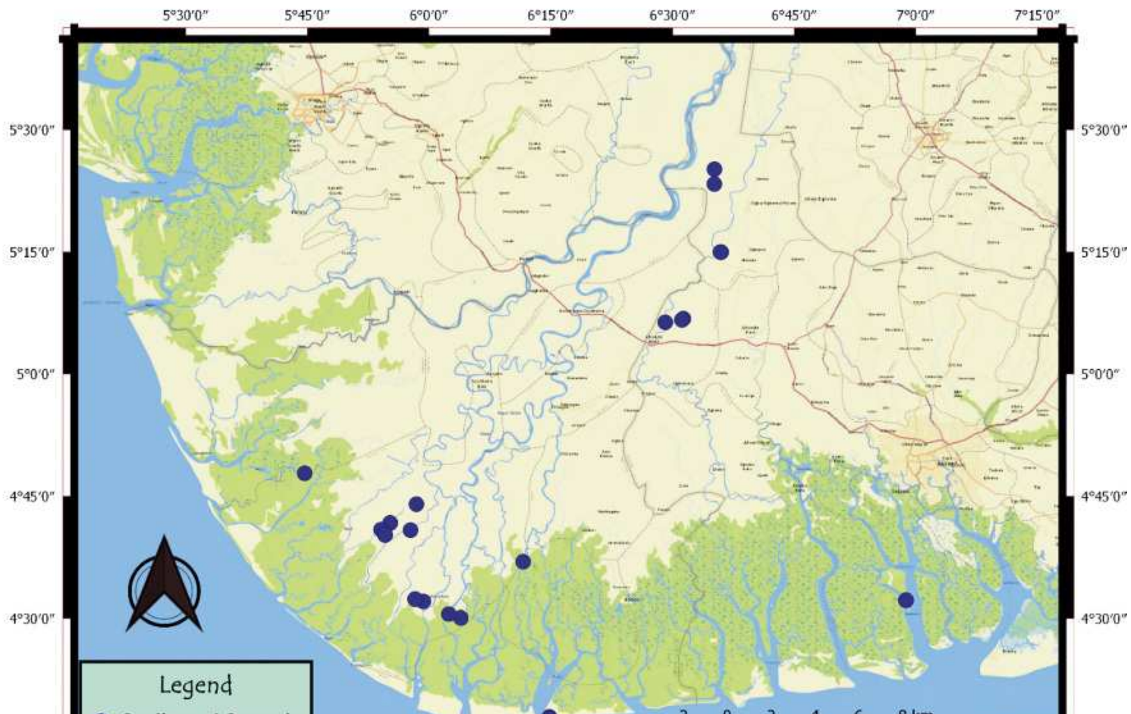


Fig. 3: Location of sediment sample points

Evaluation of Ecological Risk Index

Metal pollution index of the study area was evaluated using ecological risk posed by multiple element pollution from a sample (PERI). The remediated sites were categorized with respect to their evaluated trace heavy metals (Lead (Pb), Cadmium (Cd), Chromium (Cr), Nickel (Ni), Vanadium (V), Copper (Cu) and Zinc (Zn)). For this analysis the target values were used as the background values to maintain uniformity in results and accuracy. Values with "< (less than) detection limit" were calculated by substituting one half of the detection limit (Deustscher Verband fur Wasserwirtschaft und Kulturbau (DVWK), 1990). The ecological risk posed by multiple element pollutions, PERI was determined using classification given by Muller (1981) and Hakanson (1980), respectively. Formula, methods, and terminologies used in the calculation are as follow;

$$\boldsymbol{PERI = \sum E_i},$$

$$\boldsymbol{E_i = T_i * CF_i} \text{ ....(1)}$$

$$\boldsymbol{CF_i = \frac{C_m}{B_m}},$$

$$\boldsymbol{PLI = (CF_1 * CF_2 * \ldots * CF_n)^{(\frac{1}{n})}} \text{ ....(2)}$$

Where *Cm* is the measured concentration of the examined metal in the soil samples and *Bm* is the geochemical background value of the same metal (target value). 1.5 is a constant used for the possible variations of the background data due to the lithogenic effects.Where *Ei* is the single ecological risk index, *Ti* is the toxic response factor for a given metal (Zn = 1, Cr = 2, Cu = Ni = Pb = 5, As = 10, Cd = 30) (Muller, 1981), CF*i* is the contamination factor for the same metal and *n* is the number of metals studied.Terminologies for classification of evaluated heavy metals potential ecological risk index for the soil and sediment by Hakanson (1980) are PERI < 150 (Low PERI), 150 ≤ PERI < 300 (Moderate PERI), 300 ≤ PERI < 600 (Considerable PERI) and PERI ≥600 (Very high PERI).

Results and Discussion

Descriptive Univariate Analysis

Results of descriptive statistical evaluations were presented in tables and graphs. Table 2a, 2b and 3 showed the monthly/yearly average (mean), minimum and maximum values of individual heavy metals from remediated soil (top and bottom) and sediment, respectively. The DPR target values of each heavy metals is presented in bracket. These evaluations are important for presentation of a general overview of the environmental quality and should precede individual characterization and evaluation of the remediated sites.

