Impact of industrial activities on water and sediment quality of the Okulu River: A study of PH, Alkalinity, Cadmium, and Petroleum Hydrocarbons

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Abstract

Industrial activities, particularly in oil-producing and manufacturing regions, often release effluents containing heavy metals and hydrocarbons into nearby water bodies, posing significant environmental and public health risks. The Okulu River lies within the Eleme Local Government Area of Rivers State, Nigeria, and it is subject to the anthropogenic forces that have the potential to affect the water and sediment quality. The design of this research was a descriptive environmental assessment to explore the impact of industrial activities on water and sediment in this river. After the standard sampling methods, five surface water and sediment samples were gathered at four affected areas by industry and one control area. The samples were used to determine the pH, alkalinity, total petroleum hydrocarbons, and cadmium in a certified lab using standard procedures and calibrated instruments. We juxtaposed the findings with the whole world health organization allowed limits in order to evaluate the levels of pollution and the possible environmental and health risks. Surface water pH showed slight acidity, ranging from (6.2–6.6), while sediment pH ranged from (6.2–6.7), all within WHO limits. Surface water alkalinity was elevated at impacted sites (262.85–320.92 mg/L) compared to the control (93.2 mg/L), exceeding the WHO limit (200 mg/L). TPH levels were extremely high in surface water (13.99–3411.5 ppm) and sediments (34.17–13149.0 ppm), surpassing the WHO limit (10 ppm). Cadmium concentrations exceeded WHO standards (0.8 mg/L) in surface water (1.22–3.8 mg/L) and sediments (1.76–2.06 mg/L) at impacted sites, indicating significant industrial contamination. These results indicate severe contamination linked to industrial activities, with potential ecological and human health implications. Immediate monitoring, regulatory enforcement, and remediation strategies are essential to restore and safeguard the Okulu River ecosystem.

1. Introduction

The release of untreated or low-quality effluents released into freshwater bodies has severely impacted freshwater ecosystems in many parts of the world, affecting water quality and destabilizing the integrity of the sediments (Seiyaboh & Izah, 2017). In the Niger Delta of Nigeria, where the Okulu River is located, the oil and gas related heavy industrialization, chemical factories, and supporting infrastructure have augmented pollutant loads in the river system. They alter the pH and alkalinity of the river, introduce toxic heavy metals, including cadmium (Cd), and spread petroleum hydrocarbons (PHCs), thereby threatening the ecological and human health (Seiyaboh & Izah, 2017; Okudo et al., 2024). The state of the situation is aggravated by frequent oil spills, artisanal refining, wastewater discharges, and urban runoff, which results in chronic and acute contamination of aquatic environments (Howard et al., 2021; Okudo et al., 2024).

Water PH and alkalinity are the main indicators of river health as they affect the biochemical processes, solubility of metals, and survival of aquatic organisms. The release of industrial effluents tends to change these parameters, introducing acids and alkalis, as well as organic waste (Seiyaboh & Izah, 2017). As an example, the research of Nigerian rivers has indicated that the PH below industries is not a natural state, which is an indicator of the influence of effluent emission (Seiyaboh and Izah, 2017). Although there is limited available data on the Okulu River, a study of other waterways in the Niger Delta has shown that human actions cause pH shifts (Seiyaboh & Izah, 2017). Differences in pH can lead to higher bioavailability of metal like cadmium due to changing their speciation and mobility in water and sediment (Zhang et al., 2023). Alkalinity counteracts PH

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variation yet it is also impacted by industrial pollution. High alkalinity is a common indicator of a large amount of carbonate and bicarbonate ions found in the effluents of industrial plants and urban discharge that disrupt the normal water chemistry and pose a risk to aquatic life (Seiyaboh and Izah, 2017). Altered alkalinity is therefore a chronic stressor that may interfere with processes concerning primary production and nutrient cycling particularly when coupled with organic pollution.

Among the most recalcitrant industrial contaminants in rivers are the heavy metals since they cannot be degraded and instead, they accumulate within organisms. Cadmium is particularly toxic, even in its low concentrations, and may be caused by petroleum mining, battery disposal, metal plating, and industrial wastewater (Zhang et al., 2023; Okudo et al., 2024; Udeze, 2025). It has observed that in the Niger Delta, cadmium was found in high levels of water and sediments associated with the oil exploration and other human activities (Allison et al., 2024; Okudo et al., 2024). These results are consistent with larger-scale research regarding the introduction of heavy metals by industrial wastewater, which remain and accumulate over time (Zhang et al., 2023; Seiyaboh & Izah, 2017). Rivers like the Bonny River Estuary have been detected to contain cadmium and other metals in quantities that are more than the acceptable limits and could pose a danger to aquatic life and even to the food chain (Allison et al., 2024). Okoku River has documented the presence of cadmium, which exceeds the normal background levels, highlighting the same tendencies of contamination related to the wastewater discharge and industrial impact (Onyeugbo et al., 2021). Cadmium exposure at the chronic stage may result in kidney dysfunction, bone injuries, and carcinogenicity in humans; that is why it is highly important that the issue of cadmium monitoring and mitigation is addressed (Zhang et al., 2023; Nafiah et al., 2025).

