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Distribution and Environmental Health Implications of Manganese, Zinc, Mercury, and Arsenic in Surface Water and Sediments

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Abstract

Heavy metal contamination of aquatic ecosystems is a major environmental and public health concern, particularly in regions affected by industrial activities. This study investigated the distribution and health implications of Manganese (Mn), Zinc (Zn), Mercury (Hg), and Arsenic (As) in surface water and sediments of the Okulu River in Eleme Local Government Area, Rivers State, Nigeria. Five water and five sediment samples were collected, including four sites impacted by industrial effluents and one control site. Samples were analyzed using Atomic Absorption Spectrophotometry (AAS) and Cold Vapor AAS for Mercury. Results revealed that impacted sites exhibited significantly elevated concentrations of Mn (0.131–8.409 mg/L), Zn (0.178–13.38 mg/L), Hg (0–0.081 mg/L), and As (0–4.835 mg/L), all exceeding World Health Organization (WHO) guideline limits, whereas the control site remained within safe limits. These findings indicate a substantial risk to human health and aquatic life. It is recommended that continuous monitoring, regulatory enforcement, and pollution mitigation strategies be implemented to protect the river ecosystem and surrounding communities.

Introduction

Heavy metals such as manganese, zinc, mercury, and arsenic are naturally occurring elements in the Earth's crust, but their concentrations in surface water and sediment have been increasing due to anthropogenic activities including mining, industrial discharge, agricultural runoff, and wastewater release (Chen et al., 2023; Okafor et al., 2024). These metals are persistent, non-degradable, and can accumulate in aquatic ecosystems, posing risks to ecological integrity and human health through water consumption and food chain transfer. Assessing their distribution is therefore critical to understanding their environmental fate and potential adverse effects. Surface waters receive metals via direct discharge and runoff, and sediments act as both sinks and sources of metals depending on redox and hydrological conditions. Metals bound to sediments can be remobilized back into the water column under changing physicochemical conditions, especially in disturbed or eutrophic environments.

In a study of surface waters in China's Urumqi River Basin, manganese and zinc levels in surface water were spatially varied, with upstream and midstream sites showing higher concentrations likely related to natural geology and human activities (Chen et al., 2023). Arsenic concentrations similarly exhibited spatial variability, often elevated where industrial and agricultural influences were stronger, indicating significant anthropogenic influence (Chen et al., 2023). Surface sediments often concentrate heavy metals due to adsorption and sedimentation processes. For example, research on riverine sediments of the River Kabul (Pakistan) documented measurable quantities of Mn, Zn, and Hg in sediments, reflecting combined geogenic and anthropogenic inputs (Khan et al., 2025). Although that study did not isolate As specifically, the broader pattern mirrors global observations where sediments become repositories for a suite of toxic elements including As and Hg alongside essential metals.

In Southeastern Nigeria, sediments from surface water sources used for human consumption contained elevated manganese and zinc alongside other metals (Okafor et al., 2024). These metals were deposited in bottom sediments and act as secondary pollution sources, with potential release into overlying water under changing environmental conditions (Okafor et al., 2024). Such findings highlight that even rural or small-scale agricultural watersheds can accumulate concerning metal concentrations in sediments. While manganese and zinc are essential trace elements necessary for metabolic processes, their excessive intake—particularly through contaminated water—can have adverse effects. Elevated Mn exposure is linked to neurological effects including cognitive deficits and movement disorders, especially in children (Ahamad et al, 2024). Excessive Zn exposure can lead to gastrointestinal distress and can interfere with the absorption of other essential minerals, though Zn toxicity is less severe than that of Hg or As.

Mercury and arsenic represent severe health hazards even at low concentrations due to their high toxicity and potential for bioaccumulation. Mercury in aquatic systems is often converted by microbes into methylmercury, a potent neurotoxin that biomagnifies in fish and shellfish, leading to significant exposure through seafood consumption (global meta-analyses of toxic metals point to persistent Hg risks across continents; see meta-analysis across water bodies). Chronic mercury exposure is linked to neurological and kidney damage and developmental deficits in infants exposed in utero (De-Miguel et al, 2014).

Arsenic is classified as a Group 1 carcinogen with long-term ingestion linked to cancers of the skin, bladder, lung, and other organs (Aryan et al, 2024). Chronic arsenic exposure also leads to cardiovascular, respiratory, and dermatological effects that manifest after years of exposure. Exposure through contaminated surface or drinking water remains a global public health issue, particularly in areas with geological arsenic enrichment or significant anthropogenic contamination. In the Nigerian context, evidence of sediments enriched with manganese (Mn) and zinc (Zn) showing non-cancer risks, alongside cumulative cancer risks when combined with mercury (Hg) and arsenic (As), highlights broader systemic challenges related to environmental governance, land use, and regulatory enforcement (Okafor et al., 2024). Similar to how ineffective land use charge administration undermines public revenue and welfare outcomes (Odimegwu & Odumodu, 2020; Odimegwu et al., 2018), weak environmental monitoring frameworks allow potentially hazardous metal mixtures to persist in aquatic systems without adequate risk control. Studies on land-based taxation and sustainable infrastructure financing emphasize that poor policy implementation often translates into disproportionate burdens on vulnerable populations, particularly children (Odimegwu & Anyakora, 2023).

