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Original research

Geospatial and Environmental Analysis of Heavy Metal Contamination and Water Quality in the Ubeji Axis, Warri River, Nigeria

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Abstract:
The Warri River in Delta State, Nigeria, faces increasing pollution from industrial, agricultural, and urban activities. This study assesses water quality and heavy metal contamination using in-situ measurements, laboratory analysis, and geospatial techniques. Water samples were collected from three stations, with parameters like pH, Temperature, Dissolved Oxygen (DO), Electrical Conductivity (EC), Total Dissolved Solids (TDS), and Biochemical Oxygen Demand (BOD) measured on-site. Heavy Metals (Lead, Zinc, Copper, Cadmium, and Chromium) and nutrients (Nitrate, Sulfate, and Phosphate) were analyzed using Atomic Absorption Spectrophotometry (AAS) and spectrophotometric methods. Although some parameters were within regulatory limits, significant pollution was detected. DO levels at all stations, especially Station 2 (4.02 mg/L), were below safe thresholds, indicating organic pollution. Lead and Cadmium levels exceeded permissible limits at Stations 2 and 3, with Cadmium particularly high at Station 2. Notable correlations were found between pH and Cadmium, and EC and Chromium, suggesting interactions between water chemistry and metal solubility. Geospatial analysis revealed that higher Cadmium concentrations coincided with lower TDS, while Lead and Chromium increased proportionally across stations, pointing to industrial discharge and urban runoff as key sources of contamination. The Nemerow Pollution Index (NPI) classified the river as "heavily polluted" with a score of 37.84, and the Water Quality Index (WQI) indicated poor water quality with a score of 717.60. These findings underscore the need for urgent remediation and pollution control to protect both the river ecosystem and local communities.

Keywords: Warri River, Geospatial Interpolation, Water Quality Index, Nemerow Pollution Index, Heavy Metal Contamination, Industrial and Urban Runoff, Physicochemical Parameters.

1- Introduction

Rapid urbanization, industrialization, and agricultural expansion have caused significant degradation of water quality, with contaminants from wastewater, agricultural runoff, and industrial discharges particularly heavy metals, which pose severe risks to aquatic life and ecosystem stability even at trace concentrations posing major threats to these ecosystems (Okoye and Iteyere, 2014; Briffa et al., 2020).

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In Nigeria, the Warri River in the Niger Delta is particularly important, not only for its ecological value but also for its role as a critical resource supporting industrial activities, particularly in the oil and gas sectors. The Warri River's proximity to urban centers and industrial zones makes it highly susceptible to pollution, as effluents containing hydrocarbons and heavy metals are routinely discharged into its waters, exacerbating water quality issues (Ertaş et al., 2021). The interconnected water bodies around Warri, such as Effurun Waterside, Ubeji, Ifie, and Ovwain rivers, are similarly affected, with industrial operations and urbanization placing increasing pressure on their health.

The Ubeji Axis of the Warri River, located in a tropical swamp forest belt, is particularly vulnerable to pollution from oil and gas activities. Seasonal rainfall exacerbates this by increasing runoff and mobilizing contaminants, further degrading water quality. This poses a severe threat to aquatic biodiversity and disrupts the balance of nutrients and pollutants in the river's ecosystem.

Despite the numerous studies focusing on the Warri River's water quality, including assessments of physicochemical parameters and heavy metal contamination (Adewoye and Fodeke, 2020; Akporido and Agbaire, 2017; Okaka and Odhiambo, 2019; Wokoma and Opute, 2017; Ogbeibu et al., 2014), there remains a critical gap in the integration of geospatial analysis with heavy metal pollution studies. Traditional approaches often lack the spatial and temporal resolution needed for a comprehensive understanding of pollution dynamics. Advanced geospatial techniques, such as Geographic Information Systems (GIS) and Inverse Distance Weighting (IDW) interpolation, provide more detailed assessments by mapping pollution hotspots, tracking seasonal variations, and correlating pollution data with potential sources. This integration is crucial for informed decision-making and the development of targeted mitigation strategies (DeepChand et al., 2022).

2. MATERIALS AND METHODS

The study area is located in the Ubeji Axis of the Warri River, situated within the tropical swamp forest belt between latitude 5° 31′ 5.5544″ N and longitude 5° 45′ 5.7932″ E (Fig. 1). This region experiences distinct seasonal variations due to tidal influences, with the upstream section characterized by freshwater and dense forest vegetation, while the downstream area features brackish water and sparse mangrove vegetation (Okoye and Iteyere, 2014). The Ubeji Axis, in particular, faces significant environmental pressures from industrial activities, such as oil exploration, refining, and transportation, which contribute to the release of pollutants like heavy metals and hydrocarbons into the river system. In addition, deforestation and land development in the area have led to increased soil erosion, resulting in higher sedimentation levels in the river. Seasonal flooding during the rainy season further exacerbates the dispersion of pollutants, causing them to spread throughout the river system and affect water quality.

The selection of sampling stations was based on their proximity to different pollution sources, capturing the influence of urban, industrial, and natural sites. Station 1 (5°34'50.95"N, 5°40'54.18"E) is located upstream in a freshwater zone with dense vegetation, relatively removed from direct industrial impact. This site provides a baseline for comparing water quality with downstream locations more affected by pollution, while still offering insights into the effects of urban runoff and deforestation. Station 2 (5°34'9.49"N, 5°41'11.23"E) is positioned closer to industrial facilities, where effluents from oil refining and transportation are discharged into the river. This station is critical for assessing the direct impact of industrial pollutants, including heavy metals and hydrocarbons, on water quality and sediment levels. Station 3 (5°33'9.13"N, 5°41'7.11"E) is located downstream in a brackish zone, where freshwater and saltwater mix. This site captures the cumulative effects of both upstream and industrial pollution, providing a view of how contaminants are distributed during tidal and flooding events.

By selecting these stations, the study ensures a comprehensive evaluation of water quality across the Ubeji Axis, accounting for the varying impacts of natural, urban, and industrial activities.

