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Pollution Analysis of an Active River Bottom Sediment in Borokiri (Ikpukulu River), Niger Delta, Nigeria

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Abstract:
The Niger Delta region, endowed with significant oil and gas resources, faces environmental challenges linked to artisanal petroleum refining activities. This study explores the environmental repercussions of these activities on the ecosystem health of Ikpukulu River bottom sediments in Borokiri, Niger Delta, Nigeria. The study incorporates an assessment of heavy metal and hydrocarbon contamination using geoaccumulation index (Igeo), pollution load index (PLI), and potential ecological risk index (PERI). Three sampling points (X, Y, and Z) along the Ikpukulu River were investigated. While heavy metal concentrations generally fell within background levels, hydrocarbon content, particularly Total Hydrocarbons (THC), exhibited significant pollution. The PERI values for all three points indicated very high ecological risk, demanding immediate attention and remediation efforts. The Ikpukulu River serves as a potential sink for waste from illegal hydrocarbon refining, highlighting severe coastal river pollution in the region. Proactive measures and stringent pollution control regulations are recommended to safeguard the ecosystem's health. The study contributes valuable insights for remediation efforts and policy development in addressing the environmental challenges associated with artisanal petroleum refining in the Niger Delta.

Keywords: artisanal petroleum refining, sediment contamination, Ikpukulu river, Niger Delta, risk, hydrocarbon pollution.

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1. Introduction

The foundational premise of Newton's third law of motion, positing that every action elicits an equal and opposite reaction, finds resonance in the context of the Niger Delta region. The historical mistreatment and neglect endured by its populace have constituted a significant catalyst for hostility, environmental degradation, and the sabotage of oil facilities. This, in turn, has repercussions on the nation's production rates and economic vitality. Adebayo [1] underscores that interference with the livelihoods of Niger Delta residents, coupled with inadequate compensation, begets a cycle of poverty and idleness. Ikelegbu [2] further observes the paradoxical circumstance wherein, despite being the primary contributor to Nigeria's oil and gas output, the Niger Delta remains one of the country's most impoverished and underdeveloped regions.

Communities that are home to oil production sites, the federal government, and oil companies are all now at odds with one another due to this paradox. Oil spills, artisanal crude oil refining (also called "improvised refineries"), illegal bunkering, extensive pipeline damage, and armed clashes are the most obvious manifestations of this dispute. Due to people's lack of knowledge and reliance on simple methods, a significant amount of oil is being dumped into the environment. Together, these impacts represent serious threats to the health of humans, as well as to flora, fauna, and the ecological community in both local and distant areas. Oil spills, as evidenced in the study area, are typically washed into water bodies through surface runoff, persisting in the attached media for extended periods. Approximately 50% of spilled oil evaporates, while the remainder undergoes migration driven by wind and tidal waves, emulsification, or inconspicuous sinking to the riverbed's bottom and permeation into bottom sediments [3]. Notably, most spilled oil types are hydrophobic, exhibiting an affinity for firm adherence to bottom sediments. These sediments serve as habitats for breeding fin and shellfish, furnish vital nutrients for the aquatic food chain, and significantly influence the physiochemical characteristics of rivers or creeks. Active stream sediments, representing a composite sample of weathering and erosion products upstream from the sampling point, emerge as pivotal sinks for hydrocarbons in aquatic systems.

Due to their physical and chemical properties, sediments play a crucial role in marine ecosystems. They take on the dual role of being both sinks and sources of pollution. Markovic [4] asserts that species extinction and harm to ocean floor creatures can result from excessive sediment pollution Furthermore, polluted bottom sediments pose a significant environmental risk because they store harmful chemicals for an extended period of time. Because these sediments can dissolve in water and food, they pose a threat to humans and other animals. These effects persist regardless of whether the water above them satisfies typical water quality standards. This proves that the current methods of monitoring and controlling water and effluent quality are inadequate to safeguard and repair the nation's embayments, rivers, lakes, and estuaries. Investigating the environmental impacts of artisanal oil refining on the sedimentary bed of the Ikpukulu River in Borokiri, Nigeria, a town in the Niger Delta region, is the primary motivation for this research project.

1.1. Study area

The Ikpukulu River front, which is located within the Borokiri axis of the Port Harcourt Local Government Area in Rivers State, Nigeria, is the primary focus of this study. Approximately thirty kilometers in length and one hundred meters in width, the river has a variable average depth that ranges from seventy to ninety meters (Figure 1). Particularly noteworthy is the fact that the Ikpukulu River is a tidal river that also functions as a drainage network for the mangrove ecosystems that are located on both opposite banks. After a long journey, it eventually empties into a tributary that is connected to the Atlantic Ocean. There are distinct wet and dry seasons that vary throughout the region [5]. Rainfall is at its highest during the months of June and July, which coincide with the beginning of the rainy season in March and ending in October. The rains are brought on by winds that blow from the Atlantic Ocean in a south-westerly direction. The month of August is typically the time when the "August Break" occurs, which is a brief intermission that occurs during the rainy season [6]. During the dry season, on the other hand, which lasts from November until March, there is a brief harmattan period that occurs in December and early January. This is caused by dry winds that blow from the northeastern direction and cross the Sahara Desert. The weather in this region is characterized by high relative humidity levels that are greater than 80 percent, and the average annual temperature is approximately 28 degrees Celsius.

