Impact Of Anthropogenic Activities on Groundwater Quality: A Case Study from Mbo LGA, Akwa Ibom State, Nigeria

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Abstract- The coastal areas of Mbo Local Government Area in Akwa Ibom State, Nigeria, are vital hubs of socioeconomic activity, including oil exploration, fisheries, tourism, and urbanization. However, these anthropogenic activities contribute to heavy metal pollution in water sources, posing risks to human health and ecosystems. This study assessed heavy metal concentrations in water samples from seven boreholes in the area using atomic absorption spectrometry. Metals analyzed included lead (Pb), zinc (Zn), copper (Cu), manganese (Mn), iron (Fe), nickel (Ni), cobalt (Co), cadmium (Cd), and mercury (Hg). Results revealed that metals like Pb, Fe, and Ni exceeded World Health Organization (WHO) permissible limits in several sites, particularly Sites 1, 5, and 7, indicating severe contamination. A Metal Index (MI) analysis underscored the urgent need for remediation in these locations. While trace metals like Zn, Cu, and Mn are essential for biological processes, their elevated levels can be toxic, alongside the highly detrimental effects of lead and cadmium. Recommendations include prioritizing remediation efforts, regular monitoring, stricter industrial regulations, and public awareness campaigns to mitigate health risks. This study highlights the necessity for sustainable management of water resources to ensure environmental and public health.

Indexed Terms- Anthropogenic activities, environmental contamination, heavy metals, pollution, health risks

I. INTRODUCTION

The coastal areas of Mbo Local Government Area of Akwa Ibom State had witnessed active ports activities, oil drilling, coastal fishery and agricultural activities, tourism-related projects, industrial activities, urbanization and other socioeconomic activities over the years. These anthropogenic activities taking place within and around coastal waters depend to a large extent, on the quality of good water for land-based activities and marine life (Sahavacharin et al, 2022). The effect of these activities and the expanding coastal populations is exerting pressure on the coastal waters, leading to negative impact on the coast, surface water and underground water due to the pollution of the water bodies (Bakari, 2014). Our oceans had become the dumping ground of trash and refuse which accumulate on our shores to the point of saturation and becoming an eyesore. These endanger marine life and also cause serious pollution in our water bodies (Ashiru et. al., 2017). Anthropogenic activities contaminate both surface and groundwater resources through discharge of pollutants related to the nature and degree of such activities. Where agricultural activities predominate, agro-chemical metabolites (such as pesticides, fertilizers etc.) and nutrients such as nitrates etc. are the major pollutants and contaminants (Akporido and Onianwa, 2015).

Groundwater is the water located beneath the ground surface in soil pore spaces and in the fractures of the rock formation (USGS, 2009). Globally, about two-thirds of fresh water is found in groundwater (Annenberg, 2012) and it is estimated that about two billion of world population depend on this, for different purposes. Further, more than 50% of the

United States population uses groundwater for drinking (USGS, 2009). In Africa including Nigeria, a majority of the population rely on ground water supplies for drinking and other household uses (Anand et al., 2019). Therefore, groundwater must be protected from contamination resulting from anthropogenic activities. Groundwater pollution is a process where human activities cause gradual or sudden changes in its natural composition thereby causing deterioration in its quality and ceases to meet the standards set for drinking, irrigation and other purposes (Musa et al., 2013) Human activities generate human wastes, municipal solid waste, industrial wastewaters which contain faecal materials that include pathogens which causes microbial pollution of waste water (AGR, 2012).

