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ASSESSMENT OF HEAVY METALS, WATER QUALITY INDICES AND HEALTH IMPACT OF MMILI OCHA RIVER, ABAKPA NIKE-ENUGU EAST, NIGERIA

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Abstract
This study evaluated the water quality, heavy metal concentrations, and associated health risks of Mili Ocha River in Abakpa Nike, Enugu East LGA, Enugu State, Nigeria, to determine its suitability for domestic and drinking purposes. Water samples were collected from upstream, midstream, and downstream locations during the rainy (May–July) and dry (December–February) seasons and analyzed in triplicate using standard APHA and AOAC methods. Physicochemical parameters recorded were: pH 6.29–7.22, temperature 25.94–28.08 °C, electrical conductivity 149.28–354.84 µS/cm, total hardness 142.67–183.67 mg/L, total dissolved solids 166.55–275.67 mg/L, BOD 1.56–2.02 mg/L, nitrates 34.59–60.32 mg/L, sulphates 13.60–46.52 mg/L, phosphates 0.042–1.71 mg/L, and chloride 43.73–67.45 mg/L. Heavy metal concentrations included cadmium 0.0005–0.0051 mg/L, arsenic 0.0027–0.032 mg/L, iron 0.175–0.298 mg/L, zinc 0.161–0.417 mg/L, chromium 0.103–0.241 mg/L, lead 0.0148–0.046 mg/L, and mercury 0.00343–0.0123 mg/L. Comparison with WHO standards showed that most parameters were within permissible limits; however, temperature, nitrate, cadmium, arsenic, and lead exceeded limits during the rainy season, while cadmium, arsenic, lead, and mercury exceeded limits in the dry season. Correlation analysis indicated common anthropogenic sources, mainly acid mine drainage from the upstream Onyeama Coal Mine and leachate from nearby dumpsites. Water quality indices revealed significant pollution. The Weighted Arithmetic Water Quality Index classified the river as Grade E (WQI >100), indicating it is unsuitable for drinking without treatment. The Heavy Metal Pollution Index showed contamination in the dry season (HPI >100 at Stations B and C), while the Metal Index indicated severe contamination (Class VI, MI >1) across all seasons. Health risk assessment showed total hazard index values below the safety threshold (children: 0.204; adults: 1.3×10^{-4}), with ingestion as the main exposure pathway and children more vulnerable. Overall, the river is polluted and unsafe for direct consumption, requiring urgent pollution control, monitoring, and public health interventions.
Keywords: River, Heavy metals, physicochemical parameters, water quality indices, health risk assessment

INTRODUCTION

Water is an essential natural resource that supports life and sustains both human and environmental activities. It is needed for drinking, agriculture, industrial processes, sanitation, transportation, and the survival of aquatic organisms. Water also contributes significantly to climate regulation and ecological balance. However, in recent years, increasing population growth, urbanization, industrial development, and other human activities have placed enormous pressure on the quality and availability of water resources worldwide (UNESCO, 2009). Water resources are broadly categorized into surface water, such as rivers, lakes, streams, and oceans, and groundwater found beneath the earth's surface in aquifers. Both sources are important for maintaining environmental sustainability and supporting human existence (Zeyneb, 2021).

Despite the importance of water, pollution of water bodies has become a major environmental concern globally. Water pollution occurs when harmful substances enter rivers, lakes, streams, and other water bodies, making them unsafe for human use and aquatic life. Industrial waste, agricultural runoff, sewage discharge, mining operations, and domestic waste disposal are some of the major sources of contamination. These activities introduce different forms of pollutants into aquatic environments, including chemical, biological, and physical contaminants, which negatively affect water quality and ecosystem health (WHO, 2022; UNEP, 2021). In many developing countries, inadequate waste management systems, poor wastewater treatment, and weak environmental regulations have further increased the problem of water pollution.

Among the various pollutants found in water bodies, heavy metals are of particular concern because they are toxic, persistent, and capable of accumulating in living organisms over time. Metals such as cadmium (Cd), arsenic (As), lead (Pb), mercury (Hg), chromium (Cr), zinc (Zn), and iron (Fe) can enter aquatic systems through natural processes as well as human activities including industrial discharge, agricultural practices, mining, and improper waste disposal (Jaishankar *et al.,* 2014). Unlike some pollutants that break down naturally, heavy metals remain in the environment for long periods and may accumulate in water, sediments, and aquatic organisms. This can lead to bioaccumulation and biomagnification within the food chain, thereby posing serious threats to both aquatic ecosystems and human health.

Exposure to heavy metals through contaminated water can result in various health problems depending on the

level and duration of exposure. For instance, lead may affect the nervous system and mental development, cadmium can damage the kidneys, mercury may cause neurological disorders, while arsenic exposure has been linked to skin diseases and cancer-related conditions. Because these metals can accumulate in body tissues over time, even low concentrations may become harmful after prolonged exposure.