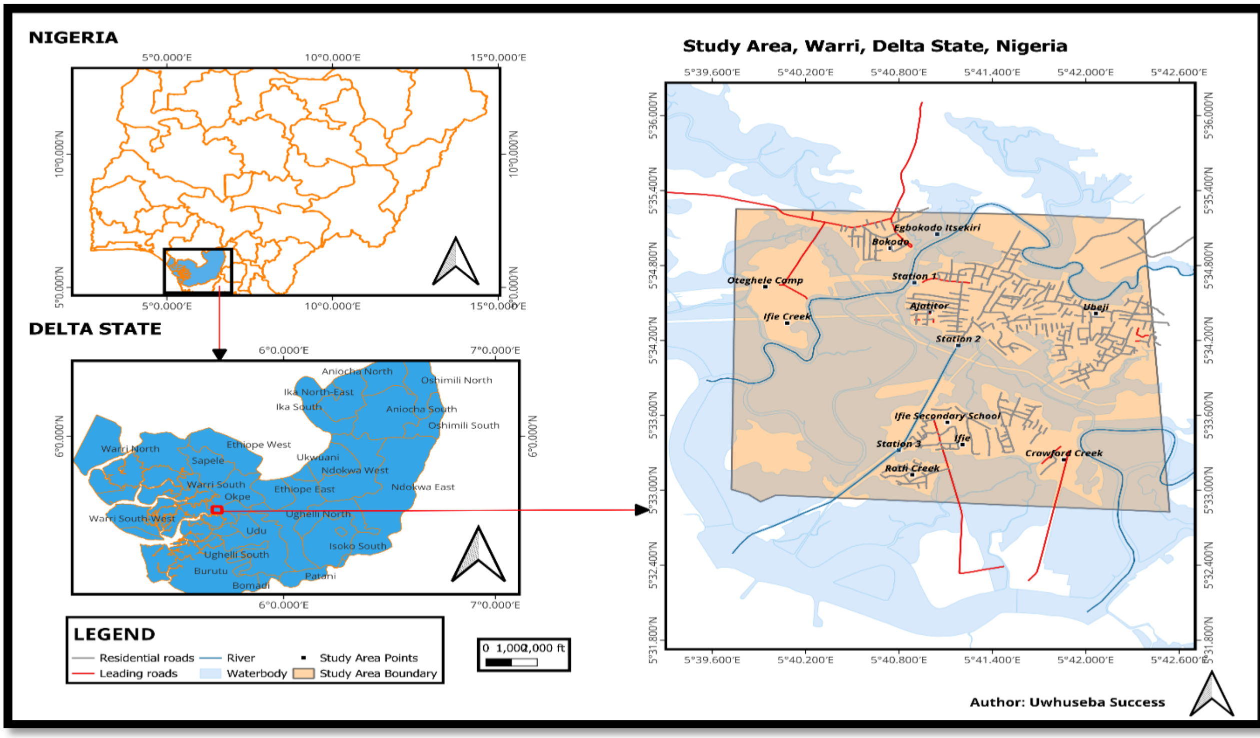

Figure 1: Map highlighting A: Nigeria, B- Delta State, C – Ubeji River, environs and sampling stations

2.1.Approach of Study

The study, conducted from June to September 2021, followed U.S. EPA guidelines for water sample collection and focused on analyzing physicochemical parameters such as Dissolved Oxygen, Biological Oxygen Demand, heavy metals, and nutrients. Standard methods were employed for analysis, with samples processed at the Animal and Environmental Biology Laboratory and the Advanced Research Center at Delta State University. Quality control measures included regular equipment calibration, the use of blanks and duplicates to ensure result accuracy, and data validation through statistical analysis. Geospatial modeling was performed using QGIS Desktop 3.38.2, utilizing the Inverse Distance Weighting (IDW) interpolation and the Contour tool to map spatial distributions of pollutants and identify hotspots. Statistical techniques such as ANOVA, Pearson correlation, and Canonical Correspondence Analysis (CCA) were used to explore relationships between parameters. The Nemerow's Pollution Index (NPI) and Water Quality Index (WQI) were calculated to provide a comprehensive evaluation of water quality, standardizing measured concentrations against regulatory limits to assess pollution levels across the Warri River.

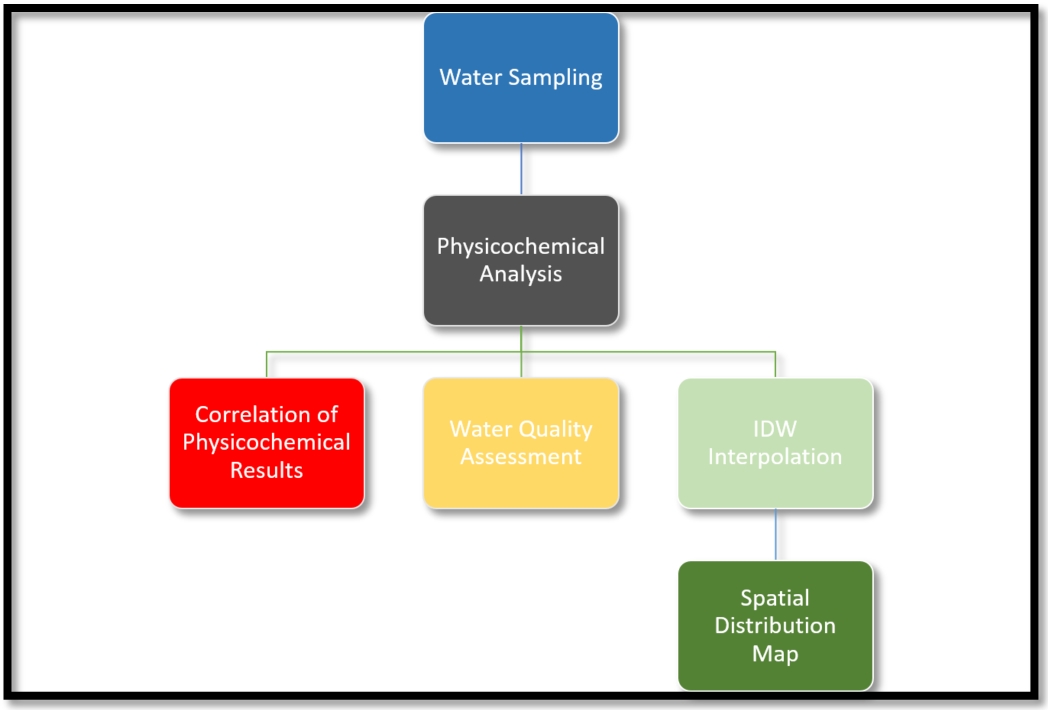

Fig.2: Methodology Flowchart

2.2.Sample Collection

Sample were collected from June to September 2021, following the U.S. EPA guidelines for sampling unpreserved classical chemistry constituents (2016). Prior to sample collection, all sampling bottles and caps were thoroughly rinsed with distilled water to avoid contamination. In-situ measurements of Temperature, pH, electrical conductivity (EC), and Total Dissolved Solids (TDS) were recorded using a calibrated digital meter (OEM TPH01139), adhering to standard calibration protocols and precautionary measures.

Collected water samples were preserved in an icebox and transported to the Animal and Environmental Biology Laboratory at Delta State University for initial analysis of Dissolved Oxygen (DO) and Biological Oxygen Demand (BOD). Subsequent analyses of Nitrate, Phosphate, Sulfate, Chromium, Cadmium, Copper, Lead and Zinc were performed at the Advanced Research Center, Delta State University, Abraka. These analyses utilized a Thermo Scientific Genesys 10S UV-Vis spectrophotometer. Metal digestion and analysis were carried out in accordance with the APHA (2017) Standard Methods for the Examination of Water and Wastewater, 23rd Edition

2.3.Geospatial Modelling – IDW technique

This study employed advanced GIS techniques to integrate and analyze spatial and non-spatial data, providing a detailed assessment of water quality across the study area. Using QGIS Desktop 3.38.2, the Inverse Distance Weighting (IDW) interpolation method was selected to create spatial distribution maps. IDW was chosen over other interpolation methods, such as kriging or spline, due to its simplicity, efficiency, and suitability for environmental data with localized sampling. IDW assumes that spatially closer points are more similar, meaning the predicted water quality at a given location is heavily influenced by nearby measured values, making it ideal for the river environment where pollution often disperses locally from specific sources.

The general formula for the IDW interpolation method is:–

$$Z(S_o) = \frac{\sum_{i=1}^{N} \frac{Z\,(S_i)}{d_i^P}}{\sum_{i=1}^{N} \frac{1}{d_i^p}}$$

Where,

$Z(S_o)$ = Interpolated value at the unsampled location S_o

$Z\,(S_i)$ = Known value at the sampled location S_i

$d_i =$ Distance between S_o and S_i

p = Power parameter

N = Total number of sampled points used in interpolation

The Inverse Distance Weighting (IDW) interpolation method and the Contour tool in QGIS were essential for visualizing the spatial distribution of nutrients and heavy metals across the Warri River. IDW was particularly effective in generating smooth, intuitive maps by estimating values at unsampled locations based on the assumption that points closer together have more similar values. This allowed for a clear representation of how pollutants like Nitrates, Phosphates, and heavy metals are distributed, highlighting the impact of nearby land-use activities such as agriculture, urbanization, and industrial operations. The use of IDW helped identify pollution hotspots, providing valuable insights into areas where water quality interventions may be needed.

In addition to the IDW method, the Contour tool in QGIS was used to create contour lines, offering a detailed visualization of water quality gradients. This enhanced the analysis by allowing for a clearer depiction of concentration variations throughout the river. The contour maps helped highlight spatial trends and provided a better understanding of how pollutants disperse from their sources.