Table 2a: Monthly/yearly average (mean), minimum and maximum values of individual heavy metals from remediated soil (top 0-15cm).

Variables	*Month/Year*																		
Cr(100)	**M1**	**A1**	**F11**	**J11**	**S11**	**O11**	**Ja12**	**F12**	**M12**	**AP12**	**MA12**	**J12**	**JU12**	**Ja17**	**JUE17**	**JUO17**	**M18**	**A18**	**MA18**
Mean	0.003	0.003	19.12	15.56	12.14	15.86	23.33	21.47	23.77	16.95	11.99	16.03	18.26	35.12	12.7	5.442	6.18	4.953	7.926
Min	0.002	0.002	8.96	2.81	1.84	7.74	13.46	7.56	2.26	2.4	3.93	9.42	4	0	0.58	0.118	0.875	1.524	0.629
Max	0.005	0.004	42.09	46.34	22.95	25.99	42.85	36.16	66.95	36.46	26.79	31.42	37.64	1401	28.34	14.44	14.8	10.83	17.59
Pb(85)																			
Mean	6E-04	4E-04	14.79	15.25	10.87	13.32	21.02	23.58	17.05	18.67	13.96	18.06	21.99	20.99	6.51	5.612	15.54	15.42	14.8
Min	5E-04	1E-04	2.48	5.07	0	8.44	12.92	8.14	4.79	4.86	4.74	10.84	11.37	0.001	0.32	0.393	3.921	0.378	2.384
Max	0.001	8E-04	30.81	43.1	28.09	20.94	32.37	52.69	35.9	61.45	34.76	33.63	38.64	87.18	22.6	17.95	24.39	23.27	34.21
Cu(36)																			
Mean	0.366	0.26	32.47	14.79	14.41	37.6	22.62	29.88	24.85	25.3	23.72	30.5	41.12	23.23	12.69	5.804	19.26	18.79	16.65
Min	0.32	0.24	18.14	3.36	6.124	15.81	9.5	8.99	10.83	10.61	3.33	15.66	12.85	2.225	8.362	1.25	9.799	10.71	4.217
Max	0.412	0.289	81.42	28.63	25.81	125.6	35.42	83.79	55.85	91.1	119.7	65.42	75.61	62.06	15.8	13.9	29.69	35.42	49.49
Cd(0.8)																			
Mean	9E-04	1E-04	14.47	3.699	2.737	8.742	5.981	7.937	10.02	8.549	5.942	9.355	10.45	3.259	0.601	0.933	0.81	0.952	1.035
Min	5E-04	1E-04	7.24	0.13	0.405	6.29	3.88	1.54	4.34	2.39	0.85	4.83	8.45	0.054	0.467	0.028	0.259	0.397	0.218
Max	0.001	3E-04	31.83	14.18	4.42	12.04	8.61	12.82	16.02	13.65	12.56	11.07	11.86	50.59	0.806	2.306	1.218	2.212	15.1
Ni(35)																			
Mean	0.019	0.001	17.91	14.03	13.42	15.43	24.71	24.35	21.1	33.03	20.6	23.17	19.59	24.41	8.198	3.593	7.75	7.638	7.736
Min	0.001	5E-04	8.43	2.42	7.69	10.46	11.51	8.43	5.89	4.08	2.1	12.1	8.14	0.001	3.309	0.122	1.56	3.346	0.896
Max	0.052	0.003	25.42	39.34	22.91	23.27	35.37	38.07	36.5	66.95	32.17	35.42	45.46	95.45	13.81	14.5	22.51	16.63	18.1
Zn(146)																			
Mean	*	*	58.92	25.79	26.02	55.5	46.86	49.35	43.09	43.52	28.21	41.24	46.43	44.34	31.47	28.47	36.78	38.31	57.42
Min	*	*	28.26	10.49	14.28	22.6	24.04	19.39	15.29	14.61	8.35	24.22	17.96	3.91	10.96	9.73	13.61	21.87	11.01
Max	*	*	142.2	49.72	46.27	179.4	75.16	97.08	83.77	136.5	78.42	90.65	90.65	230.1	47.82	172.7	66.51	90.3	119

Table 2b: Monthly/yearly average (mean), minimum and maximum values of individual heavy metals from remediated soil (bottom 15-30cm).