Rivers and other surface water bodies are especially vulnerable to pollution because they often receive untreated sewage, industrial effluents, agricultural runoff, and wastes from surrounding communities. In many developing countries, including Nigeria, rivers are widely used for drinking, cooking, washing, irrigation, and fishing despite increasing contamination levels. Poor environmental monitoring and limited enforcement of pollution control regulations have contributed significantly to the deterioration of many freshwater systems (UNESCO, 2020). As a result, populations that rely on these water sources may face serious environmental and public health risks.

Considering these concerns, continuous monitoring and assessment of water quality are necessary to protect public health and maintain environmental sustainability. Water quality assessment helps determine the condition of aquatic systems and identify contaminants that may threaten humans and aquatic life. In addition, Human Health Risk Assessment (HHRA) is commonly used to estimate the possible health effects associated with exposure to contaminated water. This approach evaluates different exposure pathways, including ingestion, inhalation, and dermal contact, using parameters such as Average Daily Dose (ADD), Hazard Quotient (HQ), and Hazard Index (HI) to determine potential non-carcinogenic health risks (USEPA, 2011).

Therefore, this study focuses on evaluating the physicochemical quality of water and determining the concentrations of selected heavy metals in the Mmili Ocha River. The study also assesses the possible non-carcinogenic health risks associated with exposure to the contaminated water among residents who depend on the river. The findings are expected to provide useful information for environmental monitoring, pollution management, public health protection, and policy development aimed at improving water resource management and preserving aquatic ecosystems.

MATERIALS AND METHODS

Study Area

The study area, Mmili Ocha Abakpa, is situated within latitude N6°28′34.734″ to N6°28′34.41″ and longitude E7°31′3.216″ to E7°32′8.90988″ in Enugu East Local Government Area of Enugu State, Southeastern Nigeria. The area is a densely inhabited suburb that has gradually transformed from a predominantly agrarian settlement into an active urban community. This development was largely influenced by the discovery of coal during the colonial era, which attracted population influx and stimulated commercial and economic activities in the region.

Presently, Abakpa and surrounding communities such as Ugbo Chime, Ugbo Paul within the Thinkers Corner axis, and the Hausa settlement located along the riverbank are characterized by high population density and relatively low-income residents. The rapid and largely unplanned pattern of urbanization in these communities has resulted in several environmental and social challenges, including overcrowding, inadequate infrastructure, insufficient sanitation facilities, and improper waste disposal practices. These conditions have contributed significantly to environmental deterioration and pollution within the area.

The Mmili Ocha River, which serves as the focus of this study, is influenced by both natural processes and anthropogenic activities. The river originates near the abandoned Onyeama coal mine, situated approximately 6 km upstream, thereby increasing the possibility of contamination from mine-related pollutants. Furthermore, the presence of nearby dumpsites contributes additional pollutants through leachate infiltration and surface runoff. Consequently, the river is continually exposed to contamination from mining residues and urban waste materials. In view of these concerns, water samples were collected from the river and analyzed to determine heavy metal concentrations and evaluate the overall water quality status.

Sample collection and preparation

Water samples were collected from the Mmili Ocha River in Abakpa, Enugu, during, both the rainy season (May–July) and the dry season (December–February). Each month, three samples were taken, giving a total of eighteen samples for the study. For proper coverage, the river was divided into three sections: upper (A), middle (B), and lower (C), and one sample was collected from each section. The samples were taken early in the morning using clean, sterile 1000 cm^3 polyethylene bottles, at a depth of about 5–20 cm below the water surface. Before sampling, the bottles were carefully prepared by washing with detergent, rinsing several times with distilled water, soaking overnight in 10% nitric acid, and finally rinsing with deionized water to remove any possible contaminants (Wufem *et al.,* 2009). They were also rinsed with the river water just before collection. After collection, the samples were stored in a refrigerator at 4°C until analysis. This low temperature helps to slow down microbial activity and prevent biodegradation (Ademoroti, 1996).