Climate-related pressures such as erosion and desertification further exacerbate metal mobility in soils and sediments, increasing exposure pathways through water and food chains (Akanwa et al., 2024). The vulnerability of children to cumulative metal exposure mirrors broader social justice concerns raised in Nigerian legal and policy scholarship, where weak enforcement of protective laws often undermines intended public interest outcomes (Okosa, 2022; Okosa, 2023). As argued in climate adaptation and resilience studies, environmental risks disproportionately affect populations with limited adaptive capacity (Odimegwu & Ikeotuonye, 2023). Therefore, the combined health risks of ostensibly non-carcinogenic and carcinogenic metals underscore the need for integrated environmental, legal, and policy approaches that prioritize preventive regulation and child-focused environmental risk assessment (Anyakora et al., 2025; Udensi & Okosa, 2025).

Obviously, heavy metals such as lead, mercury, cadmium, and arsenic pose serious environmental health risks because they accumulate in soil, water, and living organisms. These metals often enter the environment through industrial waste, mining, improper disposal of electronics, and agricultural chemicals. Contaminated food chains and drinking water increase public health risks, especially for children and pregnant women. Educational research helps address these environmental challenges by improving science awareness. For instance, Okafor (2010) emphasized the importance of readable and well-structured science textbooks, which can help students understand environmental issues such as heavy metal pollution. Similarly, Nnorum and Okafor (2011) highlighted authentic assessment methods that encourage practical understanding of scientific problems, including environmental health risks. Studies on student motivation and modern teaching approaches, such as Ezeanyagu, Opara, and Okafor (2023) and Enem et al. (2025), further support effective learning about environmental sustainability. Ethical teaching practices (Okafor, 2019) also ensure accurate dissemination of environmental health knowledge.

The need for a study stems from growing evidence that heavy metals accumulate in the environmental and aquatic ecosystems due to industrial activities, oil spills, and agricultural runoff. Rivers in the Niger Delta region, such as the Okulu River, receive effluents from petrochemical industries and crude oil exploration, yet limited empirical data exist on how these activities influence specific heavy metals' spatial distribution and associated health risks (Okafor et al., 2024). Most regional studies focus on broader heavy metal assessments, but few isolate metals like manganese and arsenic, which have complex biogeochemical behaviors and significant health outcomes when present in high concentrations (Chen et al., 2023).

Furthermore, although mercury and arsenic toxicity is well documented globally, there is a paucity of localized research quantifying their levels in both water and sediments, and evaluating how sediment-bound metals may remobilize under changing environmental conditions (Khan et al., 2025). Current risk assessments in Nigeria often do not integrate sediment analysis with surface water data, creating a knowledge gap in true exposure pathways for communities relying on river water (Omokpariola et al., 2024). Thus, this study is crucial for targeted public health interventions and improved environmental management.

Methodology

This study adopted a analytical research design to comprehensively assess the distribution of selected heavy metals (Manganese, Zinc, Mercury, and Arsenic) in surface water and sediments of the Okulu River and to evaluate the potential health and environmental implications. The design involved systematic sampling, laboratory analysis, and comparison with international standards. Key steps included a reconnaissance survey to identify impacted and control sites, collection of primary data through water and sediment sampling, laboratory quantification of heavy metals, data presentation and statistical analysis, and interpretation of results against World Health Organization (WHO) limits. This approach allowed for both spatial and contamination-level assessment of the river system.

The study was conducted along the Okulu River in Eleme Local Government Area, Rivers State, Nigeria, located between latitude 4°35′–4°60′N and longitude 7°0′–7°15′E, covering approximately 140 km² (Junior et al, 2025). Eleme LGA is about 30 km from Port Harcourt, bordered by Oyigbo (north), Tai (east), Elelenwo (west), and Okrika/Ogu/Bolo LGA (south). The river flows through host communities such as Aleto, Ogale, and Agbonchia before emptying into the Bonny River through the Okrika creeks (Ahuchaogu et al., 2025). The Okulu River is primarily a freshwater system, although industrial activities along its course influence its water quality, potentially altering its suitability for domestic, agricultural, and aquatic uses.

A total of five water and sediment samples were collected, including four sites impacted by industrial effluents (SW1–SW4 / SD1–SD4) and one control site located at Nwenoppea. Water samples were collected using pre-washed, plastic containers rinsed with the sampled water to avoid contamination. Samples were preserved in ice-packed cooler boxes during transport to the laboratory to prevent chemical reactions and maintain integrity. Sampling points were geo-referenced and labeled to ensure accurate mapping and data analysis.

Sediment samples were collected from a depth of 0–15 cm at upper and lower attenuation zones along the river. Samples were stored in plastic bags, homogenized, and transported under cold conditions for laboratory analysis. Sampling was conducted at a 30-meter spacing interval to capture spatial variability along the river course. The study involved five surface water and five sediment samples. Four of the sampling sites were impacted by industrial activities, while one served as a control. The systematic sampling approach ensured coverage of the most affected areas and a baseline reference point for comparison. Water samples were labeled as Eleme SW1–SW4 and control, while sediment samples were labeled Eleme SD1–SD4 and control.

Physical and chemical analyses were performed at Austino Research & Analysis Laboratory Nig. Ltd, Port Harcourt, following standard protocols. Surface water samples were filtered through 0.45 µm membrane filters, acidified with nitric acid, and analyzed using Atomic Absorption Spectrophotometry (AAS) for Manganese, Zinc, and Arsenic. Mercury concentrations were determined using Cold Vapor Atomic Absorption Spectrophotometry (CVAAS). Sediment samples were air-dried, ground, sieved, and digested with a mixture of nitric and perchloric acids before AAS analysis. Quality control measures included the use of reagent blanks, triplicate analyses, standard reference materials, and daily instrument calibration. Results were expressed in mg/L for water and mg/kg for sediment and compared with WHO guideline values to evaluate compliance and health risks.