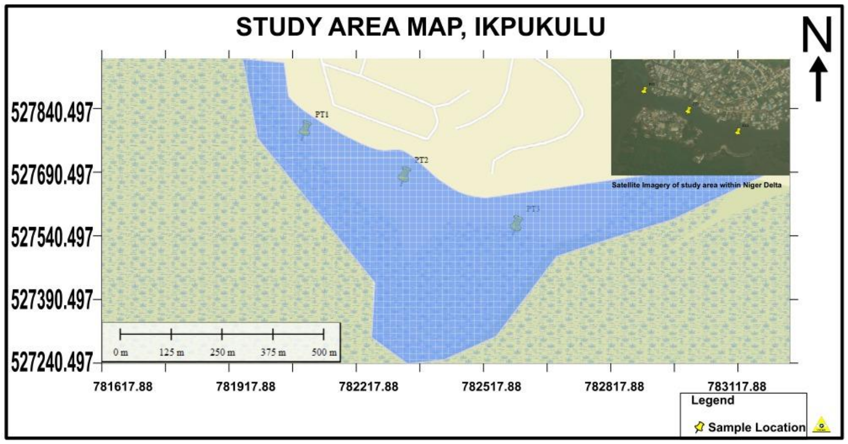

Figure 1. Study area

1.2. Regional geologic setting of the Niger Delta

The region known as the Niger Delta, which encompasses the Niger Delta Province, is located in the Gulf of Guinea [7]. This particular prograding delta is one of the few regressive deltas on Earth that is of such a large size. Depressions have been present throughout the entirety of its evolutionary history, which begins in the Eocene and continues right up until the present day [8]. The delta basin depocenter is characterized by a thickness of more than 10 kilometers, a volume of sediment measured at 500,000 kilometers squared, and an area of approximately 300,000 kilometers squared [9,10]. When these facts are taken into consideration, the geological significance of the delta becomes clear [11]. There is only one oil system in the Niger Delta province, which is located in Nigeria. This system is referred to by its official name, the Akata-Agbada Tertiary Niger Delta Petroleum System [9,12]. Extremely close proximity exists between the borders of the province and the space boundaries of the system.

1.3. Literature review

Sediment and waste pollutants are produced by land-based activities such as the illicit refining of crude oil in the area under investigation. These contaminants make their way into the Ikpukulu River via various pathways, including surface runoff and groundwater runoff. This process mirrors the introduction of chemical ions into streams via runoff and groundwater observed during rock weathering and mineral exploitation [13]. The role of rivers as sinks for pollutants from land-based activities is well-established [13].

"Bunkering," typically referring to ship refueling, takes on the sinister connotation of "illegal bunkering" in the Niger Delta region, signifying oil theft [14,15]. While prevalent, the environmental consequences of this practice remain inadequately addressed in literature. Unlike regulated refineries with waste treatment protocols, illegal refining practices often indiscriminately dump waste back into the river, leading to environmental degradation.

Consistent oil spillage in the region poses a grave threat to coastal ecosystems, endangering hatcheries and contaminating fish, a vital source of economic empowerment for indigenous communities [16]. This threatens long-term sustainability and poses potential mass poisoning risks. Albert et al. [17] argue that oil spills in this region rank among the worst globally, triggering protests and violence as affected communities seek justice for environmental damages.

Studies like Ansa and Francis [18] on the Andoni flats have examined the impact of crude oil spills on river surfaces. Chemical, physical, and heavy metal concentration studies revealed negative effects attributed to corrosion and damage of crude oil pipelines. The illegal distillation process, involving Jerry tanks and wooden barrels, further contributes to elevated pollutant levels. Notably, their study conducted during the rainy season might have underestimated pollution due to increased water dilution.

Igbinovia [19] describes various forms of oil infrastructure tampering in Nigeria, including oil bunkering, pipeline vandalism, and the recent "Kpoo-fire" phenomenon. Make-shift refineries, often hidden underwater, engage in illegal practices like "hot tapping" at night, exacerbating environmental degradation.

The detrimental impact extends beyond immediate areas. The atmosphere in most parts of the Niger Delta is heavily polluted by petroleum hydrocarbons and smoke from oil fires, posing health risks to inhabitants [18]. Burning residues contribute to acid rain and climate change, further compounding environmental damage.

Rivers in the Niger Delta act as open systems receiving pollutants from various sources, including the atmosphere, soil, and human activities. Pollutants settle in water bodies through geomorphologic processes like overland flow and groundwater flow. Sediments transported downstream reflect long-term environmental quality and have potential implications for aquatic biota and ecosystem health.