The PHCs are organic contaminants that oil spill, leaks and fuel handling releases. Crude oil spills and illicit refining are common practices in the Niger Delta and have resulted in widespread PHC pollution in rivers (Howard et al., 2021; Okudo et al., 2024). PHCs contain complex blends including polycyclic aromatic hydrocarbons (PAHs), which are hydrophobic, persistent and bioaccumulative. These contaminants are frequently retained by sediments, where they may accumulate and subsequently re-enter the water column, and become dangerous in the long term to benthic organisms and higher trophic levels (Howard et al., 2021). Studies of the coastal and inland rivers in Rivers State indicate the presence of PHCs in water and sediment, and the concentration is associated with the distance to oil industry activities and processing plants (Howard et al., 2021). High PHC concentrations reduce dissolved oxygen, change microbial communities, and cause toxicity to aquatic plants and animals. Besides causing ecological harm, PHC contamination may impact human health by consuming contaminated fish and water, thus highlighting the relationship between environmental and public health hazards.

Throughout the literature, industrial operations continuously harm the quality of river water and sediments in various ways. They change physicochemical parameters, contain toxic metals such as cadmium, and emit petroleum hydrocarbons. All these stressors are synergistic, increasing ecological disturbance. Oil exploration, artisanal refining, urbanization, and poor wastewater treatment compound these effects in the Niger Delta by increasing the level of pollutants in rivers like Okulu, Bonny and other estuarine systems (Seiyaboh & Izah, 2017; Howard et al., 2021; Okudo et al., 2024). This study was motivated by the increasing apprehensions regarding industrial pollution and deteriorating water quality in the Niger Delta rivers such as the Okulu River. Although the literature widely records industrial influences on river systems (Seiyaboh & Izah, 2017; Howard et al., 2021), there is limited site-based data on the Okulu River and especially on the interaction of pH, alkalinity, cadmium, and petroleum hydrocarbons in the water and sediments. The literature has been predominantly on heavy metals or hydrocarbons in isolation and has lacked information on their interactive impacts on aquatic chemistry as well as sediment quality (Okudo et al., 2024). It is important to address these gaps in order to implement effective environmental monitoring, risk assessment, and evidence-based pollution control strategies.

1.1. Objectives

a. To evaluate the pH of surface water and sediments of the Okulu River in relation to WHO permissible standards.

b. To assess the alkalinity of surface water and determine the influence of industrial activities on water buffering capacity.

c. To determine total petroleum hydrocarbon concentrations in surface water and sediments and assess the extent of petroleum pollution.

d. To evaluate cadmium concentrations in surface water and sediments and determine associated environmental and public health risks.

e. To compare water and sediment quality parameters between control and impacted sites to establish the magnitude of industrial influence.

2. Method

2.1. Research Design

This study was designed to comprehensively assess the effectiveness of environmental impact assessment and the quality of Okulu River and its environs, in Eleme Local Government Area, Rivers State, Nigeria. The research focused on evaluating the impact of industrial activities on water and sediment quality of the river covering pH, Alkalinity, Cadmium, and Petroleum Hydrocarbons. The following steps were taken in the process and accomplishment of this research work. This will include reconnaissance survey, data collection through primary and secondary sources, data presentation and analysis, test of statistical significance as well as drawing conclusion from the research findings.

2.2. The Study Area

The study area is Okulu River in Eleme Local Government Area of Rivers State, which is located within latitude 40 60'' – 40 35'' N and longitude 70 – 70 15'' E with a total land area of about 140 km (Figure 1).