Results

The Manganese Concentration of Surface Water

Manganese is a heavy metal that can pose health and environmental risks. It is primarily released into the environment through industrial activities. In this experiment, the focus was on assessing the Manganese levels in water samples collected from various sites impacted by multinationals. The control site exhibited Manganese concentration of 0.131mg/L. This value is relatively low when compared to the levels of Manganese in the other sites, but it exceeds the WHO recommended Manganese limit of 0.005 mg/L. The sites had Manganese concentrations of 3.688 mg/L, 2.334 mg/L, 4.974mg/L and 8.409 mg/L for SW1, SW2, SW3 and SW4 (Fig. 1). These other sites exhibited Manganese levels which are very significantly higher than the WHO recommended limit of 0.005 mg/L.

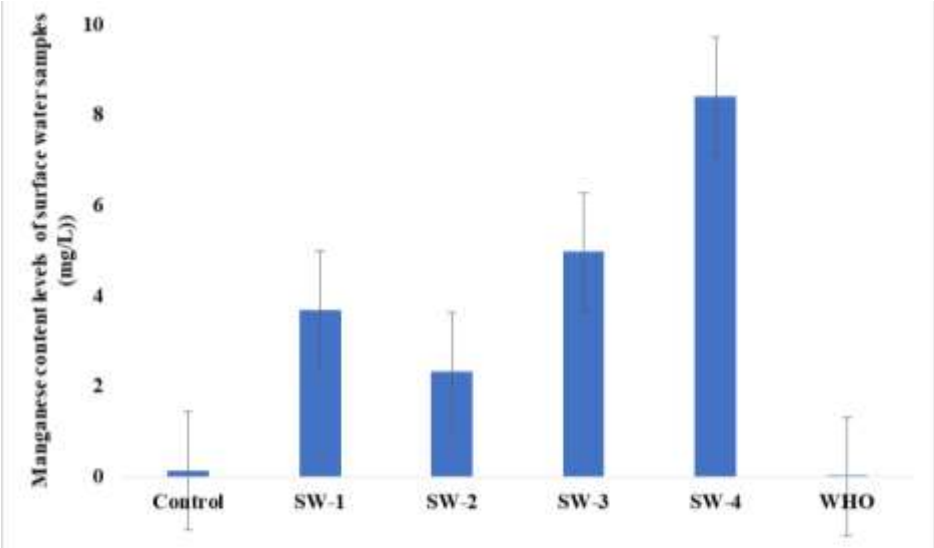

Figure 1: The Manganese Concentration of Surface Water in the study area

The Manganese Concentration of Sediment

The results of the experiment indicate the levels of Manganese in the sediment samples from various sites impacted by multinationals. Manganese can be harmful to human health and to the environment if it exists in amounts that exceed the WHO recommended limit. The values obtained for Manganese concentration in the sediment samples were compared to the World Health Organization (WHO) acceptable value of 0.005 mg/L. In the control site, 0.511 mg/L was obtained. Stations SD1, SD2, SD3 and SD4 had Manganese levels of 1.258 mg/L, 1.827 mg/L, 3.25 mg/L and 5.327 mg/L respectively (Fig 2). When comparing these values to the WHO acceptable value, it is evident that all the sites studied had Manganese levels well above the recommended limit. This suggests that the concentrations of Manganese in the sediment samples from the various sites pose significant risks to human health and the environment.

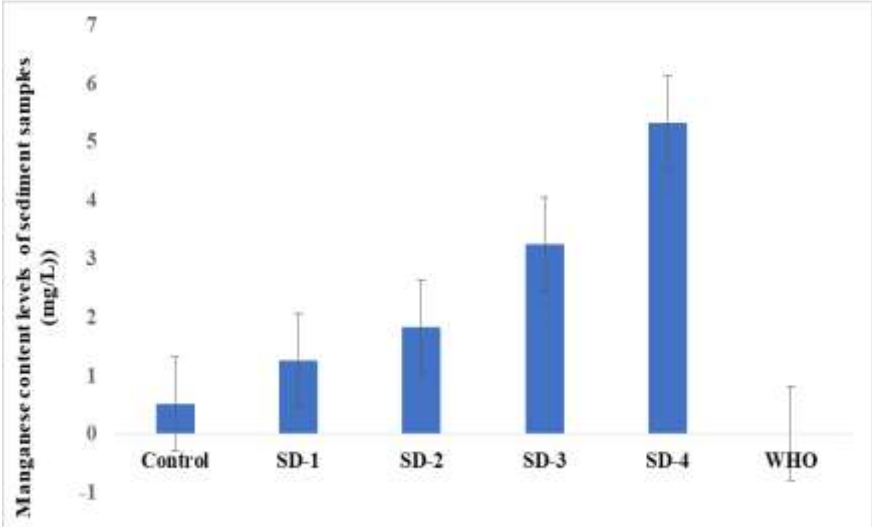

Figure 2: The Manganese Concentration of Sediment in the study area

The Zinc Concentration of the Surface Water

The results of the experiment provide insights into the levels of Zinc (Zn) in surface water from different sites impacted by multinationals. The values obtained for Zinc concentration in the surface water samples were compared to the World Health Organization (WHO) acceptable value of 0.01 mg/L The control site had zinc concentration of 0.897 mg/L. This is relatively small when compared to the levels exhibited by the other sites but exceeds the WHO recommended limit of 0.01 mg/L. 7.145 mg/L, 9.732 mg/L, 10.59 mg/L and 13.38 mg/L were Zinc levels obtained from SW1, SW2, SW3 and SW4 respectively (Fig 3). When comparing these values to the WHO acceptable value, it is evident that all of the communities studied exhibit Zinc levels exceeding the recommended limit.