Lehr [20] presents a model explaining oil spill weathering processes, encompassing rapid phenomena like spreading and evaporation alongside slower processes like biodegradation. The dynamic nature of oil slicks highlights the complexity of spill response and remediation efforts. While previous studies have documented the negative impacts of illegal oil refining, this study aims to further investigate the specific consequences for the Ikpukulu River ecosystem. Evaluating the levels and types of pollutants present, their spatial distribution, and potential ecological risks will provide valuable insights for remediation efforts and policy development.

2. Method

2.1. Materials

Active River bottom sediment made up of Sand stones, humus material, clays/silts, plant roots and moisture were used for this study.

2.2. Statistical analysis

Analysis of variance and Pearson's proximity matrix was used to determine the degree of significance of variations and similarities between the various tested parameters and the sampling sites.

2.3. Potential Ecological Risk Index

Håkanson [21,22] developed the Potential Ecological Risk Index (PERI) as a diagnostic tool for managing pollution in lake and coastal areas.

$$\mathrm{R}_I = \sum_{i=1}^{n} E_r^i;\ E_r^i = T_f^i \times C_f^i;\ C_f^i = \frac{C_s^i}{C_n^i} \quad (1)$$

Where;

R_I is determined by adding up all of the risk factors for sediment-borne heavy metals.

E_r^i is the metal's monomial potential ecological risk factor.

T_f^i is the metal's toxic-reaction factor.

C_f^i is the metals' contaminating factor.

C_s^i and C_n^i is the amount of metals present in the reference sediments/background value and the monitored sediments, respectively.

2.4. Index of Geochemical Accumulation (I_{geo})

The geochemical accumulation index was calculated using

$$I_{geo} = \log 2\ C_n / 1.5 B_n \quad (2)$$

Where;

$\mathbf{I_{geo}}$ is the index of geochemical accumulation;

$\mathbf{C_n}$ is the total concentration of metal n in the fraction of silt and clay at the moment,

$\boldsymbol{B_n}$ is the value of element n relative to the geochemical background, and

1.5 is a factor that is used for correction because of lithogenic effects

Table 1. Geo accumulation Index Classification after Singh et al. [23]

CLASS	I_{geo} VALUE	QUALITY
1	0 <0	The concentrations in the background
2	0 - 1	Unpolluted
3	1-2	The transition from polluted to unpolluted
4	2-3	It is moderately polluted.
5	3-4	Highly to moderately polluted environment
6	4-5	Excessively polluted
7	>5	Extremely polluted condition

2.5. Polution Load Index

Through the utilization of the Pollution Load Index, this study was able to ascertain the level of heavy metal contamination that was present in the soil (PLI). We calculated the PLI by summing the ratios of the initial concentrations of five target metals detected in soil samples. Finding the PLI became much simpler as a result of this. Because of this, calculating the PLI became much simpler [24]. Using this method, the overall toxicity of the metals under study can be more easily determined. The next step was to classify the PLI values according to the criteria proposed by Tomlinson et al. [25] for their study. It has been stated by Angulo [26] that the PLI is equivalent to the nth root product of the concentrations of all metals. When using this metric, it is much simpler to evaluate the state of the environment as a whole.

$$\mathrm{PLI} = \mathrm{n}\sqrt{(CF_1 \times CF_2 \times CF_3 \times \ldots \times CF_n)} \quad (3)$$

But

$$\mathrm{CF} = \frac{C_{metal}}{C_{background\ value}} \quad (4)$$

Where:

CF	**:** contamination factor;
n	: number of metals;
$\mathbf{C_{metal}}$	: concentration in polluted sediments
$\mathbf{C_{background\ value}}$	**:** background value of that metal

Table 2. Pollution Load Index descriptions according to Tomlinson et al. **[25]**

CLASS	PLI rating	QUALITY
1	< 1	Perfection
2	1	Baseline levels of pollutants
3	>1	Deterioration of soil/water quality

2.6. Contamination Factor/Pollution Index

The CF facilitates comparison of element concentrations within a sample to their natural background levels, thereby indicating the degree of soil contamination [21]. The CF equation was applied to all elements investigated in this study (see equation below). Subsequently, the calculated CF values were classified according to the scheme proposed by Lacatusu [27].

$$CF = \frac{C_{metal}}{C_{background\ value}} \quad (5)$$

Where:

CF : contamination factor;

C_{metal} : metal concentration in polluted sediments

$C_{background\ value}$: background value of that metal

Table 3. Significance of intervals of Contamination/Pollution index by Lacatusu **[27]**

CLASS	C/P VALUE	QUALITY
1	< 0.1	This contamination is very slight.
2	0.1 – 0.25	Tiny amount of contamination
3	0.26 – 0.5	The contamination is moderate.
4	0.51 – 0.75	High levels of contamination
5	0.76 – 1.0	Extremely high rate of contamination
6	1.1 – 2.0	A trace amount of pollution
7	2.1 – 4.0	Modest levels of pollution
8	4.1 – 8.0	Heavy pollution levels
9	8.1 - 16	Extensive levels of pollution
10	>16	Overabundance of pollution