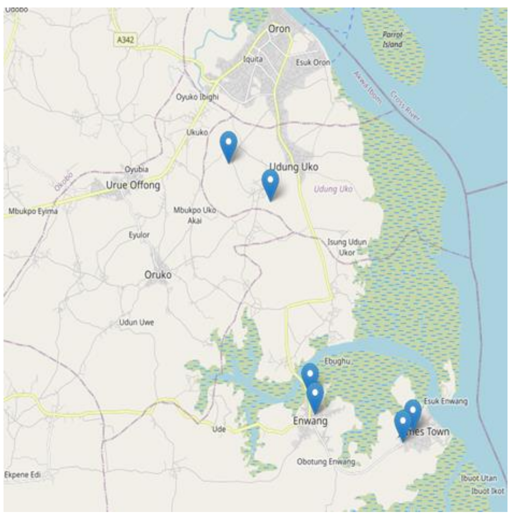
In Nigeria, studies had shown that water bodies are being contaminated by anthropogenic activities such as domestic, agricultural and industrial activities. These occur both in the urban and rural areas. A wide range of human-induced factors causing changes in the surface and groundwater quality of the study area is not recorded. It had been reported by UNICEF (2009) that 39% of world population live without access to improved sanitation while 884 million are without improved water supplies. Also, World Health Organization (2009) reported that unsafe and insufficient water is a leading cause of all infectious diseases in the world and in Nigeria; more than 3.8 million deaths are recorded annually from pneumonia and diarrheal diseases which affect mostly children under five years of age in Nigeria. Water pollution from anthropogenic activities are exacerbated by several natural processes such as precipitation, erosion, percolation and weathering of crustal materials which help to collect pollutants and contaminants from all sources and deposite them to surface and ground. The effects of these activities are in the least damage to the quality of drinking water, recreational and other purposes (Irfan and Shakil, 2012). The effects of these activities are most pronounced in the coastal areas where extreme conditions from the land coalesce with activities from the sea especially salt water intrusion. Several of these conditions have combined to worsen the socioeconomic conditions in the coastal areas of Nigeria destroying natural resources in all parts of Niger Delta.

Heavy metals are one of the major groups of toxic environmental contaminants due to their toxicity, persistence and bio accumulative properties. They originate from municipal, agricultural, and industrial wastes discharged into aquatic environments. Once the wastes enter the aquatic environment, they are transported through the water column to the sediment where they are, biomagnified and through the food chain become ecological risk to benthic organisms, fish, and humans (Sonone et al., 2020). In the coastal area, increasing population growth and pollution of the environment have resulted to overexploitation of water resources, thereby degrading the environment. These activities lead to the release of PAH, total petroleum hydrocarbon and heavy metals to the environment (Edokpayi et al., 2016). Surface and ground water sources are increasingly used as drinking water. The impact of these activities on the physiochemical and heavy metals quality on surface and ground water resources of the coastal areas of Mbo LGA has not been fully investigated. Lack of awareness regarding the water quality exposes people living in these regions to a variety of health-related problems. World Health Organization (2009) had reported that chemical contamination of water is associated with serious public health consequences. It is therefore; important to evaluate the heavy metal concentration a in the ground water resources of the coastal area of Mbo LGA in order to ascertain the potential health risks to which the population is exposed to. Such information will provide useful information to the public, government and private bodies on the effects and danger of the pollution on the coastal regions, effect on lives and how it degrades the quality of ground and surface water.

Heavy metals such as Zinc (Zn), Chromium (Cr), Mercury (Hg), Cadmium (Cd), Lead (Pb), Nickel (Ni), Iron (Fe), and Manganese (Mn) are of particular concern because they do not degrade and can accumulate in biological systems, leading to toxic effects. Water contamination due to heavy metals is a significant environmental concern, especially in areas with industrial activities, agricultural runoffs, and anthropogenic impacts. Groundwater is a crucial source of drinking water in many rural and urban communities. The residents of Mbo LGA depend heavily on groundwater for various domestic, agricultural, and commercial uses, raising concerns over its safety and quality, especially with the rise of industrial activities and potential environmental pollution sources in the region. Due to its accessibility and relatively low contamination from surface pollutants, groundwater is often considered safer than surface water. However, groundwater is also susceptible to pollution, especially from heavy metals, which can infiltrate through soil layers, posing health risks and environmental hazards. Groundwater contamination by heavy metals has been linked to various health issues, including cancer, organ damage, developmental issues in children, and other chronic health conditions. In Mbo LGA, where groundwater serves as a source of drinking water, there is limited information on the heavy metal concentrations in groundwater and the potential health implications for residents. This lack of data hampers efforts to protect community health and develop effective water quality management strategies. Evaluating the concentration of heavy metals in groundwater in Mbo LGA will provide a baseline for assessing water safety, identifying pollution sources, and implementing remediation and management strategies. The findings will be valuable for public health authorities, environmental agencies, and local governments to address groundwater contamination and mitigate health risks.