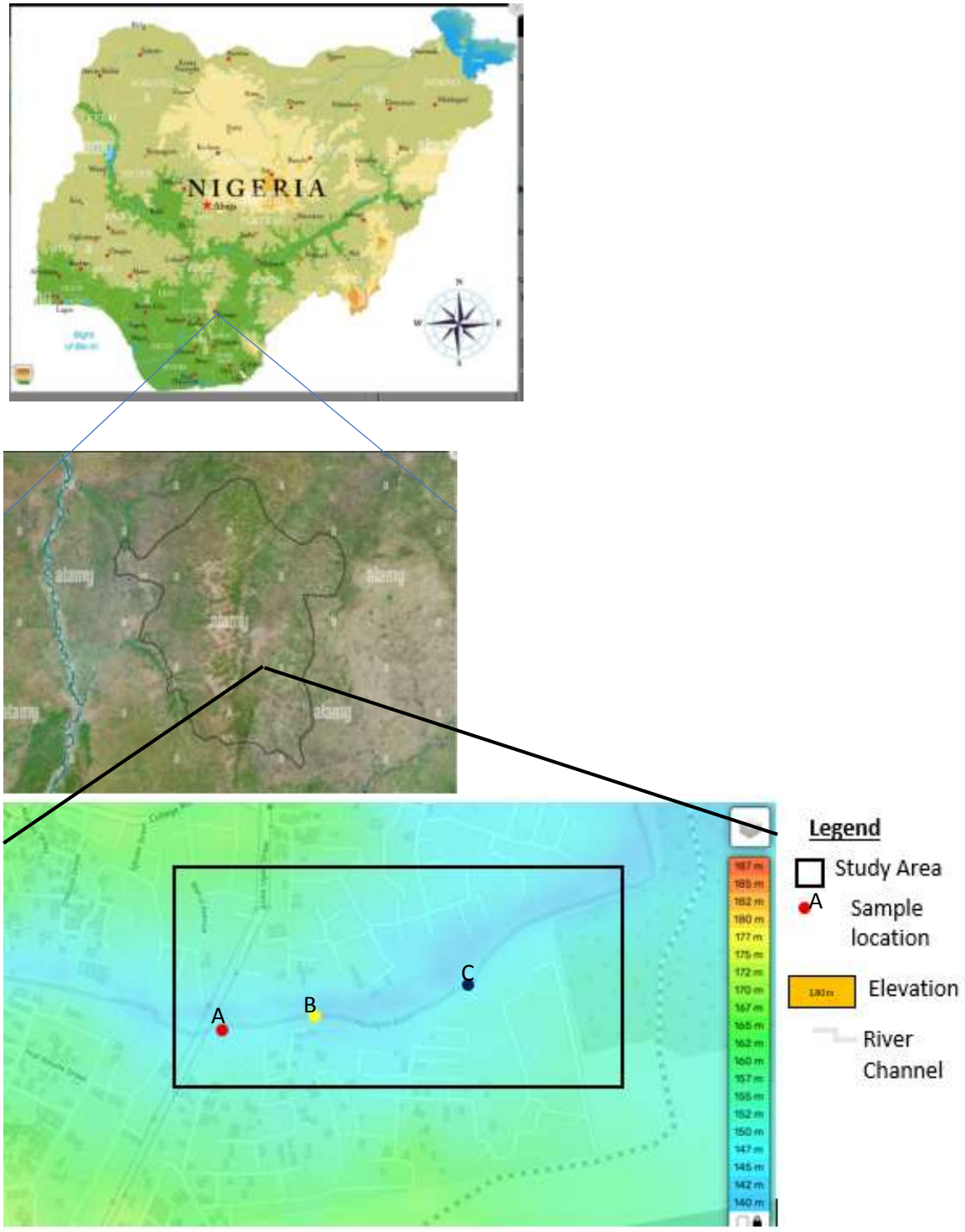

Figure 1. Map of Topographic map of Abakpa Area, Enugu, Enugu State Nigeria. Inset is the Study Area with Sample Locations.

Physicochemical Analysis for the Water Samples

The permitted limits set by WHO (2011; 2017) were used as reference standards to assess the Mmili Ocha River's water quality. A digital barbeque thermometer (model: TBT-08H, range: 50 °C to 300 °C) was used to measure the temperature. According to AOAC (2004) and Amadi *et al.,* (2004), electrical conductivity (EC) was measured using a desktop conductivity meter (model: DDS-307A) made by Mettler Toledo. A typical electronic pH meter (model: SGZ-200BS) made by Labscience, England, was used to determine the pH of the water samples. Total dissolved solids (TDS) were quantified using the gravimetric method (Amadi *et al.,* 2004), whereas total hardness, sulphate, and chloride concentrations were ascertained using the titrimetric method (AOAC, 2004).

A dissolved oxygen meter made by Hanna Instruments in Romania was used to measure biological oxygen demand (BOD) (APHA, 2015). Following AOAC (2004) guidelines, the concentration of phosphate was measured at 650 nm using a UV spectrophotometer (Spectrum 23A), and the concentration of nitrate was measured at 410 nm using a spectrophotometer (Spectronic-20). A Varian AA240 Atomic Absorption Spectrophotometer was used to do metal analysis in compliance with the Standard Procedures for the Examination of Water and Wastewater (APHA, 2015). Cadmium (Cd), arsenic (As), lead (Pb), zinc (Zn), chromium (Cr), iron (Fe), and mercury (Hg) were among the heavy metals that were examined.

The analytical data were evaluated using the Water Quality Index (WQI), Heavy Metal Pollution Index (HPI), and Metal Index (MI) to determine the overall water quality and the degree of heavy metal pollution. A risk evaluation for human health was also carried out using the findings.