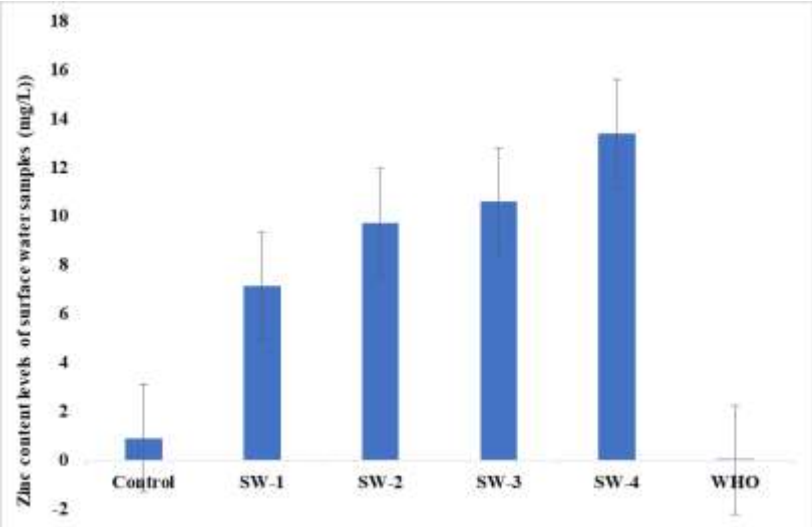

Figure 3: The Zinc Concentration of the Surface Water in the study area

The Zinc Concentration of the Sediment Samples

The results of the experiment indicate significant variations in the sediment Zinc content among the different sites studied, with elevated levels observed in all sites impacted by industries. Zinc is a naturally occurring element found in the environment. It is an essential micronutrient required for various biological processes. However, excessive levels of Zinc in the environment can have detrimental effects on both human health and the environment. The World Health Organization (WHO) has established acceptable limits for Zinc, with a recommended guideline value of 0.01 mg/L. Comparing the results obtained from the different sites to the WHO guideline value; it is evident that several areas exceed the acceptable limits, indicating a potential risk to human health. The control site had zinc concentration of 0.178 mg/L. This is relatively small when compared to the levels exhibited by the other sites but exceeds the WHO recommended limit of 0.01 mg/L. 1.791 mg/L, 3.319 mg/L, 6.001 mg/L and 9.093 mg/L were Zinc levels obtained from SD1, SD2, SD3 and SD4 respectively (Fig 4).

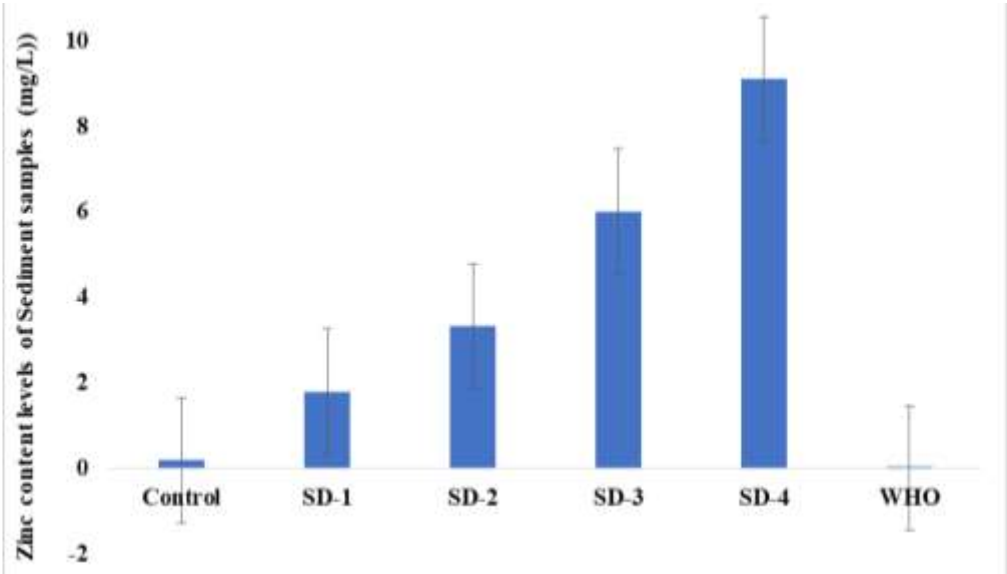

Figure 4: The Zinc Concentration of the Sediment Samples in the study area

The Mercury Concentration of the Surface Water Samples

The results obtained from the analysis of surface water samples collected from various sites revealed varying levels of Mercury (Hg) contamination (Fig 5). These findings have important implications for both environmental and human health considerations. In this experiment, the control site showed Mercury level of 0 mg/L. this is within the World Health Organization acceptable limit of 0.001 mg/L. This points out that the control site has not been impacted by multinationals in terms of Mercury contamination. Relatively comparing the value gotten from the control site to the other sites, it was ascertained that the other sites showed increased levels of Mercury contamination. SW1, SW2, SW3 and SW4 had Mercury concentrations of 0.014 mg/L, 0.033 mg/L, 0.22 mg/L and 0.044 mg/L respectively. These mercury levels exceed the WHO acceptable limit of 0.001 mg/L.