3. Results and Discussion

3.1. Potential Ecological Risk Index at Point X

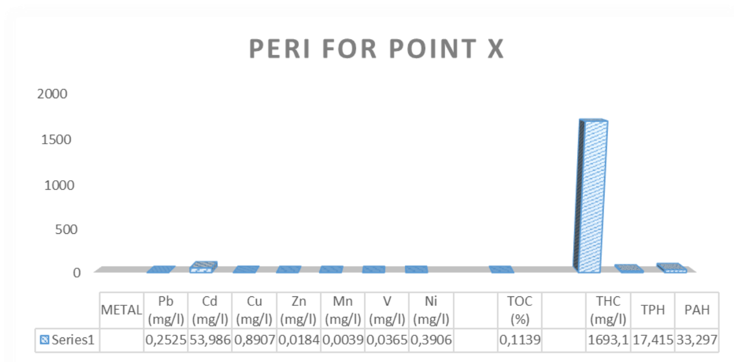

Figure 2. PERI at Point X

By comparing the measured concentrations to the background values, we were able to determine the contamination factors (CFs) for Pb, Cd, Cu, Zn, Mn, V, Ni, TOC, THC, TPH, and PAH [21]. According to Xu et al., [28] these are the worldwide toxicity factors for lead, cadmium, copper, zinc, manganese, and nickel. Unfortunately, we did not have the VA, TOC, THC, TPH, or PAH concentrations. In that sequence, the following CFs were determined for Pb, Cd, Cu, Zn, Mn, and Ni: 0.0505, 1.7995, 0.1781, 0.0184, 0.0039, and 0.0365. Applying the aforementioned toxicity factors and CFs, we arrive at a Potential Ecological Risk Index (PERI) of 1799.5484 for Point X. The PERI value at Point X indicates a very high level of environmental risk, according to Hakanson's [21] interpretation scheme. Specifically:

1) RI < 150: Low risk to the environment
2) 150 ≤ RI < 300: Moderate threat to the environment
3) 300 ≤ RI < 600: There is a significant ecological risk.
4) RI ≥ 600: A very high risk to the environment

Therefore, the heavy metal contamination at Point X of the Ikpukulu River poses a significant risk to the local ecosystem, requiring immediate attention and remediation efforts.

3.2. Potential Ecological Risk Index at Point Y

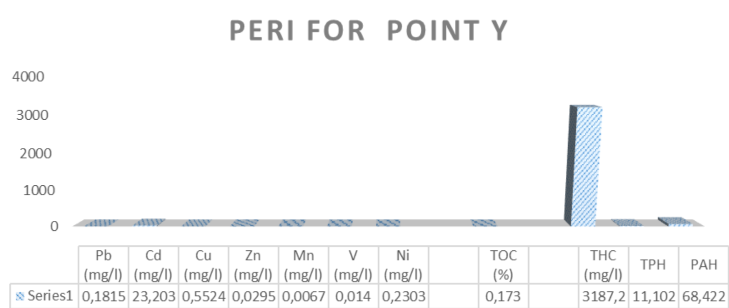

Figure 3. PERI at Point Y

From the measured concentrations of lead, cadmium, copper, zinc, manganese, vanadium, nickel, total organic carbon, tetrahydrocannabinol, and tetrahydrocannabinol, as well as PAH, contamination factors (CFs) were computed [21]. The values for V, TOC, THC, TPH, and PAH were not available, but the international toxicity factors for lead, cadmium, copper, zinc, manganese, and nickel were obtained from Xu et al. [28]. Values for these elements were not available. At Point Y, the calculated corrosion factors (CFs) for lead, cadmium, copper, zinc, manganese, and nickel were 0.0363, 0.7734, 0.1105, 0.0295, 0.0067, and 0.0140, respectively. The Potential Ecological Risk Index (PERI) for Point Y was calculated to be 3291.1339 by making use of these CFs and the toxicity factors that were available. This particular PERI value corresponds to an extremely high ecological risk at Point Y, as stated by the interpretation scheme that was proposed by Hakanson [21]. Therefore, the heavy metal contamination at Point Y of the Ikpukulu River poses a significant risk to the ecosystem in the surrounding area, which calls for immediate attention and efforts to remediate the situation.