II. MATERIALS AND METHODS

Study Area: Mbo LGA is located in Akwa Ibom State, Nigeria, and is characterized by a mix of rural and semi-urban settlements. The area is known for fishing, agriculture, and emerging industrial activities, which can contribute to groundwater pollution. Mbo Local Government Area (LGA) is located in Akwa Ibom State, Nigeria, at approximately 4°39'0" N latitude and 8°19'0" E longitude, covering an area of 365 km². It is bordered to the south by the Atlantic Ocean and the Republic of Cameroon, to the north by Urue Offong/Oruko LGA, to the west by Esit Eket and Ibeno LGAs, and to the east by Udung Uko LGA. Mbo's abundant water resources make it a focal point for oil exploration and other water-based economic activities, including fishing, marine transportation, and subsistence farming. The local population speaks the Oron dialect, with minor regional variations. Population: According to the 2006 National Population Census, Mbo LGA has a population of 104,012, comprising 55,395 males and 48,617 females. Rich in natural resources, the area has salt, gravel, and clay deposits, as well as forest reserves abundant in timber, fruits (mangoes, oranges, and pears), and cash crops like palm fruit. Mbo is also home to numerous oil wells, attracting substantial human and vehicular traffic, including heavy machinery for oil drilling and exploration, often involving collaborations between Nigeria and China. The local economy is further stimulated by these activities, and Mbo consists of approximately 60 villages divided into coastal and upland regions. Geology/climate/vegetation: Mbo LGA features sedimentary rock formations, indicative of the region's coastal and geological characteristics. The climate in Mbo LGA includes two main seasons: the rainy season and the dry season. The rainy season peaks between May and July, while the dry season extends from November to February. The area receives an average annual rainfall of approximately 2000 mm. The vegetation in Mbo includes beach ridge sands and mangrove swamps, both freshwater and saltwater, supporting a range of biodiversity. Economic Activities/occupation: The primary economic activities in Mbo include fishing, subsistence farming, fuelwood exploitation, trade, and water transportation. The area's natural resources and proximity to water bodies make these activities central to the local economy. The primary occupations of Mbo residents are fishing, marine transportation, and subsistence farming. Mbo's agricultural practices are mainly peasant farming, with crops such as yam, cassava, vegetables, cocoyam, maize, coconut, palm trees, plantain, and various fruits. The farming system includes shifting cultivation. Fishing is a primary occupation and economic mainstay in Mbo, carried out in the rivers and coastal regions. The area is rich in creeks and estuaries, such as Esuk Mma, Esuk Unyeneye, Ibaka, and TomShot Island, which support fishing settlements. Mbo is known for having one of the largest fishing terminals, and fishing activities are most active between November and March, coinciding with the low rainfall period. Common fishing gear includes drag nets, gill nets, and drift nets.



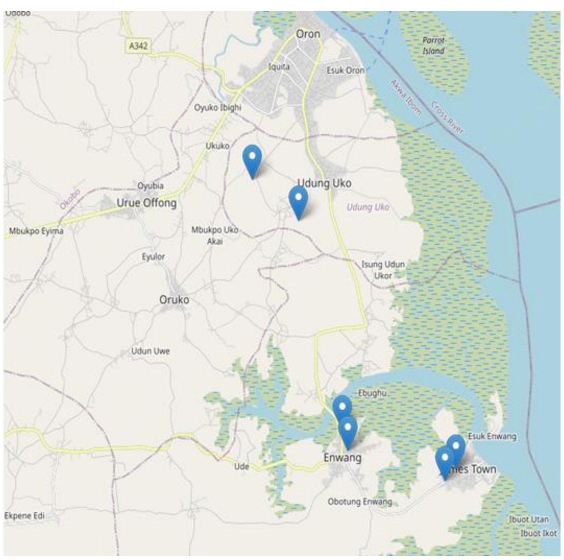


Figure 1 Map of Mbo Local Government Area, Akwa Ibom State. (Right), Sampling points (left)

Sample Collection: A total of 21 samples were collected from seven (7) boreholes using a 2.5 liters plastic container in the July, 2024. The boreholes were allowed to run for a minimum of 10-15 min before sample water was collected to guarantee the samples were from the borehole. Samples for chemical analysis were fixed with 2 mL concentrated HNO3 in-situ and preserved at 4 °C with the utilization of ice packs. The laboratory analysis for determination of metals (Pb, Cd, Cr, Ni, Fe, Zn Cu, Mn and Hg) was carried out at the Science laboratory, Akwa Ibom State, utilizing atomic absorption spectrometric (AAS, Bulk Scientific, 210/211VGp, CT, USA) with standard methods of APHA. These metals were selected because they are natural constituents of the Earth.