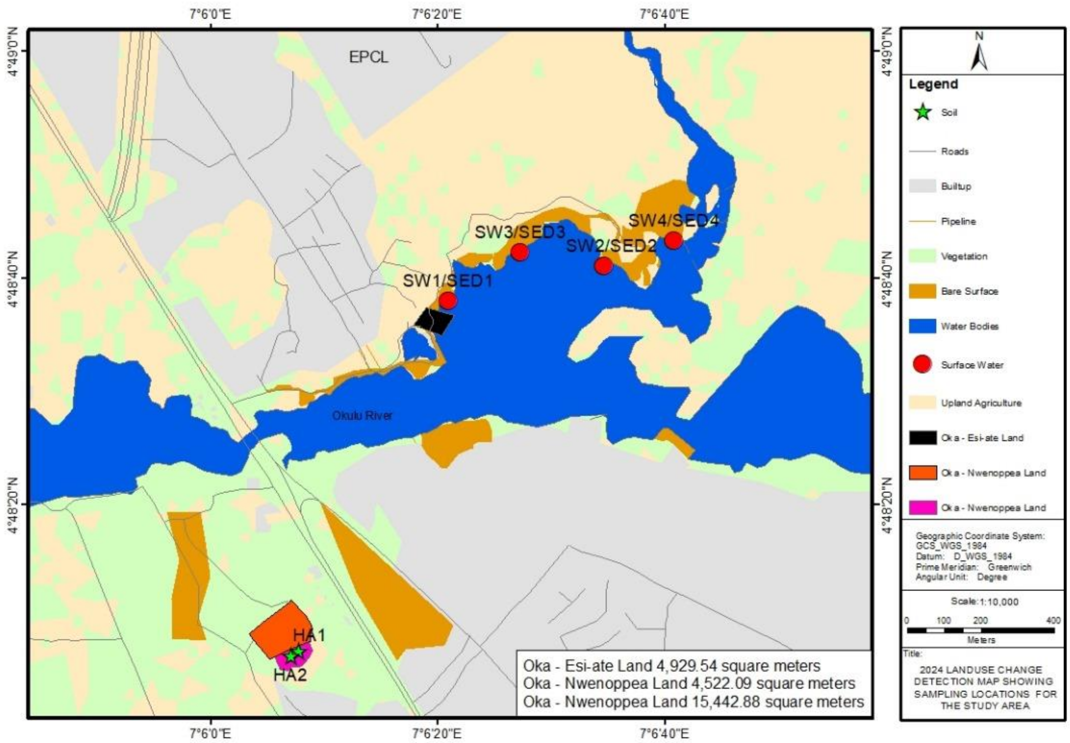

Figure 1. Map of Aleto Community showing the Okulu River

The Local Government Area is about 30 km from Port Harcourt the state capital and shares boundary with Oyigbo in the north, eastern boundary with Tai, western boundary with Elelenwo and southern boundary with Okrika/Ogu/Bolo Local Government Area. The headquarters is located at Nchia and made up of two development areas namely Odido and Nchia. It also has 10 towns namely; Ogale, Alesa, Alode, Agbonchia, Aleto, Akpajo, Onne, Eteo, Ekporo and Ebubu. Aleto community is among the host communities, with 12 sub- clans the likes of Okulu, Wilderness, Nwenoppea with Eleme Local Government population of about 200,000 persons. The Okulu River is primarily a freshwater system. However due to its proximity to industrial activities, it experiences influences that can alter its water quality, leading to its suitability for certain purposes. Studies indicate it can have varying levels of salinity, but it is generally classified as a freshwater body (Ahuchaogu et al. 2025). The Okulu River takes its course from Ogale, meandering through communities like Agbonchia and Aleto, before eventually emptying into the Bonny River through the Okrika creeks (Ahuchaogu et al, 2025).

2.3. Collection of Water and Sediment Samples - Sampling Techniques and Procedure.

A total of five (5) water and sediment samples were collected, one (1) sample eat the pipe-end of effluent discharge into the river body, and four (4) samples along the Okulu river for upper and lower and upper attenuation at a spacing distance of 30 meters. Water samples were collected into washed plastic containers; rinsed several times with sampled water before filling them. Samples were preserved by storing in ice-filled cooler boxes and transported to the Laboratories. This is to prevent chemical reaction and maintain the original quality till laboratory analysis. Water samples were geo-referenced and labeled with names and source of collection. Sampling sites were delimited at each area by the grid technique. Sediment samples were collected from identified upper and lower attenuation spots along the Okulu River within a depth of 0-15/cm. The Sediments were stored in plastic bags for analysis

2.4. Sampling size and Sampling Area

A total of five (5) surface water and sediment samples each were collected from the study sites with four (4) impacted with industrial activities and one control sample, for laboratory analysis. The sampling area in this study is the Okulu River in Eleme Local Government Area of Rivers States (Figure 2). The control area or site for the Sediment and Water samples is Nwennopea that borders and shares boundary with the study location. The Water samples are called Eleme SW1, Eleme SW2, Eleme SW3 and Eleme SW4 respectively in the raw data analysis and SW1, SW2, SW3 and SW4 in the Map and chart figures while the Sediment samples are called Eleme SED1, Eleme SED2, Eleme SED3 and Eleme SED 4 in the raw data analysis and SD1, SD2, SD3 and SD4 in the Map and chart Figure 2.