The Mercury Concentration of the Sediment Samples

The results obtained from the analysis of the sediment samples collected from various sites showed varying levels of Mercury (Hg) contamination (Fig 6). These results have important implications for both environmental and human health considerations. In this study, the control site showed Mercury level of 0 mg/L. this is within the World Health Organization acceptable limit of 0.001 mg/L. This suggests that the control site has not been impacted by multinationals in terms of Mercury contamination. Relatively comparing the value gotten from the control site to the other sites, it was determined that the other sites exhibited elevated levels of Mercury contamination. SD1, SD2, SD3 and SD4 showed Mercury levels of 0.017 mg/L, 0.032 mg/L, 0.051 mg/L and 0.081 mg/L respectively. These mercury levels exceed the WHO acceptable limit of 0.001 mg/L.

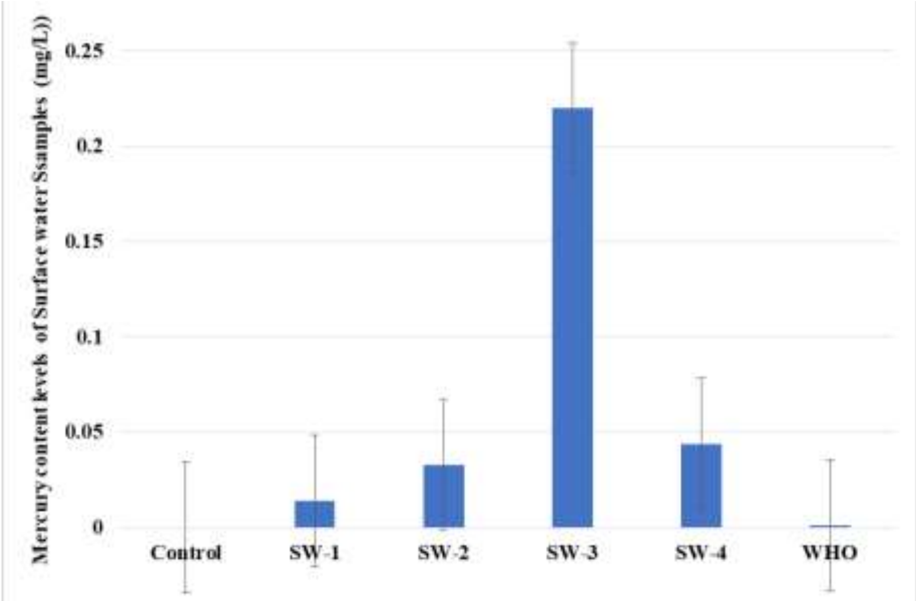

Figure 5: The Mercury Concentration of the Surface Water Samples in the study area

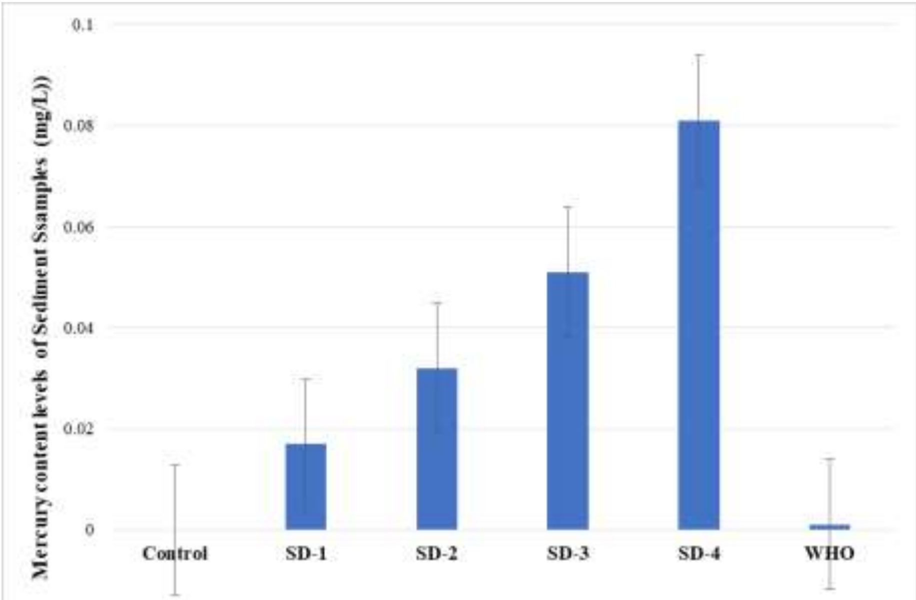

Figure 6: The Mercury Concentration of the Sediment Samples in the study area

The Arsenic Concentration of the Surface Water Samples

The results gotten from the analysis of the surface water samples collected from various sites revealed varying levels of Arsenic (As) contamination. These findings have important implications for both environmental and human health considerations. In this study, the control site showed Arsenic level of 0 mg/L. This is within the World Health Organization acceptable limit of 0.01 mg/L. This points out that the control site has not been impacted by multinationals in terms of Arsenic contamination. Relatively comparing the value gotten from the control site to the other sites, it was ascertained that the other sites showed increased levels of Arsenic contamination. SW1, SW2, SW3 and SW4 had Arsenic concentrations of 1.325 mg/L, 2.93 mg/L, 4.114 mg/L and 4.835 mg/L respectively (Fig 7). These Arsenic levels exceed the WHO acceptable limit of 0.01 mg/L.