3.3. Potential Ecological Risk Index at point Z

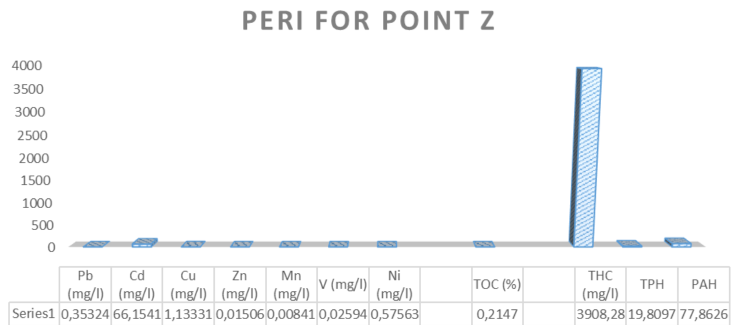

Figure 4. PERI at Point Z

On the basis of the concentrations that were measured and the background levels, contamination factors (CFs) were computed for lead, cadmium, copper, zinc, manganese, vanadium, nickel, total organic carbon, tetrahydrocannabinol, and polycyclic aromatic hydrocarbons (PAH) [21]. Pb, Cd, Cu, Zn, Mn, and Ni were all found to have international toxicity factors that were obtained from Xu et al. [28]. On the other hand, values for V, TOC, THC, TPH, and PAH were not found due to a lack of availability. The calculated CFs for the metals that were analyzed at Point Z were as follows: 0.0706, 2.2051, 0.2267, 0.0151, 0.0084, 0.0259, 0.1151, 0.2147, 3908.2783, 19.810, and 77.8626 for lead, cadmium, zinc, manganese, vanadium, nickel, total organic carbon, tetrahydrocannabinol, tetrahydrofuran, and phenol, respectively. With the help of these CFs and the various toxicity factors that are available, the Potential Ecological Risk Index (PERI) for Point Z was calculated to be 4074.4310. In accordance with the interpretation scheme that was proposed by Hakanson [21], this PERI value indicates that Point Z is associated with an extremely high ecological risk. Therefore, the heavy metal contamination that was found at Point Z of the Ikpukulu River constitutes a significant threat to the ecosystem of the surrounding area, necessitating immediate attention and efforts to remediate the situation.

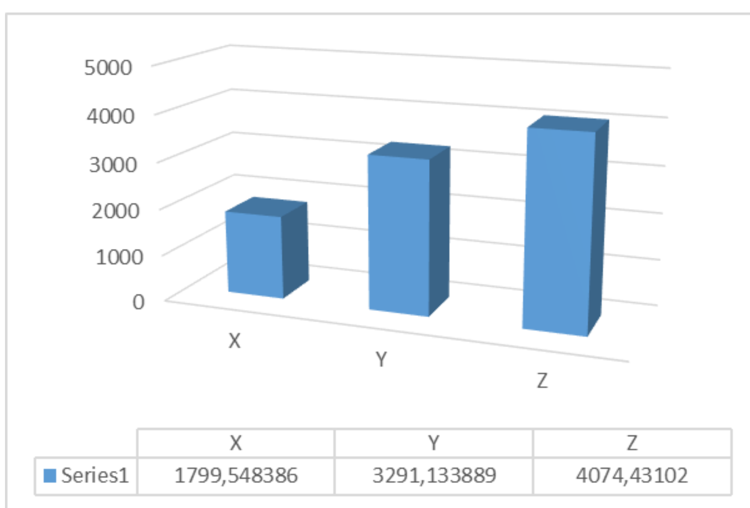

Figure 5. PERI at Points X, Y, and Z

Comparing Point Z to Points X and Y, the analysis revealed that Point Z had the highest PERI value, which indicates that this particular location poses a significantly higher potential ecological risk. According to this observation, Point Z may have been used as a formal or current illegal crude oil refining site, which would have resulted in increased concentrations of heavy metals and the ecological risks that are associated with them. Conversely, the lower PERI values at Points X and Y suggest they may represent migration pathways of contaminated sediments originating from Point Z or other upstream sources.

3.4. Geo Accumulation Index

This study evaluated the level of heavy metal contamination in sediments at three sampling points (X, Y, and Z) along the Ikpukulu River by calculating the Geoaccumulation Index (I_{geo}). The I_{geo}, based on Hakanson [21], reflects the degree of metal enrichment compared to background levels. International toxicity factors were obtained from Singh et al. [23] for classification purposes (Table 1).

1) Point X: All metals except THC, TPH, and PAH exhibited I_{geo} values below 0, indicating negligible to no pollution. THC, TPH, and PAH values suggested moderate to very high pollution.