The combination of IDW interpolation and contour mapping allowed for detailed spatial analysis of water quality, providing insights into how pollutants like heavy metals and nutrients are distributed across the Warri River. These techniques highlighted pollution hotspots, offering valuable information for targeted water quality interventions. Despite the assumption in IDW that water quality changes gradually, which may not always capture the complexity of dynamic river environments, the method proved highly effective in visualizing broad trends and pollution gradients in this study.

2.4.Statistical Analysis

The data were summarized as mean values with standard deviations using Microsoft Excel. A one-way ANOVA was conducted to determine significant differences in the concentrations of physicochemical parameters and heavy metals among sampling stations. Tukey's pairwise post hoc test was used to identify specific sources of significant differences, with a significance level set at $p < 0.05$. Pearson correlation coefficients were computed to explore linear relationships between physicochemical parameters and heavy metal concentrations. Canonical Correspondence Analysis (CCA) was performed to assess multivariate relationships and understand how physicochemical parameters and metal concentrations collectively influence water quality

2.5.Water Quality Assessment

2.5.1. Nemerow`s Pollution Index (NPI)

Nemerow's Pollution Index (NPI) provides a comprehensive assessment of water pollution by evaluating individual pollutants and their combined effects. Twelve relevant water quality parameters were selected. Afterwards, measurement of the concentration of each parameter in the water sample was incorporated. These measurements were standardize against regulatory values to determine their sub-indices. For each parameter, the sub-index (SI) was calculated by dividing the measured concentration (C) by the permissible limit or standard (S):

$$SI = \frac{Cn}{Sn}$$

Where:
Cn = Concentration of nth parameter
Sn = Prescribed standard limit

Nemerow's Pollution Index was calculated for using the following formula, which takes into account both the maximum sub-index and the mean sub-index:

$$NPI = \sqrt{\left(\frac{SI_{max}^2 + SI_{mean}^2}{2}\right)}$$

Where:
SI_{max} is the maximum sub-index among all parameters.
SI_{mean} is the mean sub-index, calculated as the average of all sub-indices

2.5.2. Water Quality Index (WQI)

Twelve parameters were employed to deduce the Water Quality. Calculation of Water Quality Index was performed following the Weight Arithmetic Index Method by brown et al., 1972. First the Unit weight (W_n) for each parameter was calculated using:

$$Wn = \frac{K}{Sn}$$

Where: $K = \frac{1}{\frac{1}{Si}+\frac{1}{S2}+\frac{1}{S3}+ \ldots\ldots\frac{1}{Sn}} = \frac{1}{\sum\frac{1}{Sn}}$

S_n = Standard desirable value for n^{th} parameter
The Sub-index (Q_n) was calculated for using:

$$Qn = \frac{[(Vn - Vo)]}{[(Sn - Vo)]} \times 100$$

Where V_n = mean concentration of n^{th} parameter
S_n = standard desirable value of nth parameter
V_o = Actual value of parameter in uncontaminated water

The WQI was calculated using:

$$WQI = \frac{\sum Qn}{\sum Wn}$$

3. RESULTS AND DISCUSSION

3.1.Geospatial interpolation and Physicochemical Results

Table 1: Mean, ANOVA and Tukey HSD summary of physicochemical parameters of Warri River (with range in parenthesis)

Parameter	Station 1 (mean ± std dev) (Range)	Station 2 (mean ± std dev) (Range)	Station 3 (mean ± std dev) (Range)	ANOVA p-value	NESREA Standard	WHO Standard
pH	6.215 ± 0.090a (6.12–6.31)	6.258 ± 0.071a (6.20–6.33)	6.245 ± 0.031a (6.22–6.27)	0.743	6.5–8.5	6.5–8.5
Temperature (℃)	25.90 ± 1.67a (24.23–27.57)	26.33 ± 1.87b (24.46–28.20)	27.63 ± 1.65ab (25.98–29.28)	0.38	40 ℃	NA
EC (µS/cm)	159 ± 63.00a (96–222)	123 ± 34.51b (88–158)	144 ± 63.74ab (80–208)	0.655	1000 µS/cm	1000 µS/cm
TDS (mg/l)	78.25 ± 29.58a (48.67–107.83)	61.00 ± 10.54a (50.46–71.54)	65.25 ± 16.73a (48.52–81.98)	0.64	500 mg/l	1000 mg/l
DO (mg/l)	4.6 ± 0.85a (3.75–5.45)	4.0 ± 1.52a (2.48–5.52)	4.15 ± 0.67a (3.48–4.82)	0.89	6 mg/l	6 mg/l
BOD (mg/l)	2.13 ± 0.62a (1.51–2.75)	1.35 ± 1.68a (0–3.03)	2.18 ± 0.82a (1.36–3.00)	0.538	4 mg/l	3 mg/l
Phosphate (mg/l)	0.211 ± 0.097a (0.11–0.31)	0.226 ± 0.087a (0.14–0.31)	0.229 ± 0.086a (0.14–0.31)	0.955	3.5 mg/l	5 mg/l
Sulfate (mg/l)	0.611 ± 0.140a (0.47–0.75)	0.422 ± 0.216ab (0.21–0.64)	0.209 ± 0.206b (0.003–0.42)	0.045	100 mg/l	250 mg/l
Nitrate (mg/l)	0.235 ± 0.107a (0.13–0.34)	0.212 ± 0.123a (0.09–0.33)	0.172 ± 0.051a (0.12–0.22)	0.669	50 mg/l	50 mg/l
Cadmium (mg/l)	0.286 ± 0.076a (0.21–0.36)	0.675 ± 0.113b (0.56–0.79)	0.616 ± 0.166b (0.45–0.78)	0.003	0.003 mg/l	0.003 mg/l
Chromium (mg/l)	0.144 ± 0.064a (0.08–0.21)	0.122 ± 0.044a (0.08–0.17)	0.135 ± 0.057a (0.08–0.19)	0.857	0.05 mg/l	0.05 mg/l
Copper (mg/l)	0.569 ± 0.137a (0.43–0.71)	0.762 ± 0.057b (0.70–0.82)	0.628 ± 0.040ab (0.59–0.67)	0.035	1 mg/l	2 mg/l
Lead (mg/l)	1.403 ± 0.213a (1.19–1.62)	1.657 ± 0.303a (1.35–1.96)	1.693 ± 0.194a (1.50–1.89)	0.235	0.01 mg/l	0.01 mg/l
Zinc (mg/l)	0.755 ± 0.195a (0.56–0.95)	0.853 ± 0.106a (0.75–0.96)	0.786 ± 0.133a (0.65–0.92)	0.648	5 mg/l	3 mg/l

4. N/A = Not applicable.
5. Values with the same letters (a, b, ab) indicate statistically similar groups.

Table 1 outlines the mean values of various parameters measured at three stations in the Warri River, including their standard deviations, ANOVA p-values, NESREA standards, and WHO standards. The pH levels (6.12–6.33) at all stations fall below the NESREA standard (6.5–8.5) and the WHO guideline (6.5–8.5), but there are no significant differences between stations ($p = 0.743$). Temperatures are highest at Station 3 (27.63°C), though all stations are well below the NESREA limit (40°C), and there is no significant variation in temperature across stations ($p = 0.38$). Electrical conductivity (80–222 µS/cm) and Total Dissolved Solids (48.52–107.83 mg/L) are both well within the NESREA standards (1000 µS/cm for EC, 500 mg/L for TDS) and the WHO standards (1000 µS/cm for EC, 1000 mg/L for TDS), with no significant differences between stations ($p = 0.655$ and $p = 0.64$, respectively).