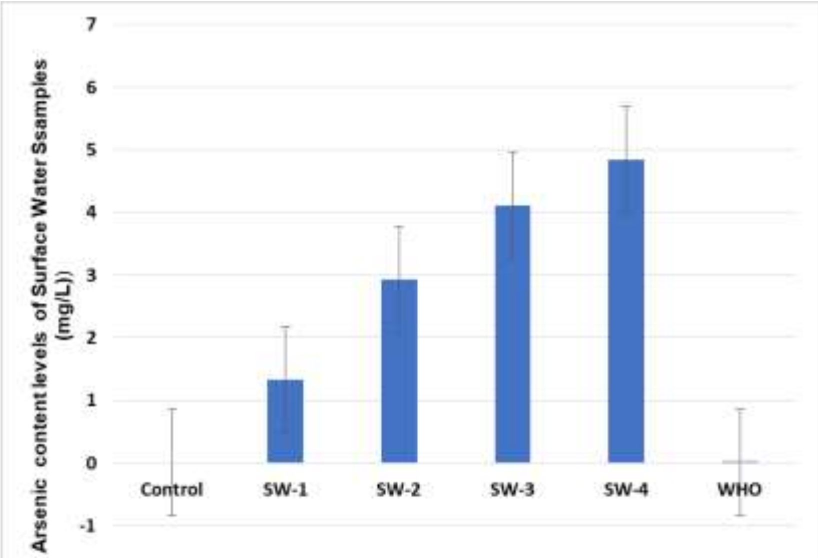

Figure 7: The Arsenic Concentration of the Surface Water Samples in the study area

The Arsenic Concentration of the Sediment Samples

The results gotten from the analysis of the Sediment samples collected from various sites revealed varying levels of Arsenic (As) contamination. These findings have important implications for both environmental and human health considerations. In this study, the control site showed Arsenic level of 0.004 mg/L. This is within the World Health Organization acceptable limit of 0.01 mg/L. This indicates that the control site has not been impacted by multinationals in terms of Arsenic contamination. Relatively comparing the value gotten from the control site to the other sites, it was ascertained that the other sites showed increased levels of Arsenic contamination. SD1, SD2, SD3 and SD4 had Arsenic concentrations of 0.218 mg/L, 0.263 mg/L, 0.505 mg/L and 0.838 mg/L respectively. These Arsenic levels exceed the WHO acceptable limit of 0.01 mg/L (Fig 8).

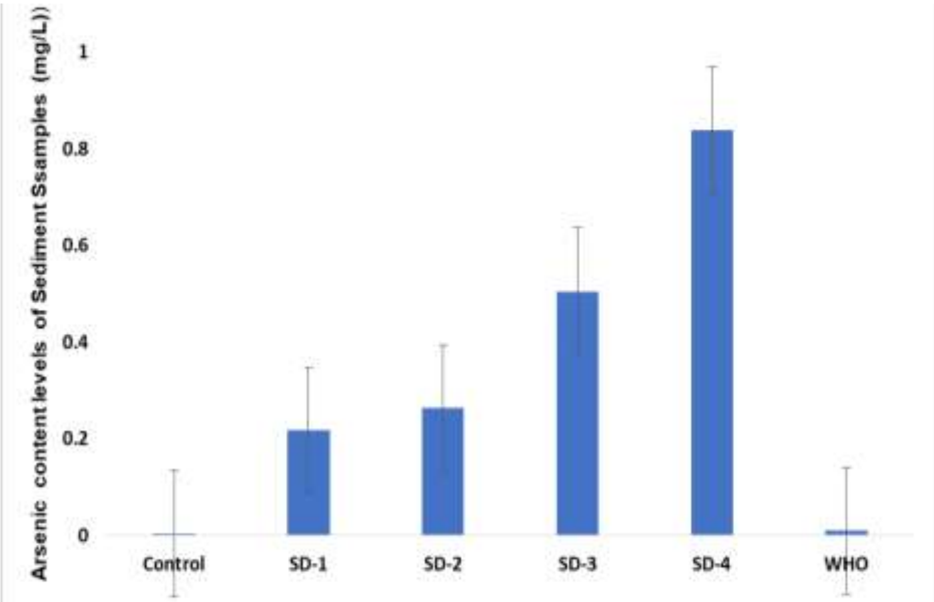

Figure 8: The Arsenic Concentration of the Sediment Samples in the study area

Discussion

The results of this study revealed elevated levels of manganese (Mn) in both surface water and sediment samples at sites impacted by multinational activities. The control site exhibited relatively low Mn in surface water (0.131 mg/L), yet this still exceeded the WHO guideline of 0.005 mg/L, and other sites recorded drastically higher concentrations (3.688–8.409 mg/L). These findings align with research by Ifite Ogwari communities, where surface waters and sediments showed elevated Mn due to anthropogenic inputs, suggesting persistent contamination in Nigerian watersheds impacted by agriculture and industrial processes (Okafor et al., 2024). In contrast, studies in relatively less industrialized rivers found heavy metal concentrations closer to guideline limits (e.g., the Pearl River Basin met WHO standards for Mn and other metals), highlighting regional differences possibly due to stronger regulatory controls and lower direct industrial discharge (Singh et al., 2024).

Sediment results similarly showed significantly elevated Mn (1.258–5.327 mg/L) when compared to the WHO acceptable limit. These elevated sediment levels are consistent with broader assessments of global freshwater sediments, where anthropogenic enrichment of Mn and other heavy metals often reflects industrial and agricultural runoff (Frontiers et al., 2025). Such enrichment can pose long-term ecological risks, as sediments act as sinks that slowly release metals back into surface waters, threatening aquatic organisms and human users (Zhou et al., 2025).