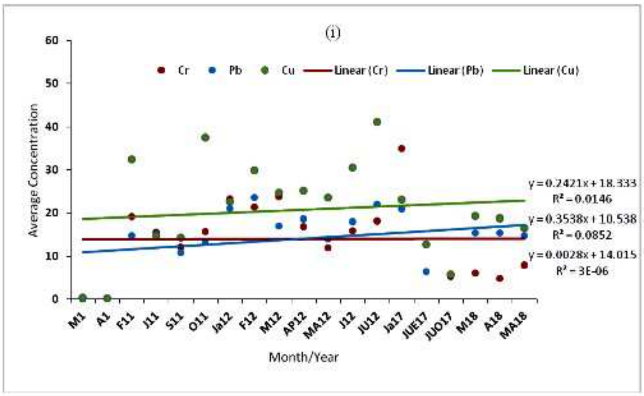
Variables	*Month/Year*															
Cr(100)	**J11**	**S11**	**O11**	**Ja12**	**F12**	**M12**	**AP12**	**MA12**	**J12**	**JU12**	**Ja17**	**JUE17**	**JUO17**	**M18**	**A18**	**MA18**
Mean	14.37	10.98	14.75	23.73	21.1	20.64	20.14	11.986	17.48	18.11	32.918	9.15	7.211	6.178	5.341	8.706
Min	1.85	2.821	8.42	14.22	8.47	1.86	5.21	4.58	8.37	4.23	0.265	2.31	0.94	1.392	1.392	1.524
Max	48	23.2	26	44.12	41.12	59.81	47.82	27.2	66.95	38.14	159.84	17.13	26.45	13.605	9.543	18.039
Pb(85)																
Mean	15.28	9.81	11.843	19.46	22	15.38	20.41	14.247	17.37	21.69	20.627	5.43	5.243	15.02	16.75	16.04
Min	4.73	0	8.36	10.33	8.02	5.11	3.91	5.16	10.22	9.91	0.001	0.98	0.093	2.97	5.022	2.724
Max	48.79	20.84	18.26	28.86	50.39	40.71	55.21	31.02	28.7	34.26	111.181	16.79	23.7	23.34	23.435	35.092
Cu(36)																
Mean	13.432	11.929	34.14	22.77	29.84	28.26	25.65	22.21	30.15	40.9	23.442	12.667	6.253	18.76	20.05	15.8
Min	2.54	5.96	14.23	12.55	8.07	11.08	4.65	5.37	16.97	20.83	1.136	9.075	0.779	8.99	9.05	4.72
Max	24.99	20.682	109.25	38.7	77.83	67.56	112.09	73.06	68.6	84.35	85.578	17.56	15.66	28.22	45.58	85.85
Cd(0.8)																
Mean	3.55	2.542	7.696	5.561	7.309	9.7	9.331	6.402	9.102	10.133	3.261	0.6805	0.9402	0.8663	1.0086	0.9681
Min	0.79	0.003	4.29	4.17	2.83	3.94	2.89	0.98	5.94	8.58	0.02	0.439	0.04	0.184	0.0665	0.249
Max	16.34	5.65	10.36	7.29	13.44	16.38	15.39	14.18	11.27	11.91	39.603	0.867	2.561	1.555	2.433	6.293
Ni(35)																
Mean	12.67	10.958	14.357	24.89	23.32	24.55	37.69	20.35	23.11	18.62	24.354	7.73	3.781	9.6	8.507	7.71
Min	0.81	5.55	9.37	13.14	6.84	6.94	8.61	1.3	12.94	7.59	0.001	1.53	0.322	2.84	3.059	0.927
Max	32.66	17.348	20.92	34.89	42.07	73.24	83.42	40	37.82	35.31	92.938	19.79	15.412	23.28	19.789	23.987
Zn(146)																
Mean	25.84	24.07	52.2	47.29	44.79	48.34	46.17	30.76	39.59	45.67	44.58	29.62	125.1	32.53	40.73	61.53
Min	6.52	10.86	19.9	22.99	20.42	15.22	12.25	8.87	18.37	18.81	1.33	9.84	3.9	7.9	23.93	24.52
Max	77.92	38.77	180.2	70.44	88.47	99.84	167.39	127.14	83.77	76.61	322.71	66.19	18722	62.13	68.17	122.15

Table 3: Monthly/yearly average (mean), minimum and maximum values of individual heavy metals from remediated sediment

Variable	***Cr(100)***				***Pb(85)***				***Cu(36)***			
M/Yr	J11	Ja17	A18	Ma18	J11	Ja17	A18	Ma18	J11	Ja17	A18	Ma18
Mean	16.15	23.65	7.6	10.88	15.7	31.3	18.36	18.17	12.41	26.17	14.29	14.51
Min	6.71	7.06	4.11	5.63	8.76	0.83	10.55	5.54	6.51	11.64	9.72	5.21
Max	30.44	62.64	21.4	16.29	27.47	76.39	23.27	30.66	15.62	45.11	20.34	24.63
Variable	***Cd(0.8)***				***Ni(35)***				***Zn(146)***			
M/Yr	J11	Ja17	A18	Ma18	J11	Ja17	A18	Ma18	J11	Ja17	A18	Ma18
Mean	5.462	2.734	0.944	1.482	14.26	31.83	6.181	5.7	31.84	46.3	40.4	55.39
Min	2.31	0.311	0.493	0.603	6.87	4.67	3.824	1.2	13.33	3.3	27.25	23.33
Max	7.06	7.295	1.253	5.214	24.33	87.62	9.369	10.32	58.64	202.2	59.85	101.56