WATER QUALITY INDICES (WQIS)

The Water Quality Index (WQI), Heavy Metal Pollution Index (HPI), and Metal Index (MI) were among the water quality indices (WQIs) used in the assessment of water quality.

Water Quality Index (*W*QI)

The Water Quality Index (WQI) was computed using the Weighted Arithmetic Index method (WAWQI) to evaluate the suitability of the river for domestic consumption. The World Health Organization (WHO, 2022) standard limits were used as reference values for calculating the WQI based on the physico-chemical parameters of the water samples. Equation (1) was used to determine the unit weight (Wn) for each parameter, in accordance with Chandra et al. (2017) and Ezechi and Diara (2025)

$$Wn = \frac{k}{S_n} \qquad (1)$$

Where $K = \frac{1}{{}^{1}/_{S1} + {}^{1}/_{S2} + {}^{1}/_{S3} + \text{----------} {}^{1}/_{Sn}} = {}^{1}/_{\sum {}^{1}/_{S_n}}$

S_n = Standard desirable value of the nth parameter

According to Chandra *et al.,* (2017), equation 2 was used to determine the sub-index (Qn) value for each parameter:

$$Q_n = \frac{[(V_n - V_o)]}{[(S_n - V_o)]} * 100 \qquad (2)$$

Vn stands for the mean concentration of the nth parameters, Sn for the standard desirable value of the nth parameters, and Vo for the actual values of the parameters in pure water, which are 0 for the majority of parameters, 7.0 for pH, and 14.0 for DO.

Equation (3) was created by combining equations (1) and (2) and is used to calculate the water quality index (WQI).

$$WQI = {}^{\sum W_n Q_n}/_{\sum W_n} \qquad (3)$$

Lastly, the water quality status was used to rate the water quality index (WQI), as indicated in Table 1.

Table 1: Water quality status based on weight arithmetic water quality index method

WQI Value	Water Quality Status	Grading	Possible usage
0 - 25	Excellent water quality	A	Drinking, irrigation and industrial use
26 - 50	Good water quality	B	Drinking, irrigation and industrial use
51 - 75	Poor water quality	C	Irrigation and industrial use
76 - 100	Very Poor water quality	D	Irrigation
>100	Unsuitable for drinking purpose	E	Requires proper treatment before use

Source: (Shweta *et al.,* 2013; Wekesa and Otieno, 2022)

Heavy Metal Pollution Index (HPI)

Using WHO (2022) drinking water regulations, the Heavy Metal Pollution Index (HPI) evaluates overall water pollution and suitability for environmental and human health by combining concentrations of different metals into a single value. HPI was computed using the formula provided by Mohan *et al.,* (1996).

$$HPI = \frac{\sum_{i=1}^{n} QiWi}{\sum_{i=1}^{n} Wi} \qquad (4)$$

where Wi and Qi stand for the ith parameter's unit weightage and sub-index, respectively. As indicated in equation (4), n is the total number of parameters to be taken into account.

$$Qi = \sum_{i=1}^{n} \frac{Mi - Ii}{Si - Ii} * 100 \qquad (5)$$

is the formula for calculating the sub-index Qi. According to equation (5), Si is the standard value of the ith parameter in parts per million (ppm), while Mi and Ii are the monitored and ideal values of the ith parameter.

The following is a classification of the heavy metal pollution index based on Kabir *et al.,* (2020):

HPI < 100: Water with no heavy metal contamination is typically regarded as safe to drink.

HPI > 100: Signifies heavy metal contamination.

HPI = 100: Indicates the hazardous contamination threshold.

Metal Index (MI)

Equation (6) of the Tamasi and Cini (2004) model was used to determine the metal index (MI), which is defined as the concentration of each element in the solution to the maximum permitted concentration for each element in the water sample. The MI calculations were performed using the World Health Organization's (WHO, 2022) drinking water heavy metal limits (Table 2).

$$MI = \sum_{i=1}^{n} \frac{Ci}{MACi} \quad (6)$$

The metal index is represented by MI, the observed concentrations of the íth heavy metal in the sample under analysis are represented by Cí, and the maximum permitted concentration (permissible limit) of the íth heavy metal, as indicated by equation (6), is represented by MACí. According to Caeiro *et al.,* (2005) and Bakan *et al.,* (2010), the metal index was categorized as follows:

Table 2: Water quality status based on metal index

Class	Status	MI value	Range	Interpretation / Description
I	Very pure	<0.3	MI < 1	Water sample free from heavy metal pollutant
II	Pure	0.3 - 1	MI < 1	Water is within acceptable limits
III	Slightly affected	1 - 2	MI < 1	Slight level of heavy metal contamination
IV	Moderately affected	2 - 4	MI > 1	Water sample polluted with heavy metal
V	Strongly affected	4 - 6	MI > 1	High level of heavy metal pollution
VI	Seriously affected	>6	MI > 1	Severe heavy metal contamination