Zinc (Zn) levels in surface water also greatly exceeded WHO limits (0.01 mg/L), with control and affected sites showing values between 0.897 mg/L and 13.38 mg/L. Elevated Zn has been reported in multiple Nigerian studies, including reservoirs and rivers near industrial or agricultural zones, indicating that Zn contamination is a widespread issue in Nigerian water bodies (Okafor et al, 2023). Furthermore, seasonal river assessments noted that Zn and other metals may vary over time but often remain above guidelines in impacted areas, underscoring persistent contamination issues (Hassan et al, 2025). These findings agree with the current study's observation of consistently high Zn across all impacted sampling points.

In sediments, Zn ranged from 0.178 mg/L at the control to 9.093 mg/L at contaminated sites, again exceeding WHO limits. This corroborates evidence from systematic global analyses where Zn often exceeds recommended limits in sediments due to industrial and urban runoff contributions (Abubakar et al, 2024). Elevated Zn in sediments is often linked to high ecological risk indexes, emphasizing that sediments can serve as reservoirs for long-term contamination. Mercury (Hg) in surface waters was absent at the control but elevated (0.014–0.220 mg/L) at impacted sites, consistent with observations from Ghana's mining districts where Hg and other metals in drinking water sources frequently exceed safe levels due to mining and industrial activities (Ewool et al., 2024). Sediment Hg levels similarly exceeded WHO limits, reinforcing that Hg is a persistent contaminant in regions with industrial influence. Arsenic (As) concentrations showed a similar pattern: negligible at the control and high at impacted sites (1.325–4.835 mg/L in water and up to 0.838 mg/L in sediments). This result corroborates studies documenting As exceeding WHO thresholds in watersheds influenced by mining and industrial discharge, such as in Ghana and other Nigerian rivers, indicating that As contamination is a significant health concern in similar environments.

Conclusion

The study on the distribution and health implications of Manganese (Mn), Zinc (Zn), Mercury (Hg), and Arsenic (As) in surface water and sediments revealed that all sites impacted by industrial and multinational activities exhibited significantly elevated concentrations of these heavy metals compared to the control site and the World Health Organization (WHO) recommended limits. Manganese and Zinc were found at particularly high levels in both water and sediment, indicating substantial anthropogenic contributions likely from industrial discharges and improper waste management. Mercury and Arsenic, though naturally occurring, also exceeded permissible limits, particularly in sediments, highlighting their potential for bioaccumulation and long-term ecological risks.

These findings underscore the serious health and environmental risks associated with heavy metal contamination. Prolonged exposure to these metals may result in neurotoxicity, kidney and liver dysfunction, and other chronic health conditions, while elevated sediment levels suggest a persistent reservoir for contamination that can affect aquatic life and downstream water users. Comparisons with recent literature indicate that such contamination patterns are consistent with studies in similar industrialized regions, emphasizing that industrial and human activities are primary drivers of heavy metal pollution. The study confirms that the aquatic environment in the study area is under considerable stress from heavy metal contamination. Immediate and sustained mitigation measures, including regular water quality monitoring, stricter enforcement of industrial effluent regulations, and public awareness campaigns, are imperative to reduce exposure and protect both human health and ecological integrity. Future research should focus on the bioaccumulation of these metals in aquatic organisms and the effectiveness of remediation strategies to further safeguard the environment and public health.

References

Abubakar, M. Y., Ahmad, K. B., Mathew, T. S., Shamsudden, R., Muhammad, H. M., Haladu, M., & Adam, A. B. (2024). Heavy metal pollution in aquatic ecosystems: A review of toxic impacts and remediation strategies. *African Multidisciplinary Journal of Sciences and Artificial Intelligence*, *1*(1), 75-86.

Ahamad, M.I., Yao, Z., Ren, L., Zhang, C., Li, T., Lu, H., Mehmood, M.S., Rehman, A., Adil, M., Lu, S. and Feng, W., 2024. Impact of heavy metals on aquatic life and human health: a case study of River Ravi Pakistan. *Frontiers in Marine Science*, *11*, p.1374835.

Ahuchaogu, W. R., Osita, J. C., & Numbere, M. (2025). Impact of Pollution on Aquatic Macroinvertebrate Abundance in the Okulu River, Eleme, Rivers State, Nigeria. *International Journal of Research and Innovation in Social Science*, IX (II):3694-3701.

Akanwa, A. O., Iko-ojo, I. V., Ezeomedo, I. C., Ikegbunam, F. I., & Igwe, P. U. (2024). Effects of climatic risks on soil erosion and desertification in southern and northern Nigeria using GIS/remote sensing analysis. *Climate Crisis: Adaptive Approaches and Sustainability*, 151–170.

Anyakora, M. I., Odimegwu, C. N., Ikeotuonye, C. M., & Onwubuya-Ezeala, S. O. (2025). Prospects and challenges of adopting green maintenance approach in commercial property management for eco-friendly environment. *FESCON Conference Proceedings*, *5*(1), 244–260.

Aryan, Y., Pon, T., Panneerselvam, B., & Dikshit, A. K. (2024). A comprehensive review of human health risks of arsenic and fluoride contamination of groundwater in the South Asia region. *Journal of water and health*, *22*(2), 235-267.

Chen, Y., Yang, H., Mamattursun, A., Ablikin, K., & Mijit, N. (2023). Spatial Distribution of Al, Zn, Fe, As, Pb, Mn, Cr, and Cu in Surface Waters of the Urumqi River Basin, China, and Assessment of Risks to Ecosystems and Human Health. *Water*, *15*(17), 3079.