The heavy metals, Cr, Pb, Cu, Cd, Ni and Zinc were analyzed and compared to the DPR target values. Figure 4a showed the trend in average concentrations of Cr, Pb, Cu, Cd, Ni and Zn values of topsoil samples from remediated sites. The graph showed an upward trend in the average concentration levels of Cu and Pb, and a downward trend in the concentration level of Cr. While the trends indicated variations in the remediation process, increase in the average concentrations of Cu and Pb showed deterioration in environmental quality indicated by decline in quality of the remediation process. And the reduction in the concentration of Cr, Cd, Ni, and Zn in the topsoil showed there was improvement in the environmental quality and accordingly an enhancement in the remediation process. When compared with the DPR target values of 100mg/kg, 85mg/kg, 36mg/kg, 0.8mg/kg, 35mg/kg, and 146mg/kg for Cr, Pb, Cu, Cd, Ni and Zn, respectively, it showed that the average concentrations of the metals were within the given limits but Cu had some average values slightly above the stipulated target. Also, Cd had average concentrations above the given target value, while Ni and Zn concentration levels in the topsoil were within the DPR target values.

The average concentration levels of Cr, Pb, Cu, Cd and Ni of bottom soil samples from remediated sites in figure 4b showed downward trends, although Zn showed an upward trend as displayed in the graph, but its values were much below the given target. The average concentrations of the metals were within the target limits of the DPR which showed improvement in remedial measures. There was an exception for Cd which showed downward trend in average concentration although with values above the DPR target.



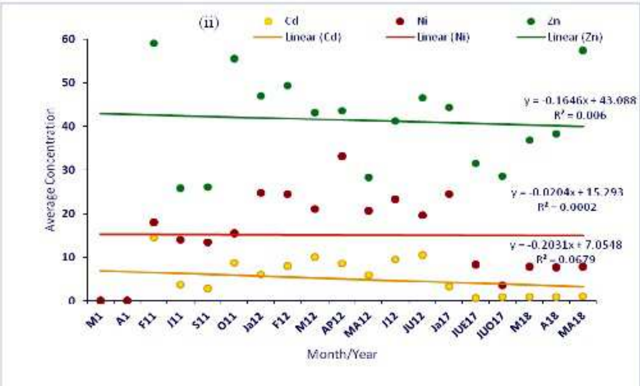
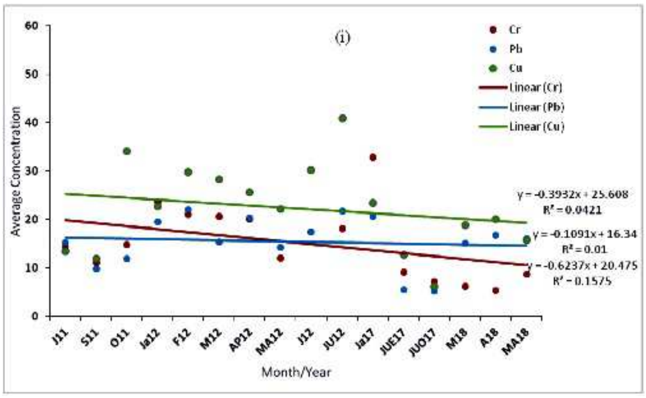


Fig. 4a: Trend in average concentration of Cr, Pb, Cu, Cd, Ni and Zn values of top soil samples (0-15cm) from remediated sites.



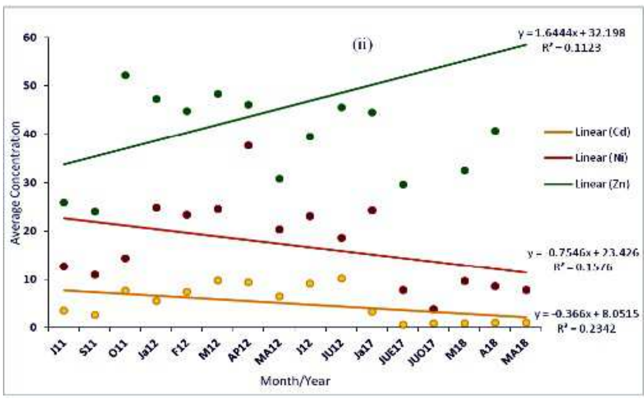
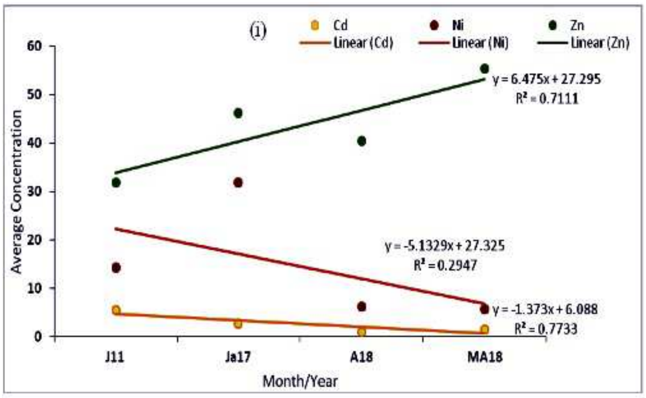


Fig. 4a: Trend in average concentration of Cr, Pb, Cu, Cd, Ni and Zn values of top soil samples (0-15cm) from remediated sites.