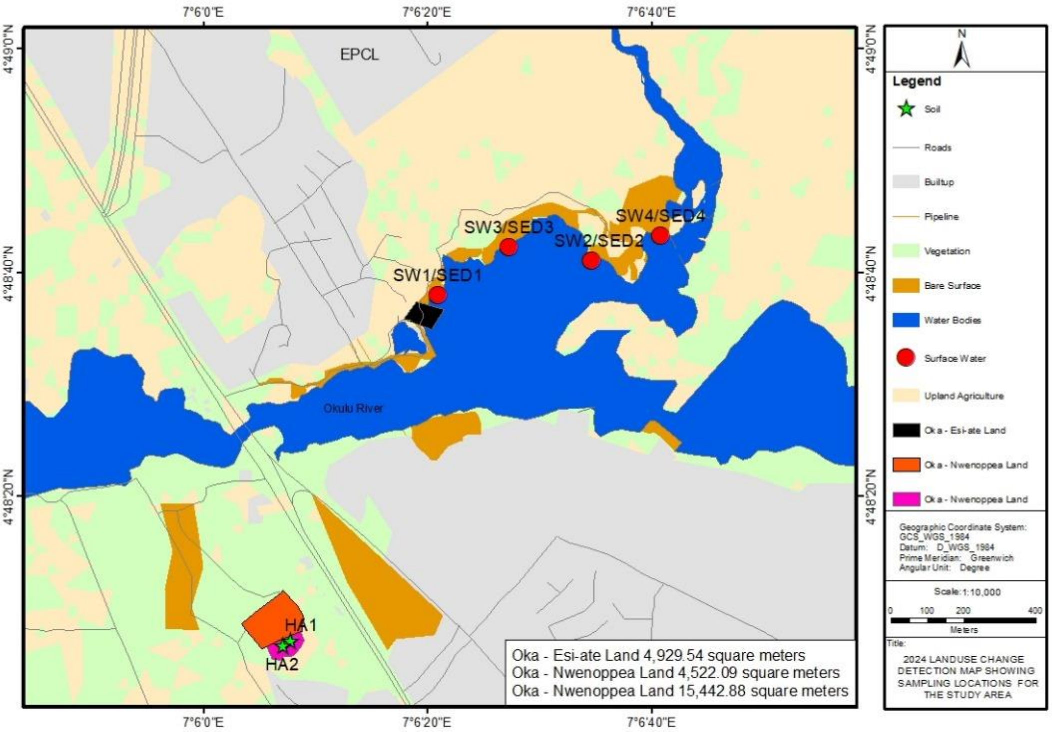

Figure 2. Sample locations within the Study Area

2.5. Methods and Procedures for Laboratory Analysis.

Physical and chemical analysis of surface water and sediments samples were carried out at Austino Research & Analysis Laboratory Nig. Ltd, No. 2 UPTH Road, Alakahia, UNIPORT, Port Harcourt.

The pH of surface water samples was determined using a calibrated digital pH meter equipped with glass electrodes. Prior to measurement, the pH meter was standardized using buffer solutions of pH 4.0, 7.0, and 9.2. Water samples were filtered, and 50 mL aliquots were measured in clean beakers. The electrode was immersed in each sample, and readings were recorded after stabilization. For sediment pH determination, air-dried sediment samples were homogenized and mixed with distilled water in a 1:2.5 sediment-to-water ratio. The mixture was stirred thoroughly and allowed to equilibrate, after which the pH was measured using the same calibrated pH meter. This procedure ensured consistency and accuracy in comparing water and sediment pH values across sampling locations.

Surface water alkalinity was determined using the titrimetric method. A 50 mL aliquot of each water sample was transferred into a 250 mL conical flask. Two drops of methyl red indicator were added, and the sample was titrated against a standard 0.01 M hydrochloric acid (HCl) solution until a pink endpoint was observed. The volume of acid used was recorded, and total alkalinity was calculated using standard alkalinity equations. The results were expressed in milligrams per liter (mg/L).

Total petroleum hydrocarbons in surface water samples were determined using solvent extraction followed by spectrophotometric analysis. Water samples were extracted with an appropriate organic solvent, and the extract was analyzed to quantify hydrocarbon content. For sediment samples, dried and homogenized sediments were subjected to solvent extraction to release adsorbed hydrocarbons. The extracted hydrocarbons were then quantified and expressed in parts per million (ppm). This method enabled comparison of hydrocarbon contamination between surface water and sediments.

Cadmium concentrations in surface water samples were determined after acid digestion using appropriate reagents to ensure complete dissolution of metals. Sediment samples were oven-dried, ground, and digested using a mixed-acid digestion procedure. The digested samples were analyzed for cadmium concentration using Atomic Absorption Spectrophotometry (AAS). Calibration was carried out using standard cadmium solutions, and results were expressed in milligrams per liter (mg/L). All analyses were conducted in triplicate to ensure reliability. Blank samples and standards were included to maintain analytical accuracy. The results obtained were compared with World Health Organization (WHO) permissible limits to assess the extent of pollution and potential environmental and health risks associated with industrial activities along the Okulu River.

3. Results and Discussion

3.1. Result

3.1.1. The pH of Surface Water

The study showed slight variations in the surface water pH levels of the samples collected (Figure 3). The control had a pH of 6.6. The other surface water samples showed pH values that were slightly similar or negligibly different from the control. The pH value for SW1 and SW2 was 6.4, while SW3 and SW4 had lower pH values of 6.2. These values indicate that these affected surface water samples were mildly acidic in nature even though they fall into the WHO acceptable pH range (5-7), indicating that the pH of these surface water samples were still within acceptable limits for human consumption. However, it is worthy of note that slight pH changes can alter chemical reactions in water and consequently affect aquatic life and ecosystem balance. Hence, continuous monitoring is essential in order to detect the slightest of deviation from the acceptable pH ranges for surface waters.