Heavy metal analysis: Heavy metal content, including lead, copper, mercury, cadmium, cobalt, and nickel, was analyzed at the Laboratory Unit of the Ministry of Science and Technology in Uyo, Akwa Ibom State, using an atomic absorption spectrophotometer (AAS). For the preparation, a 100 ml water sample was placed in a round-bottom flask, and 20 ml of concentrated nitric acid was added within a fume hood. The sample was heated on an electro-thermal heater for approximately 15-20 minutes until nearly dry to complete the digestion. After cooling, 50 ml of distilled water was added, and the mixture was swirled and filtered through Whatman filter paper into a 100 ml volumetric flask, then topped off with distilled water to reach the mark. The prepared solution was then analyzed with a computerized Atomic Absorption Spectrometer (969 UNICAM Thermo Elemental AAS) to detect and quantify the presence of metals, including copper, zinc, lead, iron, manganese, chromium, cadmium, arsenic, vanadium, and nickel, using the appropriate lamps and wavelengths for each metal. Calibration was performed using standard solutions of the target metals.

Metal Index: The Metal Index values reflect the extent to which metal concentrations surpass WHO safety thresholds: Values greater than 1 denote contamination that exceeds permissible safety levels. Higher Metal Index values indicate more severe contamination for specific metals. Metal index was calculated using this formula: Metal Index: MC/MAC; where MC is concentration of metals in test sample, MAC is the minimum permissible concentration of metals in water.

Data Analysis: Concentration levels of detected heavy metals were compare with WHO and permissible limits for drinking water. Descriptive statistical method (mean and standard error of mean) was used to present the data.

III. RESULTS AND DISCUSSIONS

Table 1: Mean metal concentrations in mg/dL

SITES	Lead	Zinc	Copper	Manganese	Iron	Nickel	Cobalt	Cadmium	Mercury
1	0.160± 0.006	0.493± 0.015	0.329± 0.017	0.129± 0.013	0.620± 0.027	0.489± 0.033	0.018± 0.001	0.800± 0.026	<0.001
2	0.025± 0.002	0.466± 0.018	0.322± 0.012	0.872± 0.003	0.328± 0.025	0.340± 0.013	0.019± 0.002	0.820± 0.000	<0.001
3	0.016± 0.001	0.446± 0.000	0.289± 0.000	0.726± 0.012	0.465± 0.063	0.259± 0.030	0.018± 0.004	0.933± 0.162	<0.001
4	0.015± 0.002	0.458± 0.029	1.329± 0.118	1.120± 0.118	0.155± 0.007	0.290± 0.012	0.021± 0.008	1.063± 0.137	<0.001
5	0.014± 0.002	0.424± 0.050	0.123± 0.002	0.017± 0.009	1.644± 0.131	0.410± 0.095	0.017± 0.004	0.830± 0.059	<0.001
6	0.020± 0.000	0.075± 0.013	0.157± 0.083	0.007± 0.004	0.866± 0.038	0.357± 0.025	0.019± 0.003	0.647± 0.071	<0.001
7	0.014± 0.002	0.219± 0.009	0.133± 0.026	0.534± 0.149	1.518± 0.249	0.430± 0.064	0.012± 0.001	0.940± 0.000	<0.001
WHO	0.01	0.10	1.00	0.40	0.30	0.07	0.03	0.00	0.01

(Source: Authors' work, 2024)

Table 1 above shows the mean concentration of heavy metals including lead, zinc, copper, manganese, iron, nickel, cobalt, cadmium and mercury of ground water samples in the seven sampling sites across Mbo LGA of Akwa Ibom State

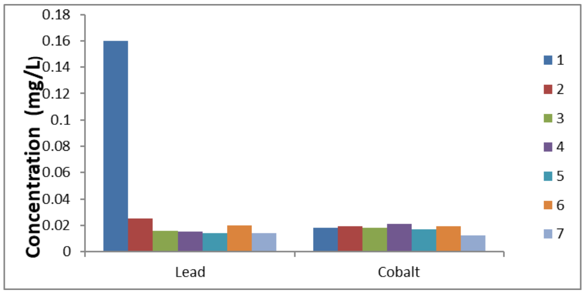


Figure 2: Mean Lead and Cobalt Concentrations in Ground water in Mbo LGA (Source: Authors' work, 2024)