De-Miguel, E., Clavijo, D., Ortega, M. F., & Gómez, A. (2014). Probabilistic meta-analysis of risk from the exposure to Hg in artisanal gold mining communities in Colombia. *Chemosphere*, *108*, 183-189.

Enem, E. S., Enemuo, C. J., & Okafor, T. U. (2025). Effect of technological gamification on upper basic education students' achievement and interest in computer studies in Awka education zone. *South Eastern Journal of Research and Sustainable Development (SEJRSD)*, *18*(1).

Ewool, J., Blankson, E. R., Quartey, J. K., Kyerematen, R., & Gbogbo, F. (2024). Heavy metal concentrations in drinking water sources in two mining districts in Ghana. *Heliyon*, *10*(13).

Ezeanyagu, N. D., Opara, F. M., & Okafor, T. U. (2023). Motivation and self-esteem as predictors of secondary school students' achievement in biology in Awka educational zone of Anambra State. *UNIZIK Journal of Educational Research and Policy Studies, 16*(2), 219–228.

Hassan, M. N., Reza, A. S., Rasel, M. I. A., Mahim, M. M. A., & Jannat, M. F. T. (2025). Pollution and health risk assessment of heavy metals in surface water of the industrial region in Gazipur, Bangladesh. *Environmental Chemistry and Ecotoxicology*, *7*, 527-538.

Junior, O. S., Isma'ila, I. K., & Marcus, N. D. (2025). Assessing the Magnitude of Petroleum Spillage on Local Economies in Eleme, Rivers State, Nigeria. *Journal of Applied Ecology and Environmental Design*.

Khan, K., Younas, M., Yaseen, M., Sher, H., Maryam, A., Ibrahim, S.M., Adnan, A., Ali, A., Fawad, M., Khan, A.Z. and Khan, N., (2025). Heavy metals pollution in riverine sediments: Distribution, source, and environmental implications. *Environmental Monitoring and Assessment*, *197*(3), p.225.

Nnorum, N. R., & Okafor, T. U. (2011). Authentic assessment method in science: Study of issues for teachers. *Journal of Integrated Knowledge, 1*(1), 202–209.

Odimegwu, C. N., & Anyakora, M. I. (2023). Land value capture through land-based taxation for sustainable infrastructure finance in Anambra State, Nigeria. *COOU African Journal of Environmental Research, 4*(1), 121–138.

Odimegwu, C. N., & Ikeotuonye, C. M. (2023). Climate change adaptation: Climate change education and real estate resilience in Anambra State, Nigeria. *FESCON Conference Proceedings, 4*(1), 21–35.

Odimegwu, C. N., & Odumodu, A. I. (2020). Tax assessment and revenue performance: A case of failed Anambra State property and land use charge. *COOU African Journal of Environmental Research, 2*(1), 167–186.

Odimegwu, C. N., Anyakora, M. I., & Odumodu, A. I. (2018). A comparative analysis of land use charge laws in Anambra, Edo, Lagos and Enugu States, Nigeria. *Journal of Environmental Research, 1*(2), 14–24.

Okafor, T. U. (2010). Readability and content evaluation of recommended physics textbooks in Anambra State secondary schools. *Journal of the National Association for Science, Humanities and Education, 8*.

Okafor, T. U. (2019). Unethical practices among physics education teachers in post primary schools and tertiary institutions. *Journal of Educational Research and Reviews, 7*(4), 86–91.

Okafor, V. N., Omokpariola, D. O., Obumselu, O. F., & Eze, C. G. (2023). Exposure risk to heavy metals through surface and groundwater used for drinking and household activities in Ifite Ogwari, Southeastern Nigeria. *Applied Water Science*, *13*(4), 105.

Okafor, V. N., Omokpariola, D. O., Tabugbo, B. I., & Okoliko, G. F. (2024). Ecological and health risk assessments of heavy metals in surface water sediments from Ifite Ogwari community in Southeastern Nigeria. *Discover Environment*, *2*(1), 93.

Okosa, C. B. (2022). Unconstitutionality of compulsory dress codes in Nigeria's higher institutions. *LASJURE, 3*, 9–22.

Okosa, C. B. (2023). Cameroon's liability for downstream damage by waters from its Lagdo Dam. *Nnamdi Azikiwe University Journal of International Law and Jurisprudence, 14*, 1–15.

Omokpariola, D. O. (2025). Assessment of Physiochemical Properties and Heavy Metal Contamination in River Okrika, Rivers State, Nigeria: Implications for Surface Water Quality and Ecosystem Health. In *Limnology-Surface and Groundwater Ecosystems*. IntechOpen.

Singh, V., Ahmed, G., Vedika, S., Kumar, P., Chaturvedi, S.K., Rai, S.N., Vamanu, E. and Kumar, A., 2024. Toxic heavy metal ions contamination in water and their sustainable reduction by eco-friendly methods: isotherms, thermodynamics and kinetics study. *Scientific Reports*, *14*(1), p.7595.

Udensi, B., & Okosa, C. B. (2025). Contemporary issues on repugnancy test doctrine in Nigeria. *Chukwuemeka Odumegwu Ojukwu University Law Journal*, *9*(1), 1–18.

Zhou, Q., Chen, H., Liu, G., & Wang, X. (2024). Occurrence, sustainable treatment technologies, potential sources, and future prospects of emerging pollutants in aquatic environments: a review. *Frontiers in Environmental Science*, *12*, 1455377.