Source: (Caeiro *et al.,* 2005 ; Gülfem *et al.,* 2010)

Human Health Risk Assessment

Heavy metal exposure through inhalation (ADD_i☐☐), ingestion (ADD_i☐g), and dermal absorption (ADD_{er}☐) was evaluated in accordance with USEPA (1989, 1996) standards (Ihedioha *et al.,* 2017).

$$ADD_{inh} = \frac{C \times R_{inh} \times EF \times ED}{PEF \times BW \times AT} \quad (8)$$

$$ADD_{ing} = \frac{C \times R_{ing} \times EF \times ED \times 10^{-6}}{BE \times AT} \quad (9)$$

$$ADD_{derm} = \frac{C \times SL \times SA \times ABS \times EF \times ED \times 10^{-6}}{BW \times AT} \quad (10)$$

The average daily doses (mg/kg/day) for non-carcinogenic exposure through ingestion, inhalation, and dermal contact are represented by $ADD_{(}inh_{)}$, $ADD_{(}ing_{)}$, and $ADD_{(}derm_{)}$. These doses are determined using standard exposure parameters (body weight, intake rates, exposure duration/frequency, skin area, adherence, absorption, and particle emission). The Hazard Quotient (HQ), which is the ratio of ADD to the reference dose (RfD) and defines a safe daily exposure level unlikely to generate negative effects over a lifetime, was used to evaluate health hazards.

$$HQ = \frac{ADD}{RfD} \quad (11)$$

ADD is the average daily dosage (mg/kg/day), and RfD is the reference dose. $RfD_{(}inh_{)}$ is computed from RfC after body weight and age-specific inhalation rates are taken into account. The Total Hazard Index (THI), which is the sum of the individual HQs, represents the overall danger from numerous metals.

$$\text{Total hazard index } (THI) = HQ_1 + HQ_2 + \cdots + HQ_n \quad (11)$$

If THI < 1.0, significant additive or toxic effects are unlikely; no further evaluation is needed.

If THI > 1.0, there may be concern for non-cancer health effects.

Data Analysis

All determinations were conducted in triplicates and data generated were analyzed statistically using (SPSS) version 27 and Microsoft Excel 2016. Pearson correlation was applied on the data obtain from water analysis to ascertain if they were correlated.

RESULTS AND DISCUSSION

The results of the physicochemical parameters of the evaluated water samples studied, the WHO (2022) and NSDWQ (2015) recommended standard are represented in Tables 3 and 4.

Table 3: Results of the physicochemical parameters of the evaluated river during rainy season

PARAMETERS	UNIT	STATION A	STATION B	STATION C	NSDWQ	WHO
Ph	Nil	7.22 ± 0.84	7.09 ± 0.74	6.89 ± 0.611	6.5-8.5	6.5 -8.5
Temperature	°C	25.94 ± 1.22	26.39 ± 0.86	26.40 ± 0.89	25	25
EC	µS/cm	186.55 ± 16.03	192.31 ± 4.36	149.28 ± 42.103	1000	1000
Total Hardness	mg/L	142.67 ± 4.04	143.00 ± 4.36	152.00 ± 5.000	150	300
TDS	mg/L	170.20 ± 18.59	166.55 ± 13.74	172.93 ± 6.002	500	500
BOD	mg/L	1.64 ± 0.086	1.57 ± 0.100	1.56 ± 0.15	NA	5
Nitrates	mg/L	60.32 ± 22.48	57.68 ± 24.02	54.29 ± 25.04	50	50
Sulphates	mg/L	19.47 ± 3.18	13.60 ± 7.18	14.09 ± 5.20	100	250
Phosphates	mg/L	0.047 ± 0.042	0.0424 ± 0.039	1.71 ± 2.85	5	5
Chloride	mg/L	56.07 ± 4.103	54.15 ± 2.21	54.06 ± 3.56	250	250
Cadmium	mg/L	0.0005 ± 0.0005	0.0044 ± 0.005	0.0047 ± 0.006	0.003	0.003
Arsenic	mg/L	0.032 ± 0.036	0.0027 ± 0.002	0.0033 ± 0.003	0.01	0.01
Iron	mg/L	0.175 ± 0.14	0.2490 ± 0.19	0.2497 ± 0.22	0.3	0.3
Zinc	mg/L	0.161 ± 0.12	0.2751 ± 0.05	0.2953 ± 0.03	3	3
Chromium	mg/L	0.103 ± 0.097	0.1967 ± 0.28	0.1313 ± 0.16	0.05	0.05
Lead	mg/L	0.046 ± 0.033	0.0205 ± 0.02	0.0148 ± 0.015	0.01	0.01
Mercury	mg/L	0.004 ± 0.006	0.00343 ± 0.006	0.0050 ± 0.004	0.001	0.006