Results as seen in figure 2 shows that Lead concentration in all sites exceed the WHO permissible limit of 0.01 mg/L. The highest concentration is at Site 1 (0.160 mg/L), which is significantly higher than other sites. Site 5 shows the lowest concentration (0.014 mg/L) but still exceeds the WHO limit. This work support work done by Effiong et al 2023. High lead could be runoff from contaminated soil, couple with anthropogenic activities. High intake of lead contaminated water can lead to poor mental and physical retardation in children, neurological damage, kidney disease, anemia, cardiovascular issues. Cobalt levels are below the WHO guideline across all sites as seen in figure 2, indicating no significant contamination. Site 7 shows the lowest concentration (0.012 mg/L), while Site 4 is slightly higher at 0.021 mg/L. Cobalt helps in Vitamin B12 synthesis. In high concentrations, it may results to Cardiomyopathy, respiratory irritation, thyroid dysfunction

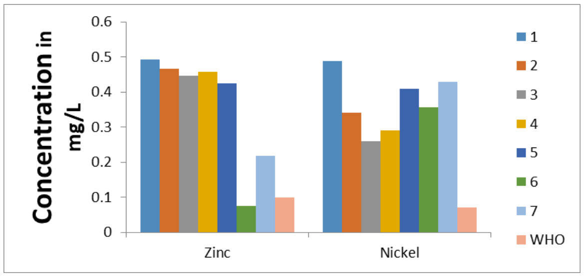


Figure 3: Mean Zinc and Nickel Concentrations in Ground water in Mbo LGA (Source: Authors' work, 2024)

Zinc levels exceed the WHO guideline of 0.10 mg/L at all sites (figure 3). Site 1 has the highest concentration (0.493 mg/L), while Site 6 has the lowest (0.075 mg/L), the only site falling below the WHO limit. (Charity et al., 2018; Okereafor et al., 2020 reported that high zinc concentration is harmful to aquatic organisms, and can also affect human well beings. Despite the fact that zinc function as an enzyme cofactor and antioxidants which qualities that protect people's skin and muscles from premature aging (Ak, 2019). In the body system, on high concentration, it can lead to gastrointestinal distress and immunological deficiency. Shuaibu et al 2023 ascertained high zinc concentrations in boreholes can cause health risks in environmental and human health. Regular monitoring and control of zinc concentrations in borehole water to reduce potential hazards is very crucial (Charity et al., 2018). High levels of zinc in boreholes can be attributed to piping and fittings (Okereafor et al., 2020). All sites exceed the WHO guideline of 0.07 mg/L for nickel (figure 3). Site 1 has the highest concentration (0.489 mg/L), significantly above the safe limit, while the lowest concentration is at Site 4 (0.290 mg/L). In trace amount, nickel is needed for enzymes function. High concentration of Ni in drinking water can lead to Respiratory issues, skin allergies, cancer, kidney and liver toxicity (Salem et al., 2000). The mean values recorded were similar with the report of Jonah et al. (2015)

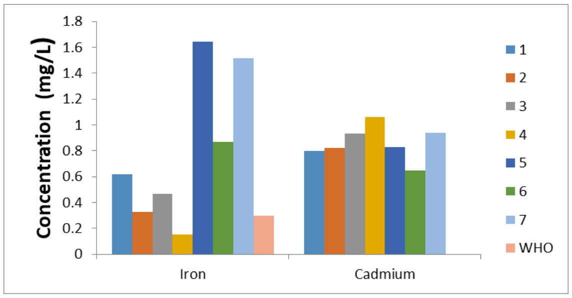


Figure 4: Mean Iron and cadmium Concentrations in Ground water in Mbo LGA (Source: Authors' work, 2024)