Dissolved Oxygen (DO) levels (2.48–5.52 mg/L) are below the NESREA and WHO standards (6 mg/L), but there is no significant variation between stations ($p = 0.89$). Biochemical Oxygen

Demand (BOD) values at all stations remain below the NESREA limit of 4 mg/L and the WHO limit of 3 mg/L, with no significant differences across stations (p = 0.538). Phosphate (0.11–0.31 mg/L) and Nitrate (0.09–0.34 mg/L) levels are well below their respective NESREA (3.5 mg/L and 50 mg/L) and WHO limits (5 mg/L for phosphate and 50 mg/L for nitrate), with no significant differences (p = 0.955 and p = 0.669).

Sulfate concentrations display significant differences between stations (p = 0.045), with the highest levels recorded at Station 1 (0.611 mg/L), though all values are below the NESREA limit (100 mg/L) and WHO guideline (250 mg/L).

For heavy metals, Cadmium levels are significantly higher at Stations 2 and 3, far exceeding the NESREA and WHO limit (0.003 mg/L) (p = 0.003). Chromium levels exceed the NESREA and WHO limits (0.05 mg/L) at all stations, but there is no significant variation between stations (p = 0.857). Copper concentrations are significantly elevated at Station 2 (p = 0.035), but all values remain below the NESREA limit (1 mg/L) and the WHO limit (2 mg/L). Lead concentrations at all stations exceed the NESREA and WHO limits (0.01 mg/L), though no significant variation is observed (p = 0.235). Zinc levels remain well within the NESREA limit (5 mg/L) and WHO guideline (3 mg/L), with no significant differences across stations (p = 0.648).

The geospatial patterns (Fig.3) and water quality concerns in the Warri River highlight significant variations in pH levels across different stations, influenced by surrounding land-use activities. At Station 1, near residential and commercial areas of Egbokodo Itsekiri Waterside, the pH ranged from 6.21 to 6.24, indicating acidic conditions likely due to urban runoff and organic waste, which negatively impacts water quality and aquatic life. Station 3, near the forested Ifie Community, had slightly more stable pH values between 6.24 and 6.25, benefiting from natural surroundings that help buffer pH fluctuations. In contrast, Station 2, located near industrial zones around Talisco New Planet Sport Bar, exhibited mildly alkaline conditions, with pH values between 6.25 and 6.26, possibly due to industrial discharges.

The temperature distribution (Fig.4) in the Warri River reflects geospatial patterns influenced by surrounding land-use types. Cooler temperatures at Station 1 (26°C–26.4°C) are linked to nearby water bodies and vegetation that provide shading, enhancing Dissolved Oxygen (DO) levels and fostering better aquatic conditions. In contrast, the higher temperatures recorded at Station 2 (26.4°C–26.7°C) and Station 3 (27°C–27.4°C) result from urban heat retention and less vegetated, open areas, leading to lower DO levels and diminished water quality.

Electric Conductivity (EC) results in the Warri River indicate distinct patterns across the stations (Fig.5). The highest EC levels are observed at Station 1 (148–153 µS/cm), which likely reflects the impact of urban runoff and waste discharge from nearby urban areas. This elevated ionic concentration suggests a reduction in water quality at this location. In contrast, Station 2, with slightly lower EC values (126–135 µS/cm), shows the beneficial effects of surrounding natural vegetation, which acts as a buffer against pollution, helping to maintain better water quality. Station 3 (141–143 µS/cm) presents intermediate values, pointing to the moderating role of its forested environment, further enhancing water quality relative to Station 1.

In the Ubeji Axis of the Warri River, TDS levels range from 61.00 mg/L at Station 2 to 78.25 mg/L at Station 1, both well below the NESREA limit of 500 mg/L and the WHO limit of 1,000 mg/L. These values are significantly lower than the 1,198 mg/L reported by Akinwole et al. (2022) in other parts of the Warri River, and the 250–350 mg/L and 270–385 mg/L ranges noted by Irabor et al. (2010) and Ushurhe et al. (2023) for the Ethiope River, respectively. Higher TDS levels reported for Bomadi Creek (200–300 mg/L) by Chukwujindu et al. (2023) indicate greater pollution impacts in those areas compared to the Ubeji Axis. In contrast, studies from Kombolcha City, Ethiopia (Adamu et al., 2023), reported TDS levels ranging from 194 mg/L to 759.5 mg/L, and the Mundeswari River in India (Ghosh and Panigrahi, 2023) recorded values from 78 mg/L to 601 mg/L, averaging 272.48 mg/L. Alitane et al. (2024) found TDS levels in Morocco ranging from 285 mg/L to 1,001 mg/L, indicating significant variability influenced by urban impacts. Overall, the TDS levels in the Warri River, including Station values of 77.3–78.8 mg/L at Station 1 and 63.5–66.2 mg/L at Stations 2 and 3, demonstrate minimal inorganic material and reflect a lower impact of pollution compared to other studied rivers; underscoring the importance of natural landscapes in maintaining water quality.

Dissolved Oxygen (DO) levels in the Warri River vary by station, reflecting the impact of land use. Station 1 has DO levels between 4.97 and 5.04 mg/L, benefiting from increased water movement and reduced organic pollution, though these values remain below the WHO standard of 6 mg/L for optimal aquatic health. These findings align with previous reports of low DO levels, such as the 3.5 to 4.0 mg/L observed by Okoye and Iteyere (2014) in the Warri River and 3.8 to 4.5 mg/L in Bomadi Creek (Chukwujindu et al., 2023). In contrast, the Ethiope River recorded significantly higher DO levels (6.5 to 7.8 mg/L) (Irabor et al., 2010; Ushurhe et al., 2023), indicating healthier aquatic environments with less organic pollution. Similarly, Ghosh and Panigrahi (2023) reported DO levels in the Mundeswari River ranging from 2.14 to 9.23 mg/L, with an average of 5.56 mg/L, reflecting varying degrees of organic pollution. Overall, these comparisons highlight the detrimental effects of urbanization on DO levels, while natural areas contribute to better oxygen availability for aquatic life. The consistent low DO levels in the Warri River emphasize the need for ongoing monitoring and effective pollution control measures, not only in this river but also in other regions facing similar challenges.

The Biological Oxygen Demand (BOD) levels in the Warri River vary across stations, reflecting different pollution sources. Station 1 has moderate BOD values (1.8–2.1 mg/L) due to urban runoff, Station 2 has lower values (1.4–1.5 mg/L) likely from better wastewater management, while Station 3 shows the highest BOD (up to 2.4 mg/L) due to industrial and agricultural pollution. Despite these variations, BOD levels remain below the NESREA limit of 4 mg/L, indicating moderate organic pollution and an improvement from past assessments. Compared to other Nigerian rivers, Warri River's BOD is similar to the Ethiope River (2.3–3.2 mg/L) but lower than Bomadi Creek (3.0–3.8 mg/L) and industrial zones (up to 7.2 mg/L). Globally, it remains less polluted than highly industrialized regions, such as the Mundeswari River, where BOD levels can reach 8.49 mg/L, though localized pollution, particularly at Station 3, warrants attention.

The spatial variations in nitrate, phosphate, and sulfate levels in the Warri River reflect different land-use patterns and pollution sources, highlighting the influence of human activities and natural buffers. Nitrate levels are highest at Station 1 due to urban runoff and fertilizers, while the lowest levels at Station 3 indicate the filtering effect of vegetation. Compared to other Nigerian and global rivers, the Warri River exhibits relatively low nitrate concentrations, suggesting less severe nutrient pollution. Similarly, phosphate levels vary across stations, with Station 3 recording the highest due to agricultural runoff, while Station 1, despite its high nitrate levels, has the lowest phosphate concentrations. Compared to more polluted Nigerian and global rivers, phosphate levels in the Warri River are moderate, reinforcing the idea that while human activities contribute to nutrient loading, the pollution intensity is lower than in heavily impacted regions.