Key: Station A = Water sample from upstream at coordinates latitude N 6°28'34.734" and longitude E 7°31'3.216"
Station B = Water sample from midstream at coordinates latitude N 6°28'34.752" and longitude E7°31'2.50212"
Station C = Water sample from downstream at coordinates latitude N 6°28'34.41" and longitude E7°32' 8.90988"

Table 4: Results of the physicochemical parameters of the evaluated river during dry season

PARAMETERS	UNIT	STATION A	STATION B	STATION C	NSDWQ	WHO
Ph	Nil	6.29 ± 0.37	6.47 ± 0.16	6.55 ± 0.28	6.5-8.5	6.5-8.5
Temperature	°C	28.07 ± 0.63	28.08 ± 0.68	28.08 ± 0.65	25	25
EC	µS/cm	354.84 ± 40.88	311.27 ± 57.07	348.38 ± 69.40	1000	1000
Total Hardness	mg/L	183.67 ± 7.09	181.33 ± 8.62	170.00 ± 14.18	150	300
TDS	mg/L	275.67 ± 46.71	275.00 ± 15.52	258.00 ± 49.87	500	500
BOD	mg/L	2.017 ± 0.07	1.87 ± 0.068	1.89 ± 0.15	NA	5
Nitrates	mg/L	36.45 ± 27.45	36.84 ± 22.15	34.59 ± 17.27	50	50
Sulphates	mg/L	34.45 ± 16.02	46.52 ± 18.36	46.49 ± 10.51	100	250
Phosphates	mg/L	0.777 ± 0.37	0.753 ± 0.46	0.693 ± 0.43	5	5
Chloride	mg/L	43.73 ± 32.12	65.09 ± 20.22	67.45 ± 13.79	250	250
Cadmium	mg/L	0.0048 ± 0.005	0.0038 ± 0.005	0.0051 ± 0.006	0.003	0.003
Arsenic	mg/L	0.0093 ± 0.004	0.0147 ± 0.006	0.0164 ± 0.018	0.01	0.01
Iron	mg/L	0.258 ± 0.22	0.298 ± 0.26	0.225 ± 0.16	0.3	0.3
Zinc	mg/L	0.401 ± 0.13	0.395 ± 0.035	0.417 ± 0.18	3	3
Chromium	mg/L	0.236 ± 0.17	0.123 ± 0.18	0.241 ± 0.21	0.05	0.05
Lead	mg/L	0.0245 ± 0.014	0.0122 ± 0.012	0.0299 ± 0.014	0.01	0.01
Mercury	mg/L	0.00081± 0.0006	0.0123 ± 0.009	0.0077 ± 0.011	0.001	0.006

Key: Station A = Water sample from upstream at coordinates latitude N 6°28'34.734" and longitude E 7°31'3.216"
Station B = Water sample from midstream at coordinates latitude N 6°28'34.752" and longitude E 7°31'2.50212"
Station C= Water sample from downstream at coordinates latitude N 6°28'34.41" and longitude E 7°32' 8.90988"

Physicochemical parameters of the water sample

pH is an important measure of water quality because it affects the chemical balance of water, the survival of aquatic organisms, and overall ecosystem health (WHO, 2007; Dewangan *et al.,* 2023). The pH values of the studied river ranged between 6.89 and 7.22 in the rainy season, and between 6.29 and 6.55 in the dry season (Tables 2 and 3). During the dry season, Stations A and B recorded pH levels below the WHO (2022) and NSDWQ (2015) permitted limits. This was probably caused by the discharge of untreated residential, industrial, and mechanical wastes as well as indiscriminate defecation, which concentrates contaminants when water levels drop. During the rainy season, the water was generally almost neutral, while during the dry season, it was slightly acidic. The data from the Ebonyi River (pH 6.3–8.5; Nwabunike, 2016), the Ekulu and Asata Rivers (pH 5.8–7.0; Ken-Onukuba *et al.,* 2021), and the Nworie River (pH 6.85–7.86; Nwosu *et al.,* 2021) are broadly in line with these findings. Despite the fact that pH does not directly endanger human health (WHO, 2007), it is crucial to maintain the right levels for efficient water treatment and disinfection.

River temperatures varied very slightly between sampling locations, ranging from 25.9 to 26.40 °C during the rainy season and from 28.07 to 28.08 °C during the dry season (Tables 3 and 4). Increased ambient air conditions are linked to the higher

temperatures observed between December and February. High water temperatures can accelerate chemical processes, alter taste and odor, decrease gas solubility, and boost aquatic organisms' metabolic activity (Khan *et al.,* 2015). The values are typical of tropical aquatic systems that support biological productivity, although exceeding WHO (2022) and NSDWQ (2015) guideline limits (Nwabunike, 2016).