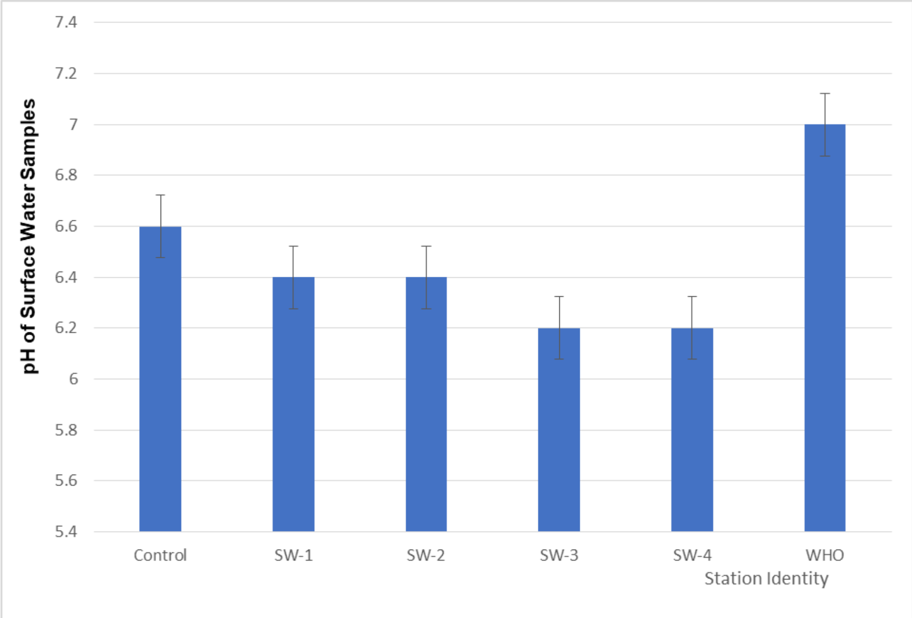

Figure 3. pH of Surface Water in the study area

3.1.2. The pH of Sediments

This study showed slight variations in the pH of collected sediment samples (Figure 4). The control sample showed a pH value of 6.7, which is within World Health Organization's (WHO) acceptable pH range. Other sediment samples showed pH values that were slightly below the control pH but were still with WHO acceptable ranges. SED1 had a pH of 6.4 indicating a mildly acidic environment. Similarly, SED2 and SED3 showed pH value of 6.3, indicating a mild acidic environment. SED4 had a pH value of 6.2, also, indicating a mildly acidic environment. These pH values are within the WHO acceptable ranges.

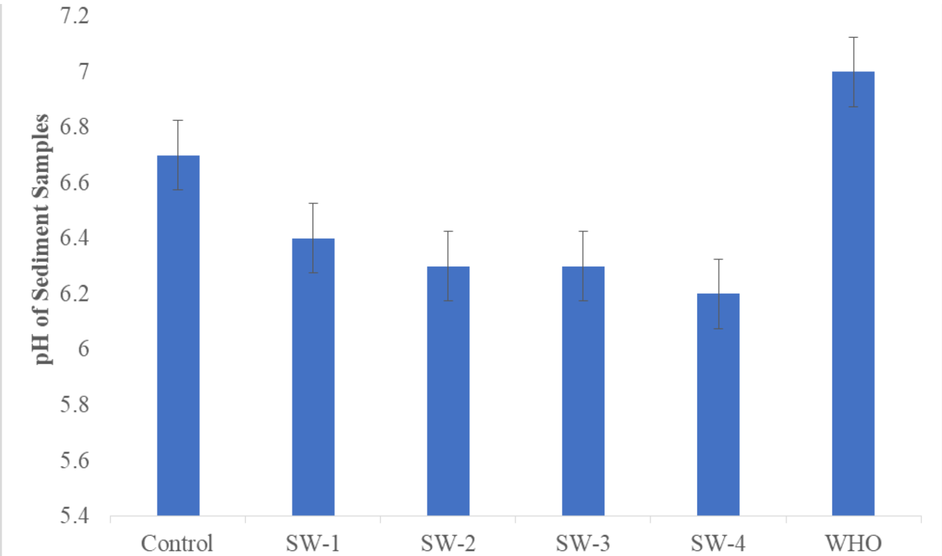

Figure 4. pH of the sediments in the study area

3.1.3. The Alkalinity of Surface Water

This study investigated the surface water alkalinity levels (Figure 5). The alkalinity levels of the samples were also compared to the WHO acceptable ranges. The control sample had an alkalinity value of 93.2 which is within the WHO acceptable range of values. The other samples, however, showed alkalinity values that did not meet the WHO standard. Samples SW1, SW2, SW3 and SW4 had alkalinity values of 262.85 mg/l, 296.89 mg/l, 320.92 mg/l and 274.23 mg/l respectively. These alkalinity values exceed the WHO standard limit of 200 mg/L. This study suggests that the activities of these industries in these communities contributed in increased surface water alkalinity. Spiked alkalinity levels can negatively affect water quality, ecosystem balance, water pH balance, nutrient availability and aquatic life.