Iron concentrations as shown in figure 4 are above the WHO permissible limit of 0.30 at Sites 1, 3, 5, and 7, with Site 5 showing the highest level (1.644 mg/L). Sites 2 and 4 have lower concentrations, with Site 4 at 0.155 mg/L, safely below the limit. The findings were in support of work done by George & Edak, 2018; Anyanwu & Umeham, 2020a; Effiong et al, 2023 and Shaibu et al., 2024 Iron (Fe) exhibited an average value of 0.551 mg/L, surpassing the WHO, (2018). Fe is the most abundant transition trace metal on earth; it helps in oxygen transportation and immune function. However, when in high concentrations, it can lead to oxidative stress, liver damage and diabetes and cardiovascular disorders. The elevated values recorded are attributed to accumulation of domestic wastes rich in Fe at the banks of the water and runoff from the underlying soil rich in Fe oxide. As Usoh et al. (2023) reported iron enters the stream and borehole through sources beyond the dumpsite leachate, including natural weathering of rocks and soils, along with runoff from nearby agricultural activities. The presence of iron in the stream and borehole can impact water quality and ecosystem health (Emeka et al., 2020). Cadmium has no beneficiary function. Cadmium concentrations in all sites have detectable levels of cadmium, with none meeting the strict WHO standard of zero tolerance (figure 4). Site 4 has the highest concentration (1.063 mg/L), while Site 6 has the lowest (0.647 mg/L). This high value could cause kidney disease, bone demineralization, cancer and cardiovascular impact. This suggest that The findings affirm the report of Ileperuma (2000) that high content of cadmium in aquatic ecosystem linked to agricultural activities with intense application pest control chemical in a farm near water bodies. However, Nwokem 2023 regarded Cd as the most toxic metal in water even at low concentration. Its concentrations in the drinking water should not be overlooked, as it associated with enormous health risk problems.

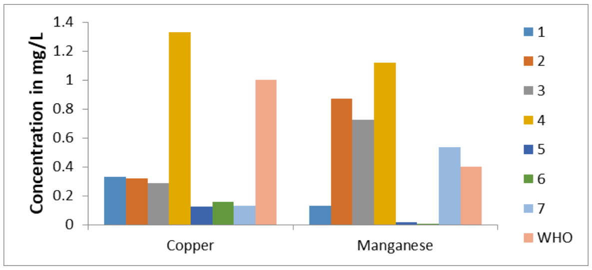


Figure 5: Mean Copper and Manganese Concentrations in Ground water in Mbo LGA (Source: Authors' work, 2024)

Copper concentrations shown in figure 5 are well below the WHO limit of 1.00 mg/L at all sites, except Site 4, which shows a sharp increase to 1.329 mg/L, exceeding the limit. The lowest copper level is observed at Site 5 (0.123 mg/L), which is within safe limits. Sites 1, 6, and 5 show manganese levels below the WHO limit of 0.40 mg/L. Sites 2, 3, 4, and 7 exceed the guideline, with Site 4 having the highest concentration (1.120 mg/L). Copper as a trace element is important in hemoglobin synthesis and iron synthesis, but when found in high concentration; it can cause liver damage, neurological effects and hypertension. The high values recorded in Site 4 may attribute to impact of precipitation and human activities around the stations. Effiong et al 2023 also observed high values of copper in some sites which was considered to be run off from industrial activities. Shaibu et al 2024) copper concentrations in all borehole water samples were below the permissible limits set by both the World Health Organization (WHO, 2018). This observation aligns with findings from Umar et al. (2023). Manganese: Manganese concentration was higher than the WHO recommended limit of 0.04 mg/l in drinking water in sites 1, 2, 3, 4 and 7. It was only in site 5 and 6 that had a lower concentration than the recommended limit as shown in figure 5. This supports work done by Nwokem et al., 2023 where higher concentrations of Manganese was observed in surface water. Manganese although it is trace element is essential for bone formation, amino acid, cholesterol, and carbohydrate metabolism. It also acts as a cofactor for enzymes in antioxidant pathways, such as superoxide dismutase. Chronic exposure of manganese in drinking water can lead to manganism, a neurological condition similar to Parkinson's disease, characterized by tremors, muscle rigidity, and cognitive decline. Excess manganese can impair liver function and contribute to hepatotoxicity. It negatively impact reproductive health and cause developmental delays in children (Ghosh et al., 2020; WHO, 2004). Mercury concentrations are consistently below the detectable limit of <0.001 mg/L across all sites.