During the rainy season, the values of electrical conductivity (EC) were 186.55 ± 16.034 µS/cm at Station A, 192.31 ± 4.356 µS/cm at Station B, and 149.28 ± 42.103 µS/cm at Station C. EC rose to 354.84 ± 40.879 µS/cm at Station A, 311.27 ± 57.071 µS/cm at Station B, and 348.38 ± 69.402 µS/cm at Station C during the dry season, with Station A exhibiting the largest rise (Tables 3 and 4). The concentration of dissolved ions, minerals, and salts in water is represented by EC (Kalagbor *et al.,* 2021), and an increase in EC is strongly associated with an increase in total dissolved solids (Vinit *et al.,* 2011). Despite seasonal variation, all measurements remained within the WHO (2022) and NSDWQ (2015) permissible levels.

Water hardness is a crucial factor in determining whether water is suitable for drinking, industrial, and residential use. It is created by dissolved polyvalent metallic ions, primarily calcium and magnesium, from sedimentary rocks, soil runoff, and related sources (WHO, 2011; Sawyer *et al.,* 2003). Tables 3 and 4 show that the total hardness of the river water under analysis varied from 142.67 to 152.00 mg/L during the rainy season and from 170.00 to 183.67 mg/L during the dry season. Station A had the lowest hardness value (142.67 mg/L) and Station C the highest (152.00 mg/L) during the rainy season, whereas Station A had the highest value (183.67 mg/L) and Station C the lowest (170.00 mg/L) during the dry season. With the exception of Stations A and B during the rainy season, the majority of readings were under the WHO (2022) permitted limit but exceeded NSDWQ (2015) permissible limits. Higher metallic ion concentrations from human activity combined with decreased water volume at high temperatures are probably the cause of the increased hardness during the dry season.

Total dissolved solids (TDS), which represent dissolved inorganic and organic substances in water smaller than 2 microns, serve as an important indicator of water quality (Phyllis & Lawrence, 2007; Majolagbe *et al.,* 2023). TDS levels were higher in the dry season, with Station A recording the highest mean value (275.67 ± 46.705 mg/L), followed closely by Station B (275.00 ± 15.524 mg/L), and Station C (258.00 ± 49.869 mg/L) (Tables 3 and 4). During the rainy season, Station C recorded the highest TDS (172.93 ± 6.002 mg/L), while Station B had the lowest (166.55 ± 13.742 mg/L). All values remained within WHO (1996; 2009) permissible limits and are comparable with findings from the Nworie River in Owerri, Imo State (Nwosu *et al.,* 2021).

One important indicator of water quality is biochemical oxygen demand (BOD), which shows how much oxygen is needed for organic matter to break down (Rubel *et al.,* 2019). According to Sawyer *et al.,* (2003), water can be classified as clean (<1–2 mg/L), fairly clean (3 mg/L), dubious (5 mg/L), or polluted (10 mg/L). During the rainy season, BOD levels in this research varied from 1.56 ± 0.152 mg/L at Station C to 1.64 ± 0.0862 mg/L at Station A. Values increased marginally during the dry season, ranging from 1.87 ± 0.0681 mg/L at Station B to 2.017 ± 0.074 mg/L at Station A (Tables 3 and 4). These low results fall within the WHO's (2022) recommended threshold for safe water use and show little organic pollution.

Nitrates (NO_3^-) are naturally occurring compounds essential for biological processes but can pose health risks at high concentrations, including methemoglobinemia and respiratory complications (Bernhard, 2010; Valentina *et al.,* 2025; Madhavi *et al.,* 2024; Majolagbe *et al.,* 2014). In this study, nitrate concentrations were higher during the rainy season 60.32 ± 22.48 mg/L at Station A, 57.68 ± 24.02 mg/L at Station B, and 54.29 ± 25.04 mg/L at Station C exceeding WHO (2022) and NSDWQ (2015) limits of 50 mg/L. In the dry season, values decreased to 36.45 ± 27.45 mg/L at Station A, 36.84 ± 22.15 mg/L at Station B, and 34.59 ± 17.27 mg/L at Station C.

Sulphates (SO_4^{2-}) naturally occur in rocks, soils, and minerals and can enter water bodies through natural processes such as mineral dissolution and volcanic activity, as well as human activities like mining, sewage discharge, and agriculture (Otero *et al.,* 2007; Man *et al.,* 2014). In this study, mean sulphate concentrations were 19.47 ± 3.18 mg/L, 13.60 ± 7.18 mg/L, and 14.09 ± 5.20 mg/L at Stations A, B, and C during the rainy season, increasing in the dry season to 34.45 ± 16.02 mg/L, 46.52 ± 18.36 mg/L, and 46.49 ± 10.51 mg/L respectively (Tables 3 and 4). These increases are likely due to reduced dilution and increased anthropogenic activity. However, all values remained below WHO (1996) and NSDWQ (2015) limits.