Sulfate levels, however, contrast with nitrate and phosphate trends, showing an inverse relationship, with the highest concentrations at Station 1 due to industrial discharges and natural mineral dissolution. Compared to Nigerian and global studies, sulfate levels in the Warri River remain considerably lower, particularly in less industrialized areas like Station 3, where vegetation buffers pollution. However, localized industrial activities at Station 1 contribute to elevated sulfate levels, aligning with global trends where industrialization significantly influences sulfate pollution. These findings emphasize the need for targeted pollution control, as even moderate pollution levels can contribute to long-term ecosystem degradation. The Warri River's lower pollution levels compared to highly industrialized areas indicate that with proper management, its water quality can be preserved, preventing the severe pollution observed in more impacted water bodies.

The findings from the Warri River, particularly in the Ubeji Axis, indicate critical environmental and public health concerns, with Cadmium (0.286–0.675 mg/L), Chromium (0.122–0.144 mg/L), and Lead (1.403–1.693 mg/L) levels significantly exceeding both the National Environmental Standards and Regulations Enforcement Agency (NESREA) and World Health Organization (WHO) standards. The WHO guideline for Lead in drinking water is 0.01 mg/L, far lower than the levels recorded in the Ubeji Axis. Similarly, the WHO limit for Cadmium is 0.003 mg/L, which pales in comparison to the concentrations observed in this study, posing significant risks to human health and aquatic ecosystems. Chromium, especially in its hexavalent form, also exceeds the WHO standard of 0.05 mg/L, highlighting the potential for serious health impacts like respiratory problems and cancer (Briffa et al., 2020). In comparison, Irabor et al. (2010) and Ushurhe et al. (2023) reported much lower heavy metal concentrations in the Ethiope River, with Cadmium, Chromium, and Lead levels all well within WHO and NESREA limits. This stark contrast underscores the severity of pollution in the Warri River, particularly in the Ubeji Axis, which is heavily affected by industrial activities, notably from oil and gas operations. Studies by Adewoye and Fodeke (2020) and Akporido and Agbaire (2017) similarly confirm the persistent contamination of the Warri River, identifying industrial effluents as a major source.

Lead levels in the Ubeji Axis (1.403–1.693 mg/L), which far exceed both the NESREA limit of 0.05 mg/L and the WHO limit of 0.01 mg/L, are particularly alarming, especially for communities that rely on the river for drinking water and food. Chronic Lead exposure has well-documented links to neurological damage in children and cardiovascular disease in adults (Okaka and Odhiambo, 2019). Similarly, Cadmium levels (0.286–0.675 mg/L) greatly exceed both NESREA (0.01 mg/L) and WHO (0.003 mg/L) limits, raising concerns over kidney damage and bone disease (Wokoma and Opute, 2017). Chromium concentrations, although within the NESREA standard, exceed the WHO limit of 0.05 mg/L, posing carcinogenic risks. When compared to global water bodies like the Yamuna River in India or the Citarum River in Indonesia, which are also heavily polluted by industrial discharges, the Warri River exhibits similar patterns of heavy metal contamination. However, zinc, cadmium, and lead levels in the Warri River remain slightly lower than in these extremely polluted rivers, indicating that while the situation is critical, it has not yet reached global extremes. Nevertheless, in the Nigerian context, the Warri River remains one of the more polluted rivers, with significant deviations from WHO standards, particularly in industrial zones.

These elevated concentrations not only threaten human health but also jeopardize aquatic biodiversity through bioaccumulation and biomagnification, leading to the potential collapse of fish populations and compromised ecosystem health (Akporido and Agbaire, 2017). The continuous presence of these metals calls for immediate remediation efforts. Comprehensive monitoring, stricter enforcement of environmental regulations, and improved industrial waste management are necessary to reduce heavy metal contamination and protect both environmental and public health in the region (Adewoye and Fodeke, 2020).

The geospatial patterns in the Warri River show significant variations in water quality across Stations 1, 2, and 3, closely linked to surrounding land-use types. Station 1, near urban areas, exhibits acidic pH (Fig.3), higher Electric Conductivity (Fig.4) Total Dissolved Solids (TDS) (Fig.5), and Sulfate levels (Fig.11), driven by urban runoff and waste. Station 2, located near industrial zones, shows slightly alkaline conditions, higher Copper levels (Fig.14), and moderate Nitrate (Fig.9), Phosphate (Fig.10), and Sulfate (Fig.11) concentrations due to industrial discharges. Station 3 surrounded by forested areas, benefits from natural filtration, leading to lower TDS (Fig.5), Nitrate (Fig.9), and Sulfate levels (Fig.11), but has the highest Biological Oxygen Demand (BOD) (Fig.8). Dissolved Oxygen (DO) (Fig.7) and Temperature (Fig.4) patterns further reflect land-use impacts, with cooler temperatures and higher DO levels at Station 1 due to shading, while warmer temperatures and lower DO levels at Stations 2 and 3 are influenced by urban heat retention. Heavy metal contamination, particularly Cadmium (Fig.12) and Lead (Fig.15), is most pronounced at Stations 2 and 3, reflecting industrial pollution. Chromium (Fig.13) was lowest in station 2 with station 1 and 3 recording the highest contamination levels while Zinc (Fig.16) was highest in station 2 and relatively low in Station 1 and 3. Overall, urban and industrial activities degrade water quality near Stations 1 and 2, while natural surroundings at Station 3 help moderate pollution impacts.

3.2. Pearson correlation of physicochemical and heavy metals

The Pearson correlation analysis (Fig. 17) reveals significant relationships between physicochemical parameters and heavy metal concentrations in the Ubeji Axis of the Warri River. A notable finding is the strong positive correlation between pH and Cadmium (0.995), Phosphorus (0.971), and Zinc (0.891), indicating that increased pH levels coincide with elevated concentrations of these elements. Conversely, pH is strongly negatively correlated with Total Dissolved Solids (TDS) (-0.993) and Dissolved Oxygen (DO) (-0.992), suggesting that as pH rises, TDS and DO levels decrease. Electrical Conductivity (EC) is positively associated with Chromium (0.910) but negatively correlated with pH (-0.930), Copper (-0.994), and Zinc (-0.996), indicating that higher conductivity corresponds to lower levels of these metals. Furthermore, Temperature exhibits a strong negative correlation with Nitrogen (-0.980), suggesting potential implications for nutrient cycling and aquatic ecosystem health, especially under climate change conditions.

Heavy metal interactions also demonstrate critical environmental implications. Cadmium exhibits an almost perfect negative correlation with TDS (-0.999), highlighting its inverse relationship with dissolved solids in the river system. Lead (Pb) positively correlates with Phosphorus (0.953) but has a strong negative correlation with Sulfate (-0.997) and Nitrogen (-0.956), implying that increased Lead levels may deplete essential nutrients.