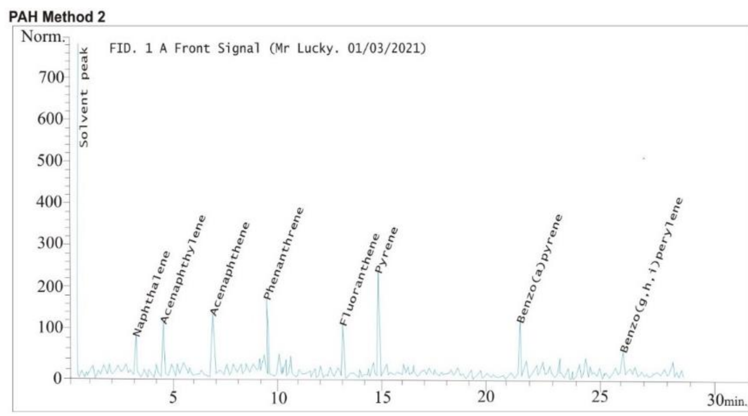

Figure 6. Chromatograph of PAHs of soil sediment at Point X

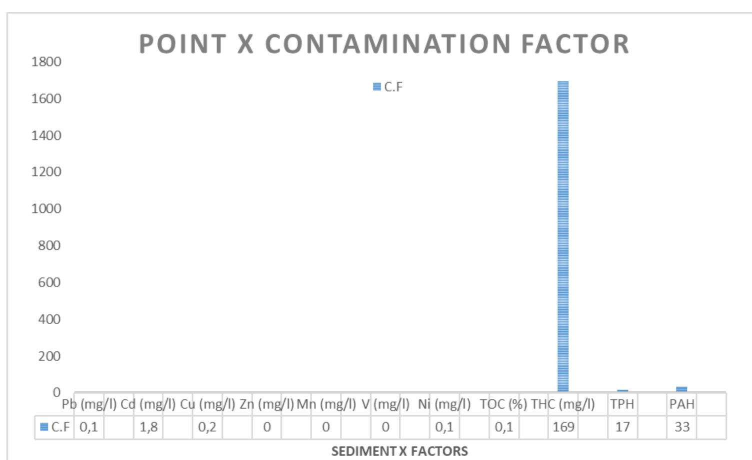

Figure 7. Contamination Factor at Point X

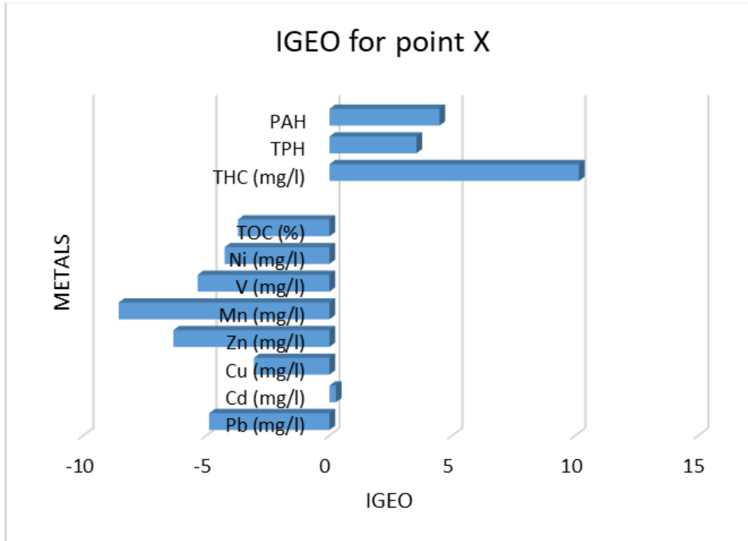

Figure 8. I_{geo} at Point X

2) Point Y: Similar to Point X, most metals displayed negligible to no enrichment ($I_{geo} < 0$). However, THC, TPH, and PAH again showed significant contamination, ranging from moderate to very high.