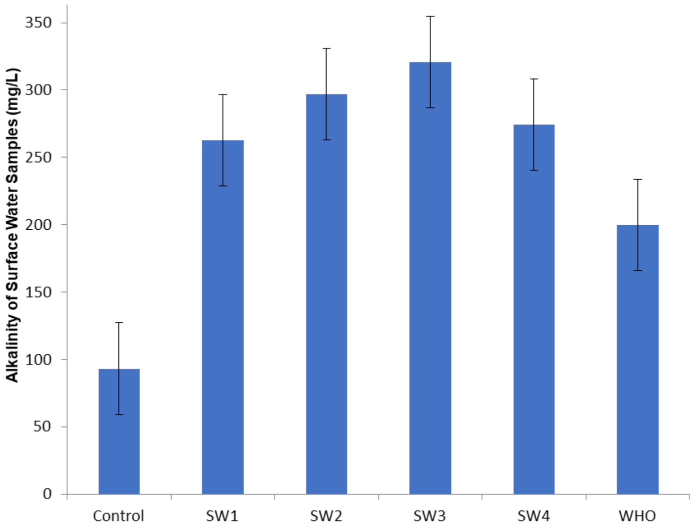

Figure 5. Alkalinity of surface water in the study area

3.1.4. The Total Petroleum Hydrocarbon (TPH) of Surface Water

This study showed varying levels of Total Petroleum hydrocarbons (TPH) in the different surface water samples collected (Figure 6). TPH is a measure of the total concentration of hydrocarbons present in water, including both aliphatic and aromatic compounds derived from petroleum sources. High TPH levels can be a marker for significant contamination and potential environmental risks. The control sample had a low TPH value of 13.993 ppm, indicating minimal or low contamination. The low TPH level in the control site can be considered as a reference with the affected sites. The stations SW1and SW2 had TPH values of 2623.4 ppm and 2386.9 ppm respectively, indicating relatively high TPH levels while the stations SW3 and SW4 had even higher TPH values of 3162.0 ppm and 3411.5 ppm respectively. Comparing the TPH values of these samples, to the WHO acceptable value of 10 ppm, it is evident that all the samples collected, including the control has TPH values that exceed acceptable limit. These obtained values suggest the immediate need for remediation and restoration efforts to mitigate the environmental and health hazards associated with the presence and impact of industrial activities in the Okulu River.

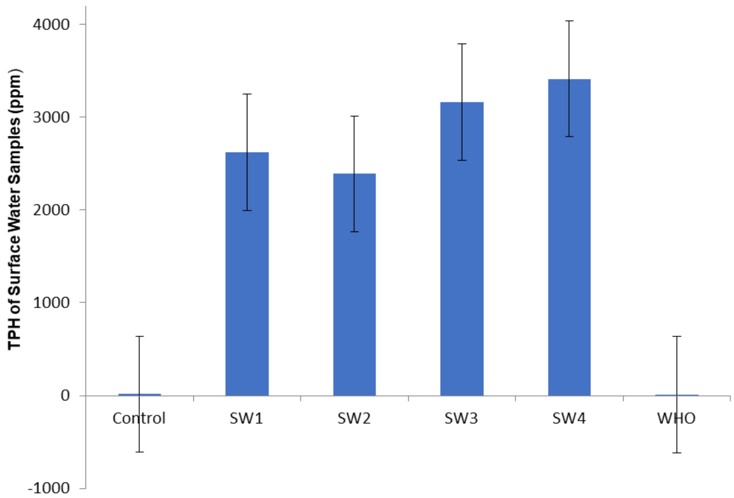

Figure 6. TPH of surface water in the study area

3.1.5. The Total Petroleum Hydrocarbon of Sediments

The results showed varying levels of TPH in the different samples collected, including control and affected sites. The control sample had a TPH value of 34.165 ppm (Figure 7). This is relatively minimal when compared to the TPH values obtained from the affected, although, it exceeds WHO acceptable limit of 10 ppm. SD1 and SD2 had very high TPH values of 9323.2 ppm and 9979.1 ppm respectively, indicating high impact by multinationals. SD3 and SD4 had even more spiked and elevated TPH levels of 10027.0 ppm and 13149.0 ppm respectively, also indicative of high impact from multinationals. All these sites, including the control site, had TPH values exceeding the WHO acceptable limit or standard.