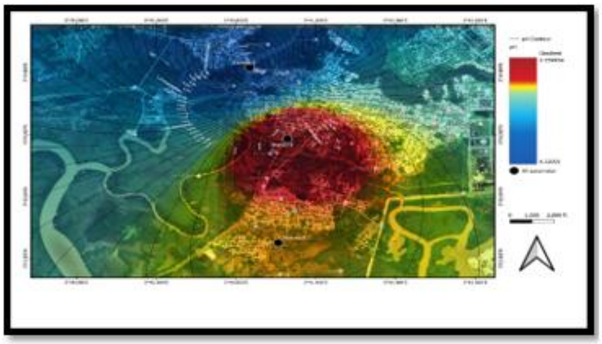

Figure 3: pH IDW interpolation

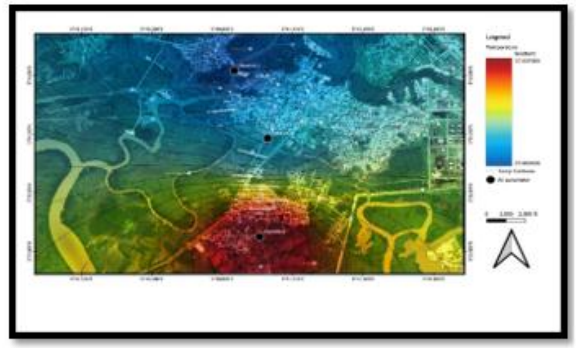

Figure 4: Temperature IDW interpolation

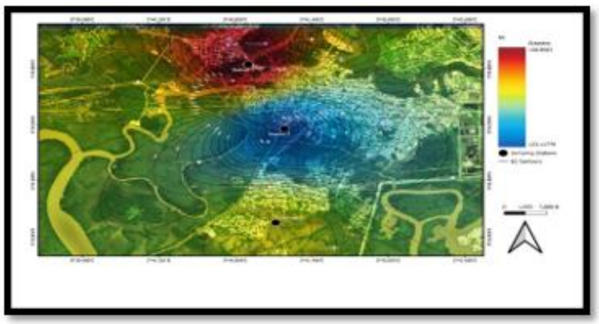

Figure 5: Electric Conductivity IDW interpolation

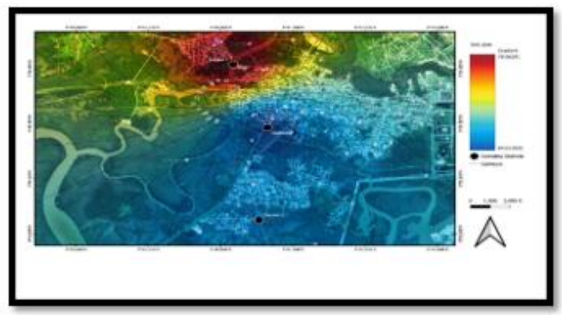

Figure 6: Total Dissolved Solids IDW interpolation

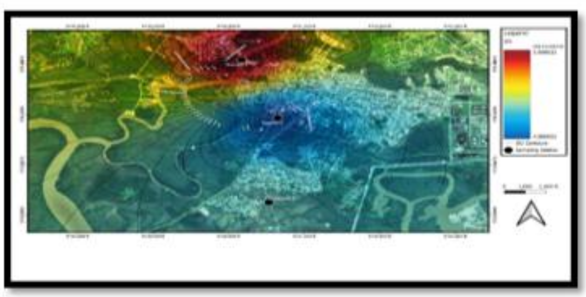

Figure 7: Dissolved Oxygen IDW interpolation

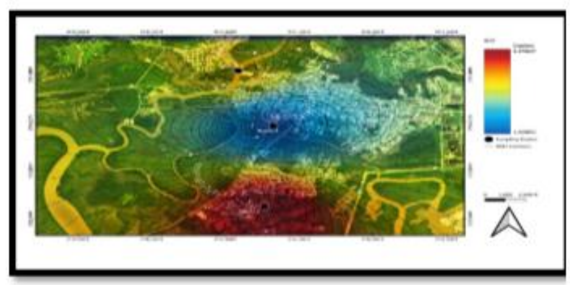

Figure 8: Biological Oxygen Demand IDW interpolation

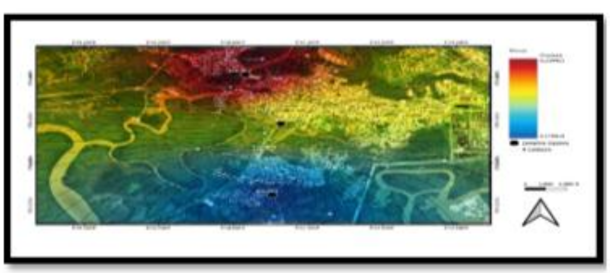

Figure 9: Nitrate IDW interpolation

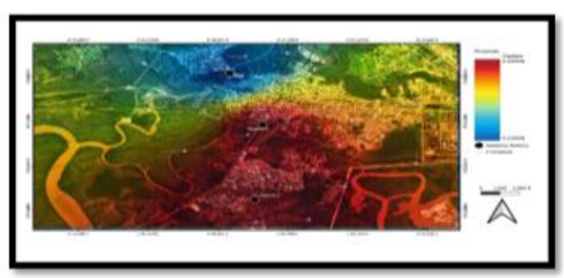

Figure 10: Phosphate River IDW interpolation

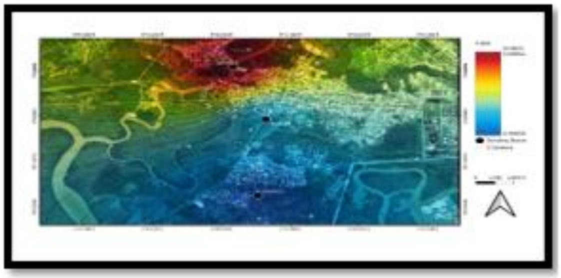

Figure 11: Sulfate IDW interpolation

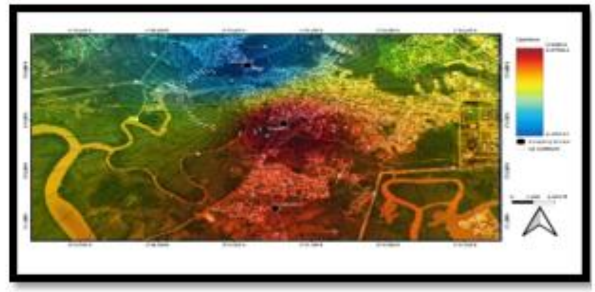

Figure 12: Cadmium IDW interpolation

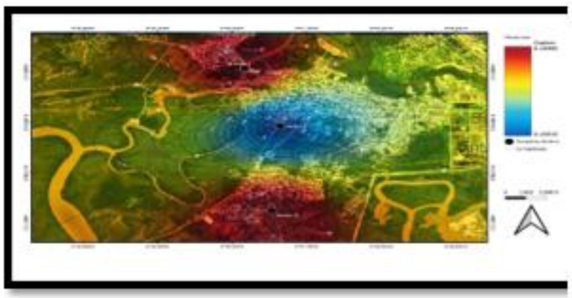

Figure 13: Chromium IDW interpolation

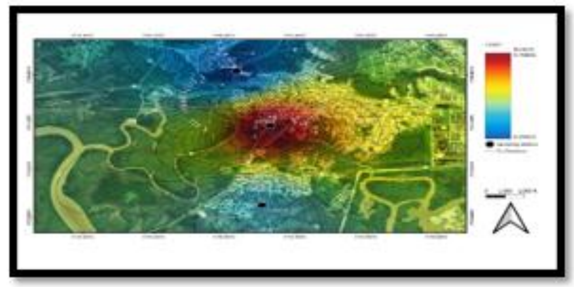

Figure 14: Copper IDW interpolation

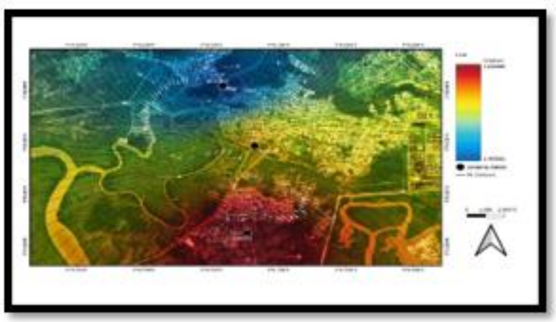

Figure 15: Lead IDW interpolation

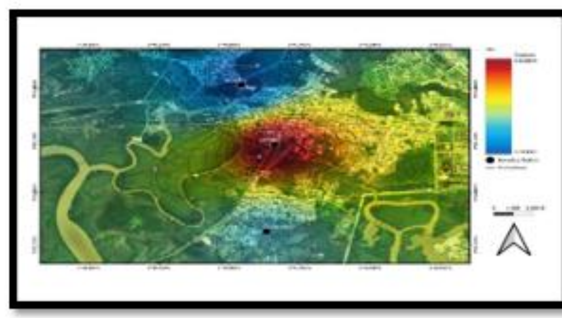

Figure 16: Zinc IDW interpolation

The nearly perfect positive correlation between Copper and Zinc (0.999) suggests they often co-occur, potentially due to shared sources of pollution. Additionally, the strong positive correlation between Biochemical Oxygen Demand (BOD) and Phosphorus (0.990) highlights that organic pollution may be contributing to phosphorus enrichment in the water. These relationships emphasize the interconnectedness of water quality parameters and the influence of industrial and environmental factors on the river's ecological balance.