Similarly, sediment samples from remediated sites showed downward trends in concentration levels of Cr, Pb, Cu, Cd and Ni in figure 5. Although Zn showed an upward trend in the graph, but its average values were much below the given target. These can also be interpreted as improvement in the environmental quality of the soil. The average concentrations of the metals were within the target limits of the DPR except Cd; Cd had some average concentration values above the target limit. Generally, the graph showed an improvement in the remediation process and environmental quality.



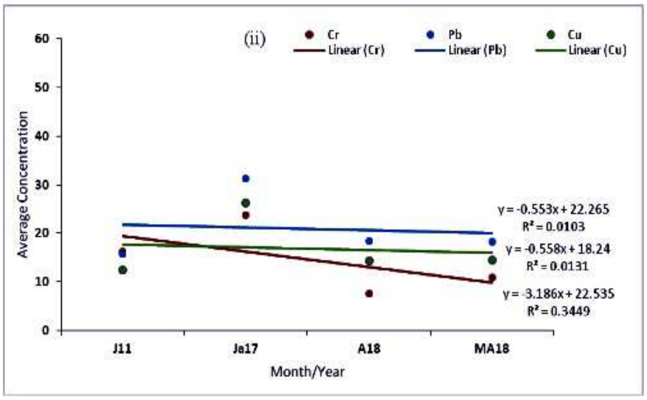


Fig. 5: Trend in average concentration of Cr, Pb, Cu, Cd, Ni and Zn values of sediment samples from remediated sites.

Heavy Metal Pollution Status of the Study Area

Risk posed by heavy metals of environmental concern was used to expatiate on the general environmental quality and to compare the quality of remedial measures applied over years in soil and sediment. The remediated sites were evaluated with respect to the following heavy metals; (Lead (Pb), Cadmium (Cd), Chromium (Cr), Nickel (Ni), Copper (Cu) and Zinc (Zn). And classification was done with respect to the ecological risk posed by multiple heavy metal pollution (PERI).

Ecological Risk index of Heavy Metals of remediated Sites

Figure 6 showed that about 70% of the remediated soil sites (topsoil and bottom) evaluated from 2010 to 2018 had low ecological risk index. While lesser percentage had moderate, considerable and very high ecological risk indices.

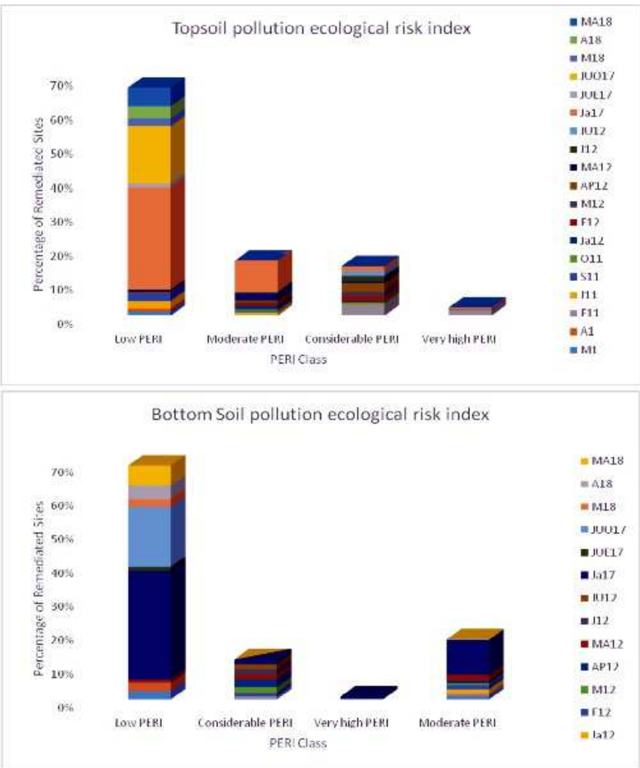


Fig. 6: Remediated site pollution ecological risk index.

In figure 7, about 73% of the remediated sediment sites have low ecological risk index, while 27% had moderate ecological risk index. The graph showed an improvement in sediment quality and remedial process because the percentage of sites with moderate PERI reduced and no sites were recorded having high PERI.

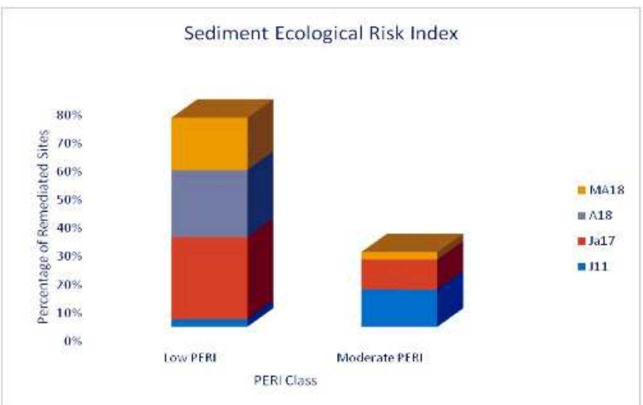


Fig. 7: Remediated sediment site pollution ecological risk index.