Metal Index

	Lead	Zinc	Copper	Manganese	Iron	Nickel	Cobalt
1	16	4.93	0.33	0.32	2.07	6.99	0.60
2	2.5	4.66	0.32	2.18	1.09	4.86	0.63
3	1.6	4.46	0.29	1.82	1.55	3.70	0.60
4	1.5	4.58	1.33	2.80	0.52	4.14	0.70
5	1.4	4.24	0.12	0.04	5.48	5.86	0.57
6	2	0.75	0.16	0.02	2.89	5.10	0.63
7	1.4	2.19	0.13	1.34	5.06	6.14	0.40

(Source: Authors' work, 2024)

The Metal Index is a commonly used environmental metric that quantifies the overall level of metal contamination in a water body, sediment, or soil. It helps to determine the cumulative impact of multiple heavy metals, providing a clear indicator of pollution severity and potential risks. The Metal Index can serve as a diagnostic tool to evaluate environmental quality and potential health hazards. The Metal Index is calculated to assess the combined impact of different metal concentrations MI < 1 is low pollution which indicates that the cumulative concentration of metals is below safe thresholds; no significant contamination, While MI between 1 and 3 is moderate pollution which suggests that metal concentrations are elevated and may begin to have mild impacts on the environment and health. MI between 3 and 6 is high pollution this indicates metal contamination is considerable, suggesting a moderate risk to the ecosystem and potential health concerns for human exposure. MI > 6 indicates very high pollution –severe contamination, posing a serious threat to the environment and human health, requiring urgent remediation.

Lead had MI of 16, 2.5, 1.6, 1.4 and 2 in Sites 1, 2, 3, 5 and 6 respectively. This suggests significant lead pollution, potentially stemming from industrial discharges or vehicular emissions. Nickel metal index (6.99, 4.86, 3.7, 4.14, 5.86, 5.1, 6.14) respectively in all seven sites were above permissible levels of critical concern, four to six times above the safety threshold, suggesting a notable pollution issue. Manganese recorded metal index of 2.1 and 1.335 in site 2 and 7 respectively. Iron recorded highest metal index level of 5.06 in site 7, 5.48 in site 5, 2.07 in site 1, 1.55 in site 3 and 2.89 in site 6. Elevated levels could indicate runoff from industrial sources or natural deposits. . Copper had MI of 1.329, marginally exceeds safe limits, possibly from agricultural runoff or plumbing systems. The elevated metal concentrations might indicate industrial discharges, urban runoff, or agricultural activities in the region. The elevated levels of toxic metals, particularly lead and cadmium, pose a significant public health risk, warranting immediate investigation and remediation efforts.

There is widespread lead contamination, especially at Site 1, indicating a potential public health concern. While zinc is an essential trace element, the elevated levels across most sites could indicate anthropogenic sources such as industrial runoff or mining activities. Copper contamination seems localized, with Site 4 requiring further investigation due to the high level observed. Cadmium contamination is severe across the sites, particularly at Site 4, indicating a critical pollution problem likely from industrial waste or fertilizers. Mercury contamination appears negligible, which is positive given its high toxicity. Cobalt does not appear to be a significant concern in these areas. Cobalt does not appear to be a significant concern in these areas. There is a consistent issue with nickel contamination across the sites, suggesting industrial pollution, possibly from metal plating or electronics. Elevated iron levels in some sites could affect water quality and indicate natural iron-rich soils or anthropogenic sources. Manganese contamination is a concern at several sites, especially Site 4, suggesting possible industrial discharge or natural mineral leaching.

CONCLUSION

While trace amounts of some metals (like zinc, copper, manganese, iron, nickel, and cobalt) are essential for biological functions, their excess can lead to severe health issues. Others, like lead, cadmium, and mercury, are purely toxic and pose significant risks even at low concentrations. Monitoring and controlling heavy metal levels in the environment are crucial to preventing their harmful effects on human health and ecosystems.

RECOMMENDATIONS

Remediation should be piriotized in Sites 1, 5, and 7 due to their high Metal Index values and severe contamination. Maintain regular monitoring at all sites should be maintained with focus on Nickel, Iron, and Lead levels to observe any changes over time.nImplement stricter regulations for industries discharging heavy metals, particularly in high-contamination areas. Increase public awareness regarding the health risks of heavy metal contamination, particularly in communities near the most affected sites.

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