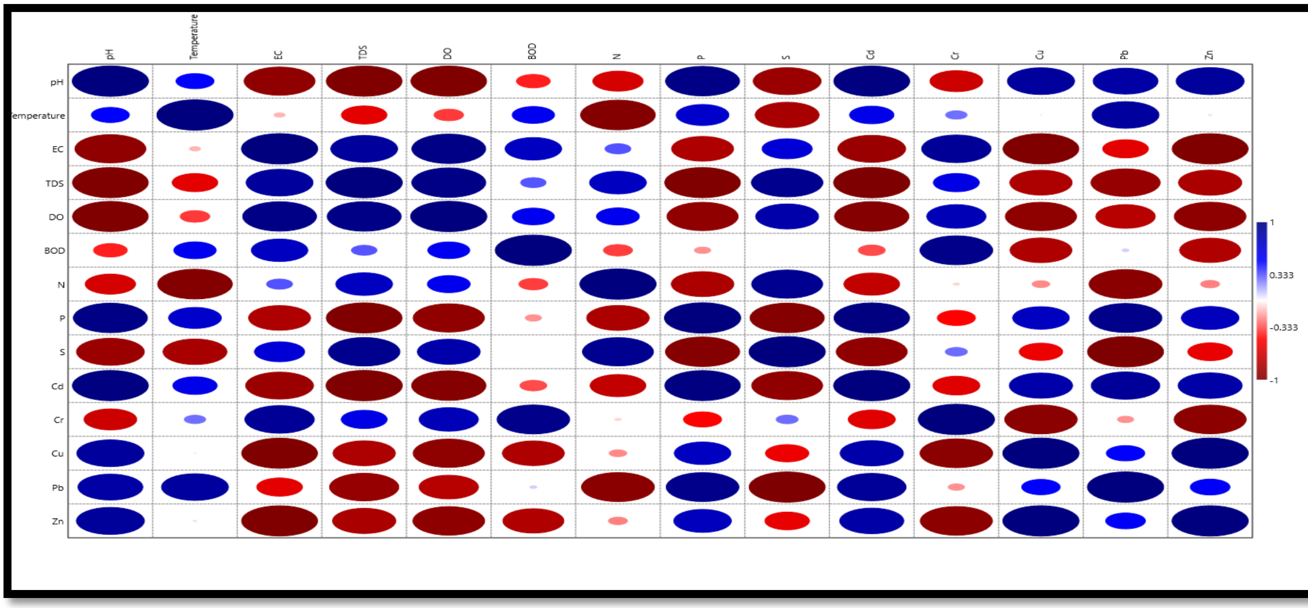

Figure 17: Spatial correlation between various physicochemical parameters measured in the Ubeji Axis of the Warri River.

3.3. Canonical Correspondence Analysis of physicochemical and heavy metals

The Canonical Correspondence Analysis (CCA) plot (Fig.18) highlights key environmental interactions between physicochemical parameters, heavy metals, and sampling stations. Cadmium (Cd) strongly aligns with the positive side of Axis 1 (2.33), suggesting that areas with higher Cd concentrations also exhibit elevated pH and phosphorus (P). Conversely, Chromium (Cr) is negatively associated with Axis 1 (-1.52), implying an inverse relationship with Cd and its correlated parameters. Electrical Conductivity (EC), Total Dissolved Solids (TDS), and Dissolved Oxygen (DO) negatively correlate with Axis 1, suggesting that lower values of these parameters coincide with Cd-rich environments. Along Axis 2, Copper (Cu) shows a strong positive correlation (1.70), distinguishing it from other metals, while Lead (Pb) and Biochemical Oxygen Demand (BOD) are negatively associated, clustering in distinct environmental conditions. The close grouping of Stations 1, 2, and 3 suggests they share similar physicochemical conditions, with slight variations in their associations with the two axes. Notably, the strong opposition between Cd and Cr on Axis 1 suggests that environments rich in one metal tend to be depleted in the other, while Cu's distinct position on Axis 2 indicates a unique environmental or pollution source. The moderate positive correlation of Sulfate (S) and Nitrogen (N) with Axis 2, alongside Zinc (Zn), suggests overlapping environmental conditions influencing their distribution.

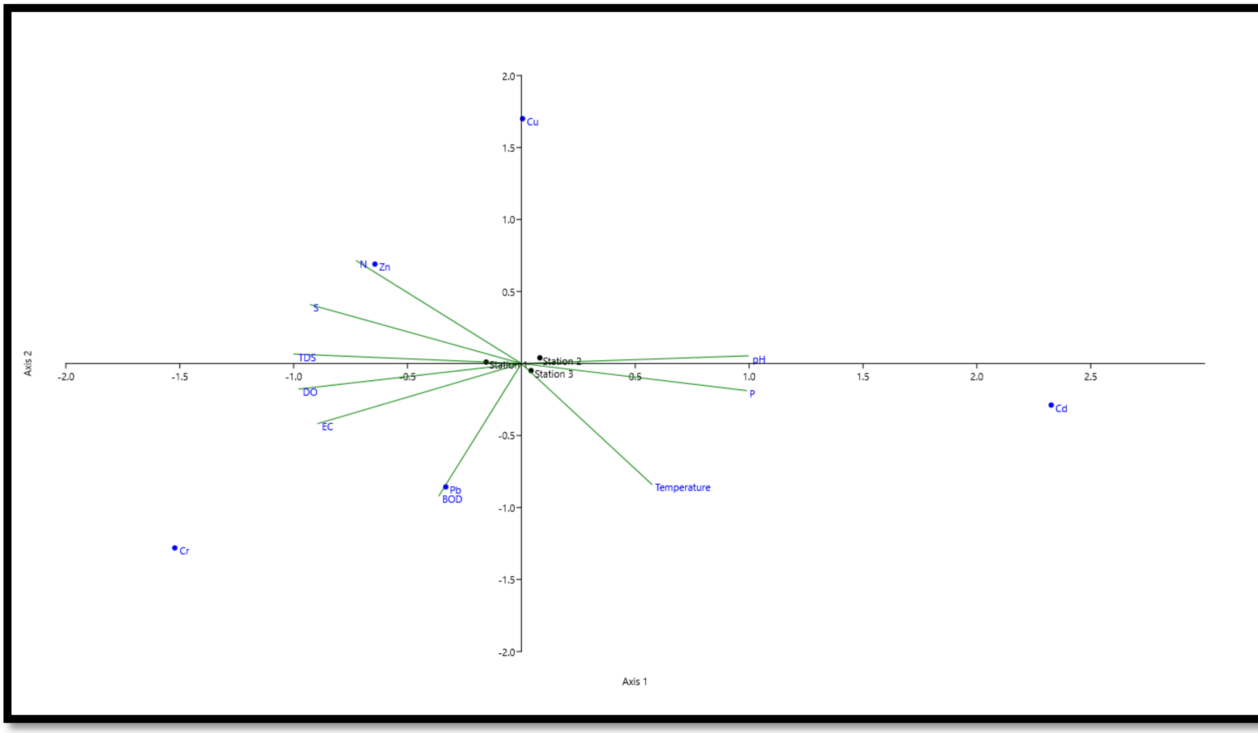

Figure 18: Spatial Plot showing the relationship and collectively influence of the physicochemical and heavy metals