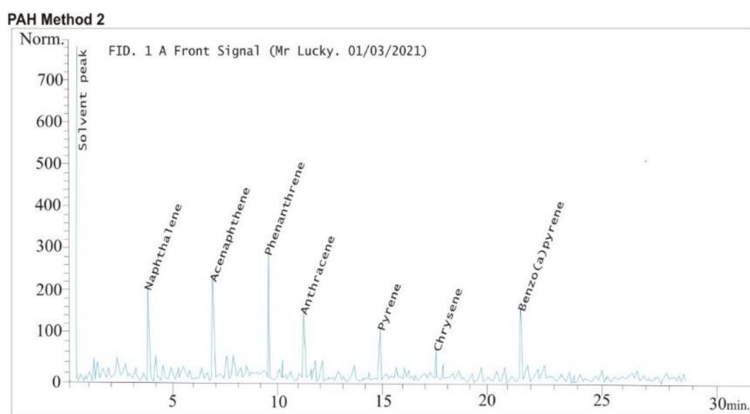

Figure 9. Chromatograph of PAHs of soil sediment at Point Y

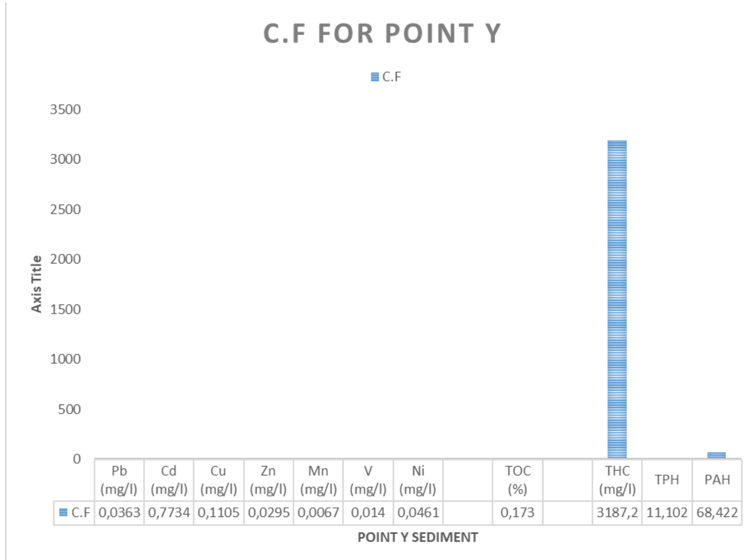

Figure 10. Contamination Factor at Point Y

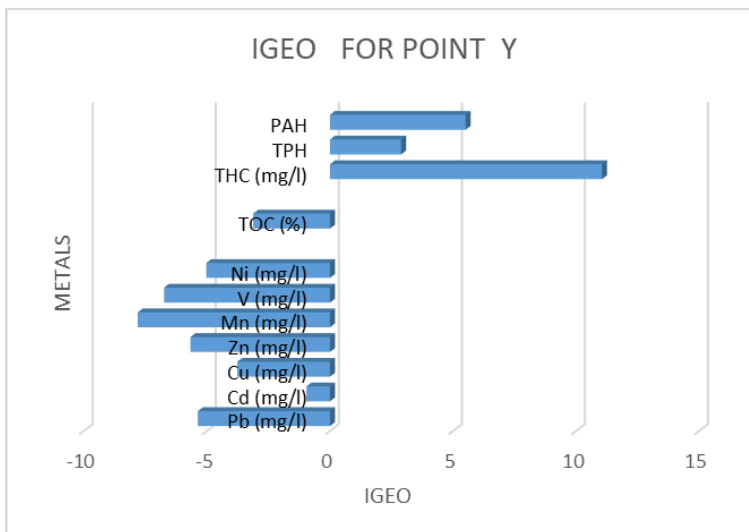

Figure 11. I_{geo} at Point Y

3) Point Z: I_{geo} values for THC, TPH, and PAH indicated moderate to very high pollution at Point Z, which was similar to the other points. However, the majority of metals remained unpolluted at Point Z.

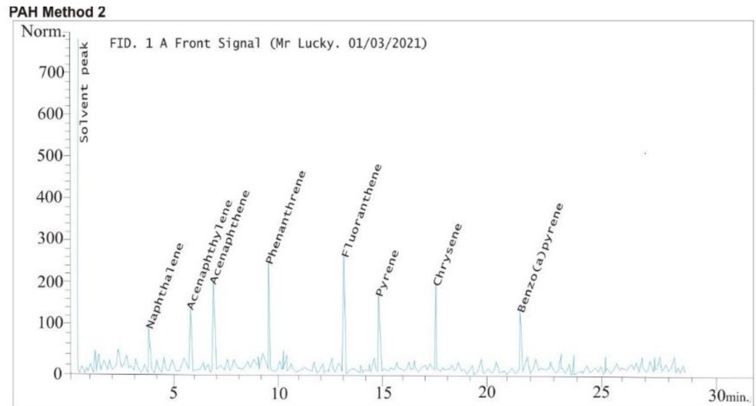

Figure 9. Chromatograph of PAHs of soil sediment at Point Z

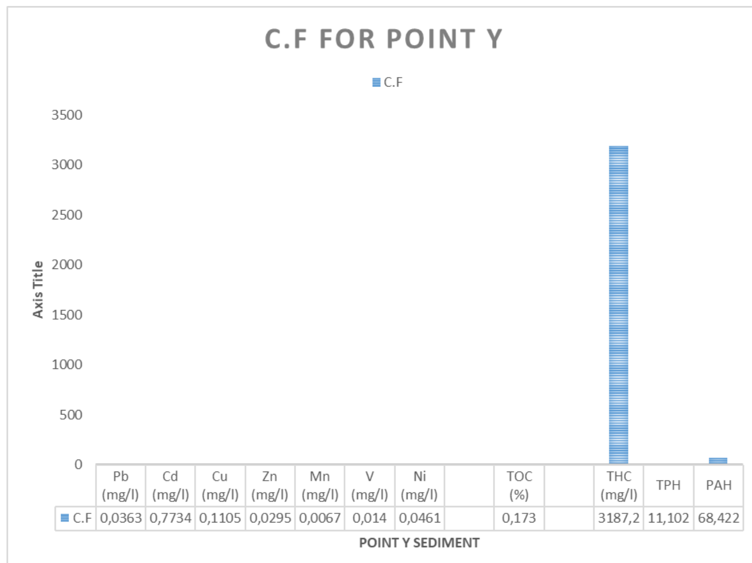

Figure 10. Contamination Factor at Point Z

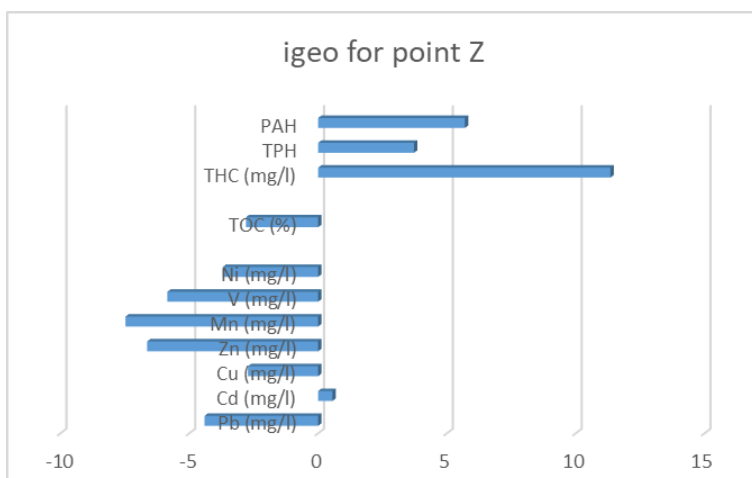

Figure 11. I_{geo} at Point Z

The results show that while there are trace amounts of THC, TPH, and PAH in the sediments from all three locations, the concentrations of enriched heavy metals are low.