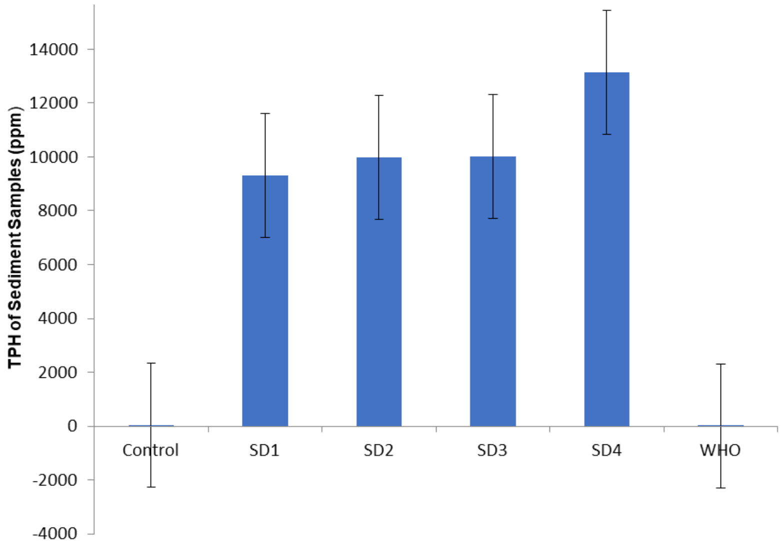

Figure 7. TPH of the sediment in the study area

3.1.6. The Cadmium Concentration of Surface Water

Cadmium is a toxic heavy metal that can cause health and environmental hazards. It is primarily released into the environment through industrial activities. This study assessed the cadmium levels in surface water samples collected from the various sites. The control sample showed cadmium concentrations of 0.0016 mg/L (Figure 8), this is within the WHO acceptable limit of 0.8mg/L, indicating that the control site has not been polluted with cadmium. The other samples, however, showed relatively high Cadmium levels. Sample from SW4 had the highest cadmium concentration of 3.8 mg/L, which obviously exceeds the WHO accepted cadmium concentration of 0.8 mg/L. Sample from SW3 had the second highest cadmium concentration of 3.3051 mg/L. This concentration level is very high relative to the WHO acceptable cadmium concentration limit. The cadmium concentrations in SW1 and SW2 are 1.2198 mg/L and 1.8971 mg/L respectively. Although the cadmium concentrations in these two samples are lower than that of SW3 and SW4, their concentrations are still relatively high, when compared to the WHO acceptable cadmium concentration limit of 0.8 mg/L.

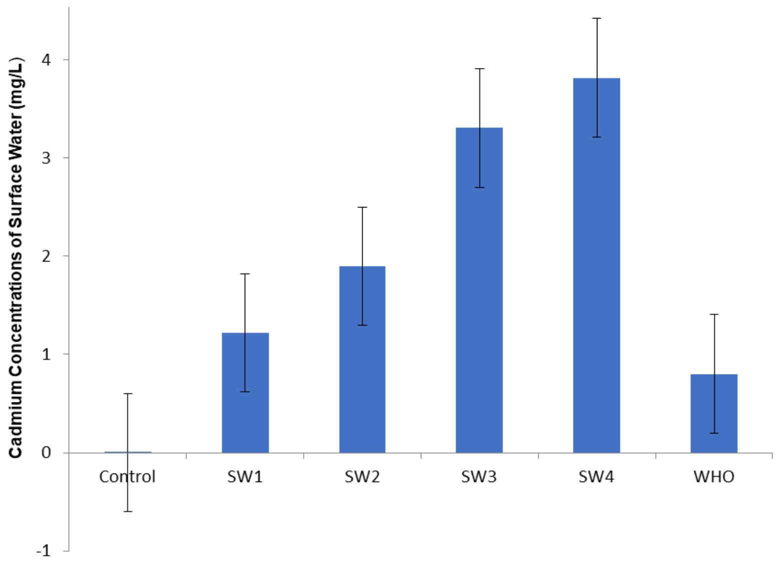

Figure 8. Cadmium concentration of the surface water in the study area

3.1.7. The Cadmium Concentration of Sediments

The results of this study show the concentrations of cadmium (Cd) in sediments from different sites. The concentrations obtained were compared to the World Health Organization (WHO) acceptable limit of 0.8 mg/L. The control samples, SD1 and SD2 showed very low cadmium concentrations of 0.0014 mg/L, 0.1319 mg/L and 0.6909 mg/L respectively (Figure 9). These values conform to WHO standards, indicating much reduced contamination in the sediment, suggesting that they are relatively not impacted by the industrial activities as regards cadmium pollution. However, samples SD3 and SD4 had appreciable cadmium concentrations of 1.76 mg/L and 2.0613 mg/L respectively. These values exceed the WHO acceptable standard of 0.8 mg/l, suggesting that these two sites are receiving cadmium from external sources.

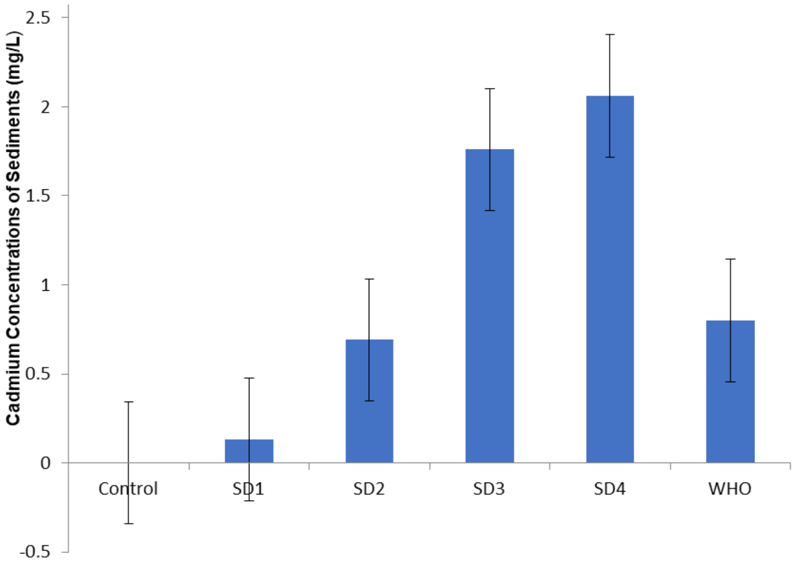

Figure 9. Cadmium concentration of the sediments in the study area

3.2. Dissussion

The assessment of physicochemical and contaminant parameters of surface water and sediments from the Okulu River reveals clear evidence of industrial influence on the aquatic environment. Variations in pH, alkalinity, total petroleum hydrocarbons (TPH), and cadmium concentrations collectively reflect early-stage to advanced ecological stress linked to anthropogenic activities.