Spatial and Temporal Overview of the Environmental Quality of the Remediated Soil and Sediment

Figure 8a to 8e, 9a to 9d and 10a 10c showed thematic models of evaluated ecological risk posed by heavy metals (Cr, Pb, Cu, Cd, Ni and Zn) on remediated soil and sediment over years.

Generally, there was improvement in soil and sediment qualities evaluated for their heavy metal concentration. The general pollution status of the study area with respect to heavy metal pollution showed increasing improvement in soil and sediment qualities in recent years. Although, Cadmium showed high values above the DPR target but had a declining trend in average concentration over years. It can be inferred that the remediation had impact in improving the environmental quality with concentrations of most heavy metals reduced over years.

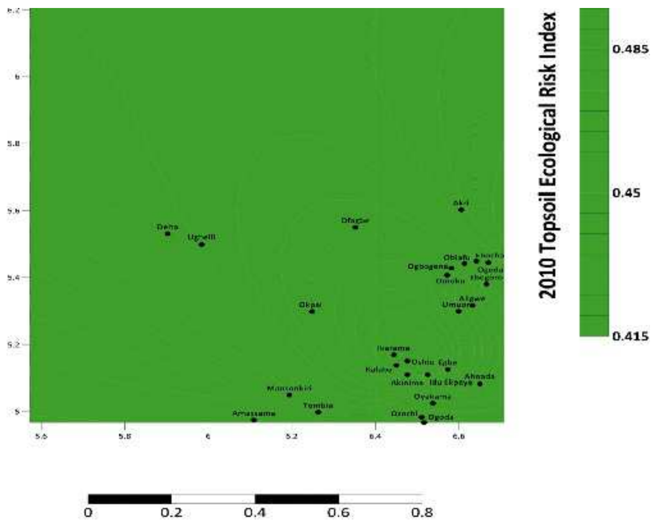


Fig. 8a: Ecological risk index of remediated topsoil in 2010

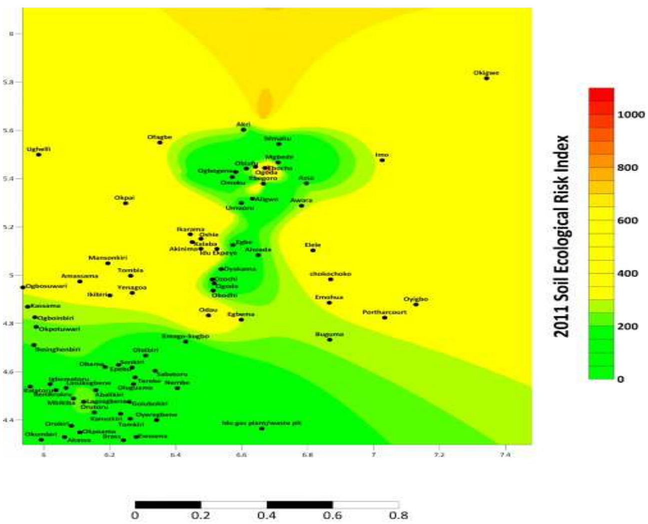