3.4. Nemerow` s Pollution Index (NPI)

Table 2: Nemerow' s Pollution Index of the Ubeji Axis, Warri River

Parameter	Mean Concentration Values (Vn)	NESREA Standard (Sn)	Pollution Index (PI)	NPI Interpretation
pH	6.24	7.5	0.832	Neutral/Low pollutant
TDS	69.67	500	0.139	Neutral/Low pollutant
DO	4.5	5	0.9	Neutral/Low pollutant
BOD	1.99	30	0.066	Neutral/Low pollutant
Phosphate	0.22	5	0.044	Neutral/Low pollutant
Sulfate	0.46	100	0.0046	Neutral/Low pollutant
Nitrate	0.21	10	0.021	Neutral/Low pollutant
Cadmium	0.53	0.01	53	Severe pollutant
Chromium	0.13	0.1	1.3	Moderate pollutant
Copper	0.65	1	0.65	Neutral/Low pollutant
Lead	1.56	0.05	31.2	Severe pollutant
Zinc	0.8	1	0.8	Neutral/Low pollutant
Mean PI			7.496	Severe pollutant
Max PI			53	Severe pollutant
NPI			37.84	Severe pollutant

Table 2 presents the Nemerow's Pollution Index (NPI) results for the Ubeji Axis, Warri River, with the corresponding NPI scale for water quality assessment detailed in Table 1. The pH value, averaging 6.24 with a pollution index (PI) of 0.832, falls within the neutral/low pollutant category, indicating that the river's acidity or alkalinity remains within safe limits. Similarly, Total Dissolved Solids (TDS) levels, with a mean of 69.67 mg/L and a PI of 0.139, suggest minimal pollution from dissolved solids. Dissolved Oxygen (DO), averaging 4.5 mg/L with a PI of 0.9, is slightly below the NESREA standard but still falls within the neutral/low pollution category, necessitating ongoing monitoring to support aquatic life. Biological Oxygen Demand (BOD), with a mean of 1.99 mg/L and a PI of 0.066, indicates minimal organic pollution, contributing to a stable aquatic ecosystem. Phosphate, Sulfate, and Nitrate levels, with mean concentrations of 0.22 mg/L (PI 0.044), 0.46 mg/L (PI 0.0046), and 0.21 mg/L (PI 0.021), respectively, all fall within the neutral/low pollutant category, reflecting minimal nutrient and chemical contamination. However, heavy metal concentrations reveal serious concerns, particularly Cadmium (Cd) at 0.53 mg/L with a PI of 53, categorizing it as a major pollutant with severe toxicity risks. Chromium (Cr), at 0.13 mg/L and a PI of 1.3, falls into the moderate pollution category, signaling potential hazards. Copper (Cu), averaging 0.65 mg/L with a PI of 0.65, poses minimal risk, while Lead (Pb), with a mean of 1.56 mg/L and a PI of 31.2, is identified as a major pollutant with significant environmental and health threats. Zinc (Zn), averaging 0.8 mg/L with a PI of 0.8, remains within the neutral/low pollutant category. The overall water quality in the Ubeji Axis, represented by a mean NPI of 7.496, is classified as severely polluted, with high PIs for Cadmium and Lead highlighting the need for urgent remediation and stricter regulatory measures to mitigate contamination and protect the aquatic ecosystem.

3.5. Water Quality Index

Table 4: Water Quality Index of Ubeji Axis, Warri River

Parameter	Mean Concentration Values (Vn)	Ideal Value (Vo)	Standard Value (Sn)	Qn Value	Water Quality Status
pH	6.24	7	7.5	-101.33	Unsuitable for Drinking
TDS	69.67	0	500	13.93	Excellent
DO	4.5	5	5	-10	Unsuitable for Drinking
BOD	1.99	0	30	6.63	Excellent
Phosphate	0.22	0	5	4.4	Excellent
Sulfate	0.46	0	100	0.46	Excellent
Nitrate	0.21	0	10	2.1	Excellent
Cadmium	0.53	0	0.01	5300	Unsuitable for Drinking
Chromium	0.13	0	0.1	130	Unsuitable for Drinking
Copper	0.65	0	1	65	Very Poor
Lead	1.56	0	0.05	3120	Unsuitable for Drinking

Zinc	0.8	0	1	80	Poor
Total				8611.19	
WQI				717.6	Unsuitable for Drinking

The Water Quality Index (WQI) for the Ubeji Axis of the Warri River highlights severe pollution, with a calculated WQI value of 717.60, categorizing the water as "unsuitable for drinking" following the WQI Scale by Brown et al., 1970. A summary of the results is presented in Table 4. The mean pH value of 6.24, with a Qn value of -101.33, indicates slight acidity, which can influence the solubility and toxicity of other substances, though it is not a major concern by itself. The Total Dissolved Solids (TDS) mean value of 69.67 mg/L and a Qn value of 13.93 are well within acceptable limits, suggesting minimal pollution from dissolved substances. Dissolved Oxygen (DO), with a mean value of 4.50 mg/L and a Qn value of -10, is slightly below the standard of 5 mg/L, potentially leading to hypoxic conditions that may harm aquatic life. The Biological Oxygen Demand (BOD) mean value of 1.99 mg/L and a Qn value of 6.63 indicates low organic pollution, supporting a relatively stable aquatic ecosystem. Phosphate, Sulfate, and Nitrate concentrations, with mean values of 0.22 mg/L (Qn 4.4), 0.46 mg/L (Qn 0.46), and 0.21 mg/L (Qn 2.1), respectively, are all within safe limits, minimizing the risk of nutrient-driven pollution. However, heavy metals present serious concerns, particularly Cadmium, with a mean concentration of 0.53 mg/L and an extremely high Qn value of 5300, signaling critical contamination levels and severe health risks, including kidney damage. Chromium levels, averaging 0.13 mg/L with a Qn value of 130, suggest moderate pollution with potential carcinogenic effects. Copper, with a mean concentration of 0.65 mg/L and a Qn value of 65, remains within acceptable limits but requires monitoring for potential toxicity. Lead concentrations, with a mean of 1.56 mg/L and a Qn value of 3120, are alarmingly high, posing severe neurological and environmental risks. Zinc levels, averaging 0.80 mg/L with a Qn value of 80, remain within acceptable limits but still necessitate monitoring. The overall WQI score, heavily influenced by the extremely high concentrations of Cadmium and Lead, identifies these metals as the primary contaminants driving water quality deterioration and underscores the urgent need for targeted remediation efforts to safeguard both human health and aquatic ecosystems.

4. Conclusion

The geospatial analysis of water quality and heavy metal contamination in the Warri River revealed alarming levels of pollution, particularly from Cadmium and Lead, both of which exceed national and international regulatory standards. The Nemerow Pollution Index (NPI) classified the river as "severely polluted," while the Water Quality Index (WQI) confirmed it to be unsuitable for drinking. These findings indicate that immediate actions are necessary to address the environmental degradation and potential health risks associated with water quality in the Warri River. To address the severe pollution in the Warri River, strengthening industrial waste management policies, particularly for the oil and gas sector, is crucial, along with enforcing the installation of effluent treatment systems to reduce toxic discharges. Implementing a comprehensive, real-time water quality monitoring system and using GIS for tracking pollution hotspots can help detect issues early. Community education and outreach programs should raise awareness about the health risks of using polluted water, while immediate remediation efforts, such as sediment removal and bioremediation, are essential to restore water quality. Integrating water quality management into national sustainability policies with stricter penalties for polluters will help ensure long-term environmental protection and human health.

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