This indicates that, with the exception of these organic contaminants, human activities do not significantly impact metal concentrations. It is worth mentioning that all three sites had moderate to very high I_{geo} values for THC, TPH, and PAH. This points to the possibility that oil spills or other waste products from oil-related activities contaminated the water.

The input parameters of the computer model of the heat-mass exchange processes in the heat exchange quasi-apparatus are as follows: initial consumption of incoming air, initial temperatures of water and air, pressure in the device Ro, liquid consumption Go, initial air humidity. Output parameters: display air consumption at the outlet, display temperature T, device pressure P, liquid consumption G.

3.5. Pollution Load Index

This study measured the amount of heavy metal pollution in sediments collected from three locations along the Ikpukulu River using the Pollution Load Index (PLI) (X, Y, and Z). Tomlinson et al. [25] states that the PLI can be used to compare the concentration of metals to the background levels. In order to classify pollution, this data is crucial (Tables 4, 5, and 6). Despite the fact that all of the points had PLI values that were lower than 1, which places them in the "perfection level" category according to Likuku et al. [29], this does not indicate that there is no cause for concern. In spite of the fact that they do not surpass the threshold for immediate intervention, PLI values that are lower than 1 do not guarantee patients' safety. It is recommended by Likuku et al. [29] that even relatively minor metal enrichments should be addressed in order to forestall the development of more severe contamination in the future. Persistent pollution, even at present levels, could cause the PLI to rise above 1, which would have devastating effects on ecological systems and the environment. Precautions are required to reduce metal concentrations and prevent contamination. We must know the origins and pathways of metals into the environment in order to devise efficient intervention strategies. Stricter regulations on pollution control and the implementation of sediment remediation methods are two potential responses to the threat to ecosystem health.

Table 4. PLI result for Point X

S/No.	METALS	CF
1	Pb (mg/l)	0.05050706
2	Cd (mg/l)	1.799525
3	Cu (mg/l)	0.17813972
4	Zn (mg/l)	0.01843307
5	Mn (mg/l)	0.00394966
6	V (mg/l)	0.03649022
7	Ni (mg/l)	0.07812029
8	TOC (%)	0.11385029
9	THC (mg/l)	1693.14357
10	TPH	17.4152056
11	PAH	33.2973018
P L I = 1.96071E-06		

Table 5. PLI result for Point Y

S/No.	METALS	CF
1	Pb (mg/l)	0.03629365
2	Cd (mg/l)	0.7734375
3	Cu (mg/l)	0.11048389
4	Zn (mg/l)	0.02950371
5	Mn (mg/l)	0.00668569

6	V (mg/l)	0.01404044
7	Ni (mg/l)	0.04605229
8	TOC (%)	0.17301658
9	THC (mg/l)	3187.21894
10	TPH	11.1023019
11	PAH	68.4221269
	P L I = 1.50635E-05	

Table 6. PLI result for point Z

S/No.	METALS	CF
1	Pb (mg/l)	0.07064847
2	Cd (mg/l)	2.2051375
3	Cu (mg/l)	0.22666167
4	Zn (mg/l)	0.01505993
5	Mn (mg/l)	0.00841061
6	V (mg/l)	0.02594267
7	Ni (mg/l)	0.11512571
8	TOC (%)	0.21470193
9	THC (mg/l)	3908.27826
10	TPH	19.8097447
11	PAH	77.8625956
	P L I = 0.001571775	

4. Conclusion

The Ikpukulu River was the site of comparison for the impacts of small-scale oil refining in this research. Using the geoaccumulation index (I_{geo}), the pollution load index (PLI), and the potential ecological risk index (PERI), we quantified the sediment pollution levels in three distinct locations (X, Y, and Z). The measured concentrations of heavy metals were determined to be below the permissible limits for background contamination following the investigation. Point Z had the highest concentrations of Total Hydrocarbons (THC), one of the many pollutants found in the hydrocarbon content. As a result of the environmental effects of the tides, our findings indicate that the contaminants may have been transported in a directional manner from Point Z to Point X. This is the conclusion that emerged from our investigation. The THC levels were above the threshold that indicates an exceptionally high environmental risk, despite the fact that the metal concentrations were not polluting according to I_{geo} values. Consistent with their 2017 study, Ezekwe and Utong [30] discovered that artisanal oil refining significantly pollutes coastal rivers. Based on elevated THC levels and potential ecological risk assessment, the Ikpukulu River appears to function as a sink for waste from illegal hydrocarbon refining and potentially suffers from spills related to oil transportation and handling. These activities have demonstrably increased contaminant levels, particularly THC, in the river sediments, potentially placing it among the world's most polluted coastal rivers. This conclusion is further supported by the work of Li et al. [31] who employed similar assessment methods to identify highly polluted coastal river systems.

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