Fig. 8b: Ecological risk index of remediated topsoil in 2011

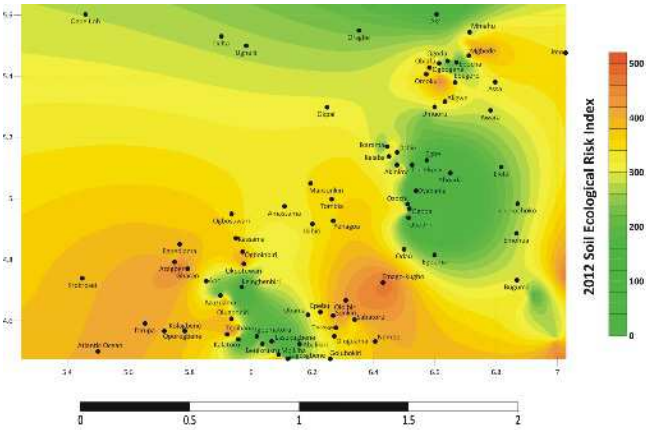


Fig. 8c: Ecological risk index of remediated topsoil in 2012

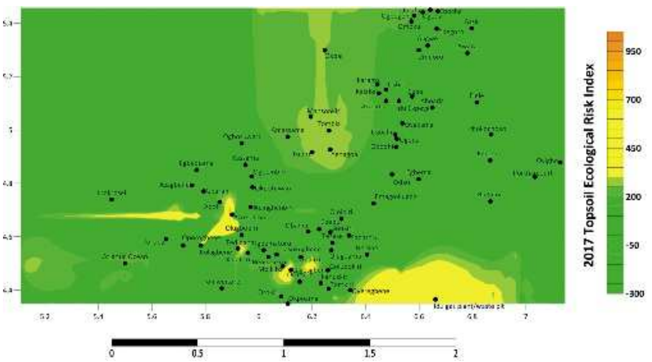


Fig. 8d: Ecological risk index of remediated topsoil in 2017

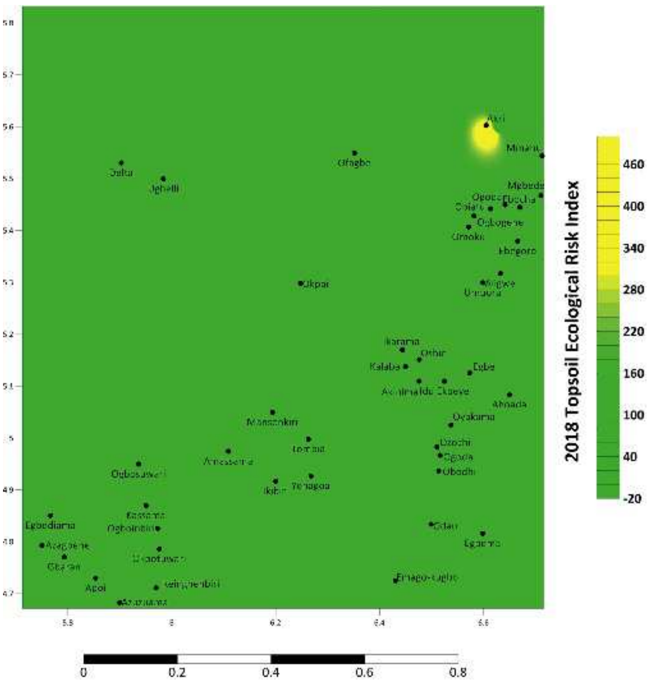


Fig. 8e: Ecological risk index of remediated topsoil in 2018

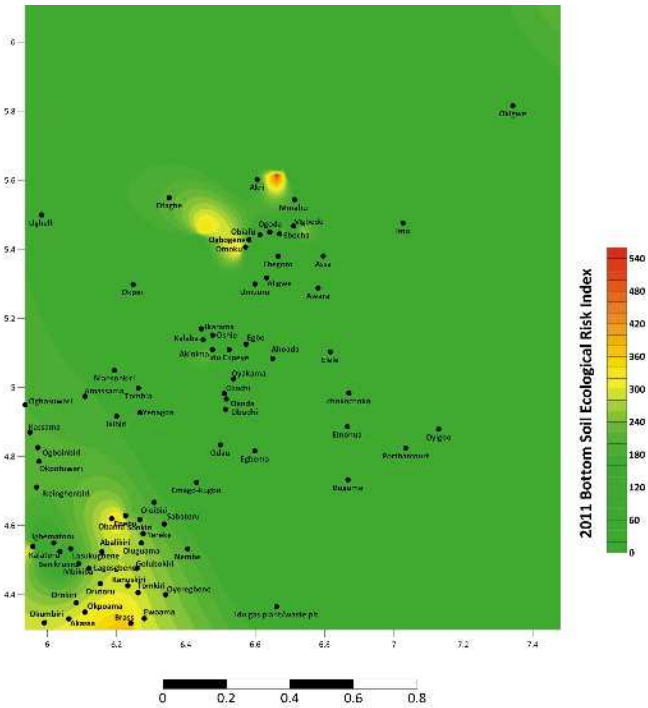


Fig. 9a: Ecological risk index of remediated bottom soil in 2011

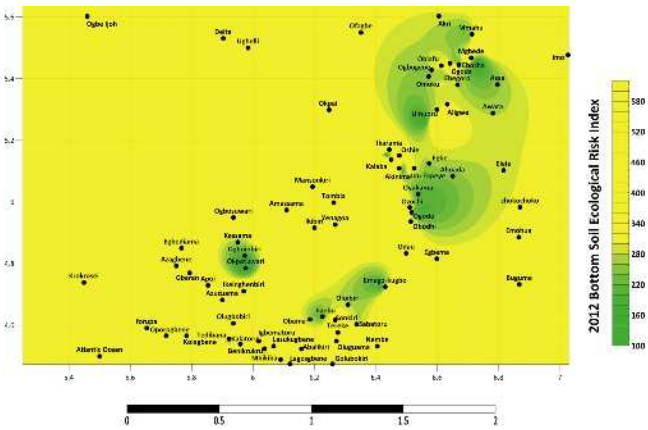


Fig. 9b: Ecological risk index of remediated bottom soil in 2012

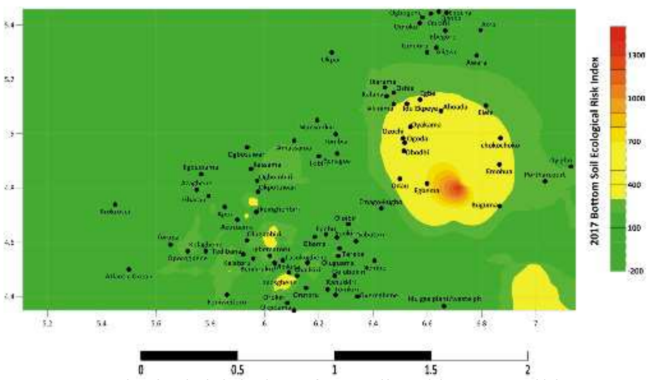


Fig. 9c: Ecological risk index of remediated bottom soil in 2017

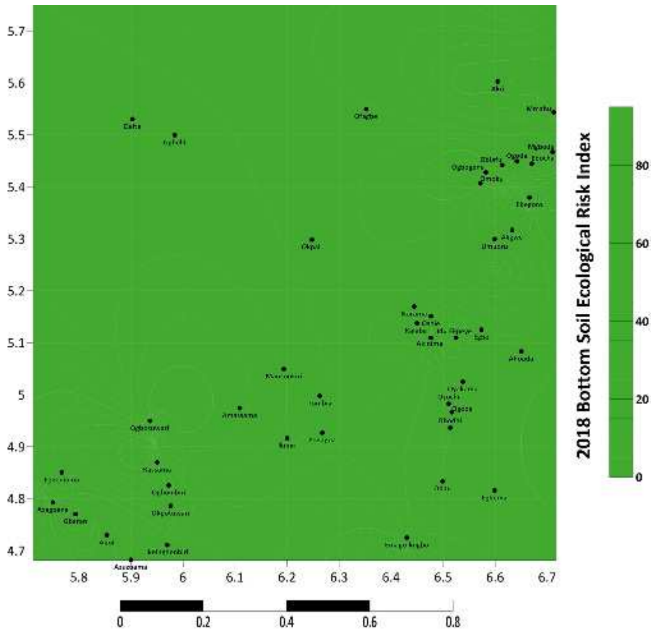


Fig. 9d: Ecological risk index of remediated bottom soil in 2018

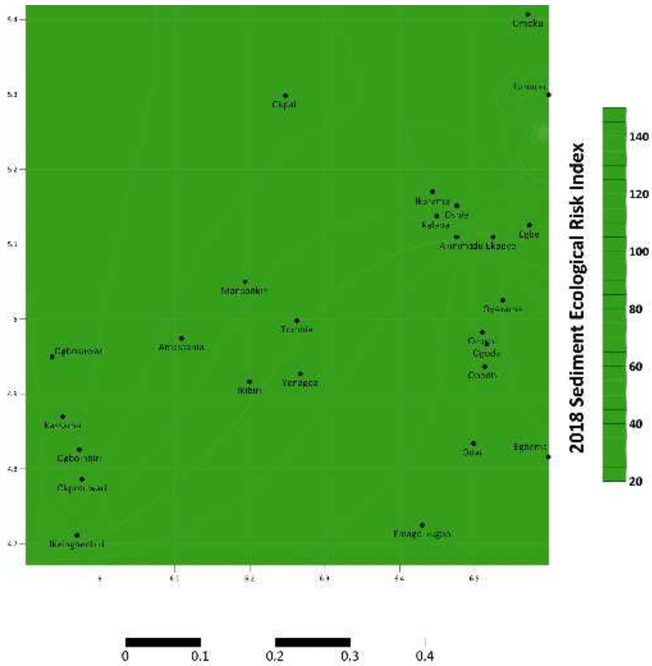


Fig. 10c: Ecological risk index of remediated bottom sediment in 2018

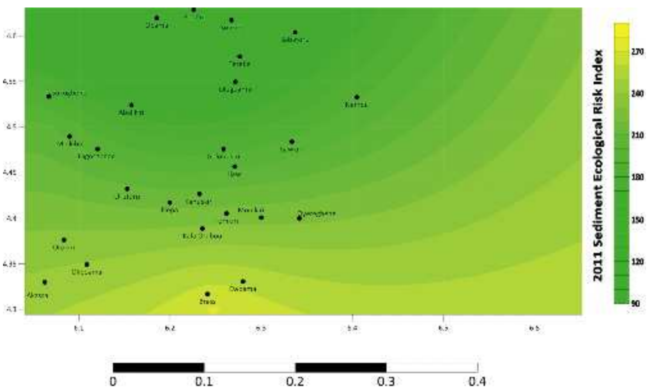


Fig. 10a: Ecological risk index of remediated sediment in 2011

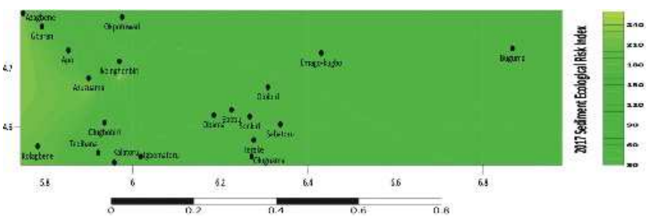


Fig. 10b: Ecological risk index of remediated sediment in 2017

Conclusions

The results of this study have provided valuable information about the present pollution status and ecological risk posed by metals on soil and sediment after remedial measures have been applied. It also evaluates the efficiency of past remediation processes and the achieved risk reduction. General pollution status of the study area with respect to heavy metal pollution showed increased improvement in soil and sediment qualities in recent years. This study promotes post remediation review and monitoring of the remediated sites for enhanced sustainability of the environment. And further study and action are recommended for management of Cadmium contamination of soil and sediment in the study area and related areas.

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