Surface water pH was 6.2-6.6 and sediment pH was 6.2-6.7. These are weakly acidic yet within the World Health Organization (WHO) drinking water and environmental safety limits (WHO, 2017). The fact that the pH is slightly lower in the affected locations than in the control indicates that there are some slight alterations due to industrial discharges. Though these pH levels are not threatening to people at all, long exposure to slightly acidic environment may damage the ecosystem. Heavy metals become mobile and bioavailable in acidic waters, and these substances expose aquatic organisms to toxicity (Adams, 2003). Likewise, there has been a presence of similar changes in industrial waters in Nigeria where effluents decreased pH (Oladimeji et al., 2024; Ochai et al., 2024). Conversely, the less industrialised catchments had close-to-neutral or alkaline pH, which points to the role played by land use and industrial pressure on water chemistry (Atugonza et al., 2025). The slightly alkaline sediment pH in this case is similar to other Li et al. (2023)- who indicated that conditions with low pH encourage the movement of metals; usually, the neutral pH is observed in minimally disturbed systems (Zhang et al., 2022).

Unlike pH, alkalinity showed pronounced deviations from acceptable standards at impacted sites. The surface water alkalinity exceeded the WHO standard of 200 ‘/L in all the affected sites, indicating that the river has had its buffering capacity impaired. Industrial effluents high in carbonates and bicarbonates are usually the source of high alkalinity, which changes the water chemistry (Adams & Gurtz, 1993). Alkalinity will neutralise acidity; however, a high concentration will impair osmoregulation in aquatic organisms as well as altering nutrient and metal availability

(Dodds & Whiles, 2010; Wetzel, 2001). High alkalinity has been reported around Nigerian industrial areas too (Egbueri & Mgbenu, 2022), but the systems in rural areas remain within safer ranges. These figures indicate that industrial discharge is the primary cause of alkalinity imbalance.

The most severe impact of industrial activities was observed in the levels of total petroleum hydrocarbons. TPH levels in both surface water and sediments exceeded WHO acceptable levels by far, with the levels being considerably higher in the sediments. This proves that sediments are long-term sinks of hydrocarbons because of adsorption and slower depreciation (Wang et al., 2017). TPH values are extremely high at the affected locations, which means that the area has a strong petroleum contamination, similar to oil-producing zones in the Niger Delta (Nwankwoala et al., 2023). High TPH reduces dissolved oxygen, interferes with the metabolism of aquatic life and impairs reproduction and survival (Neff, 2005; Boehm & Page, 2007). Carcinogenic PAHs can also amplify ecological and human health risks (Abdel-, Mansour, 2016).

The surface water and sediment cadmium also display considerable industrial impact. Although there was no violation of WHO limits in control samples, some of the affected locations were above the allowable level, which is a sign of contamination in the area. The excessive level of cadmium is of particular concern due to its toxicity, persistence, and the ability to bioaccumulate. Other reports have indicated similar trends whereby effluent release increased cadmium content in water bodies (Afzal et al., 2024). The enhancement of sediments in definite locations is consistent with the findings that at the pollution sites, sediments become heavy-metal storage sites (Li et al., 2023), whereas in the less-disturbed ecosystems, the levels remain at background levels.

4. Conclusion

This study assessed the impact of industrial activities on the water and sediment q This study examined the impact of industrial activities on the water and sediment quality of the Okulu River using key indicators such as pH, alkalinity, cadmium, and total petroleum hydrocarbons (TPH). The results indicated that both surface water and sediments had a mildly acidic pH within WHO acceptable levels. Even though these pH levels are not harmful to human use, chronic mild acidity may affect chemical reactions, augment metal mobility, and disorganize aquatic ecosystems in the long term.

The levels of alkalinity of surface water at the affected sites were greater than the WHO allowable limits, which are a sign of disruption in the natural buffering system of the river. High alkalinity indicates high levels of anthropogenic impact, mostly due to industrial discharges, and could have an impact on water quality, nutrient dynamics, and ecosystem stability. The most alarming conclusion of the work was the very high level of TPH in surface water and sediments. All the sampled locations, such as the control, were above WHO standards, with the sediments having significantly higher levels of contamination. This confirms that sediments are long-term stores of petroleum hydrocarbons and they are as such very dangerous to the ecology and health. In some of the surface water and sediment samples, cadmium levels were also found to be high and exceeding WHO levels at the affected locations. This shows that there are localized industrial contaminations, which is worrisome because of the toxicity and persistence of cadmium. The research identifies serious pollution of the Okulu River and emphasizes the importance of the strict enforcement of the regulations, constant monitoring of the river, and efficient remedial measures.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

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Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/ or publication of this article.

Data Availability

The datasets generated during and/ or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript. AI were used only to improve readability and language under strict human oversight; no content, ideas, analyses, or conclusions were generated by AI.

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