Phosphate concentrations were generally low across all stations, ranging from 0.042 to 1.71 mg/L in the rainy season and 0.693 to 0.777 mg/L in the dry season (Tables 3 and 4). All values were below the WHO (2022) and NSDWQ (2015) guideline value of 5 mg/L. Elevated phosphate levels are often associated with pollution and eutrophication and may originate from domestic, industrial, and agricultural sources containing fertilizers.

Chloride ions, which occur naturally as salts of sodium, potassium, and calcium, are common in freshwater systems (Raid, 2014; WHO, 1996). High levels can indicate pollution and may affect taste, health, and agricultural use (Sawyer *et al.,* 2003; Majolagbe *et al.,* 2023; Rajkumar *et al.,* 2004). In this study, chloride concentrations ranged from 43.73 to 67.45 mg/L (Tables 3 and 4). During the rainy season, mean values were 56.07 ± 4.10 mg/L at Station A, 54.15 ± 2.21 mg/L at Station B, and 54.06 ± 3.58 mg/L at Station C. In the dry season, values were 43.73 ± 32.12 mg/L at Station A, 65.09 ± 20.22 mg/L at Station B, and 67.45 ± 13.79 mg/L at Station C. All values remained within WHO (1996) and NSDWQ (2015) permissible limits.

Heavy metal concentrations of the water sample

Heavy metals are relatively dense elements known for their potential to be hazardous even in small amounts. They frequently build up in the environment as a result of human activity and natural processes, and extended exposure can cause major health issues such as cancer, neurological disorders, hepatorenal syndrome, and cardiovascular diseases (Manavi *et al.,* 2019; Mitra *et al.,* 2022). Cadmium, arsenic, iron, zinc, chromium, lead, and mercury were detected in the river water sample (Tables 3 and 4). Cadmium levels exceeded the WHO (2022) and NSDWQ (2015) permissible limit of 0.003 mg/L. During the rainy season, values were 0.0005 ± 0.00047 mg/L at Station A, 0.0044 ± 0.00493 mg/L at Station B, and 0.0047 ± 0.0056 mg/L at Station C. In the dry season, concentrations were 0.0048 ± 0.0051 mg/L, 0.0038 ± 0.00538 mg/L, and 0.0051 ± 0.00617 mg/L, respectively. Arsenic levels were generally within the permissible limit of 0.01 mg/L, except at Station A during the rainy season, where a higher value of 0.032 ± 0.0355 mg/L was recorded. Iron (0.175–0.298 mg/L) and zinc (0.161–0.417 mg/L) were within their respective guideline limits of 0.3 mg/L and 3 mg/L. Chromium consistently exceeded the permissible limit of 0.05 mg/L in both seasons, ranging from 0.103–0.1967 mg/L in the rainy season and 0.123–0.241 mg/L in the dry season. Lead concentrations also surpassed the 0.01 mg/L limit, while mercury exceeded WHO (2022) and NSDWQ (2015) limits (0.006 mg/L and 0.001 mg/L, respectively) at some sampling locations. Overall, chromium showed persistent exceedance, while cadmium, lead, arsenic (in certain stations), and mercury (in some cases) were also above recommended standards. In contrast, iron and zinc remained within acceptable limits.

Correlation of the physicochemical parameters of the evaluated water samples

The Pearson correlation analysis (Tables 5 and 6) revealed both positive and negative relationships among the measured parameters, reflecting the interaction of different hydrochemical processes and pollution sources. In simple terms, parameters that are strongly positively correlated tend to increase or decrease together, while negative correlations move in opposite directions.

The very strong positive correlation between sulphate and temperature ($r = 1.000$, $p < 0.01$) in the dry season clearly indicates the influence of acid mine drainage (AMD) from the Onyeama Mine. The relationship between Fe and TDS suggests that iron may be introduced through natural water–rock interactions. However, the weaker correlations between Fe and Cd ($r = 0.970$) and Fe and Pb ($r = 0.958$) show that mining is unlikely to be the main source of these toxic metals. Instead, the very strong associations among Cd–Pb ($r = 0.999$), Cd–Cr ($r = 0.983$), and Pb–Cr ($r = 0.990$), along with strong EC–metal relationships (EC–Pb = 0.951, EC–Cr = 0.985, EC–Cd = 0.936), point to dumpsite leachate as a major source of contamination.

Seasonal variation also clearly influenced pollutant behaviour. During the rainy season, strong correlations such as BOD–Cl^- ($r = 0.997$), BOD–SO_4^{2-} ($r = 0.982$), BOD–Pb ($r = 0.992$), and BOD–As ($r = 0.991$) suggest increased input from runoff and leachate entering the river. In the dry season, strong relationships such as TH–PO_4^{3-} ($r = 0.993$), TH–NO_3^- ($r = 0.992$), and TH–TDS ($r = 0.992$) indicate pollutant concentration due to reduced water volume and evaporation.

The consistent correlations among heavy metals across both seasons suggest continuous and ongoing contamination. Additionally, the relationships among NO_3^-, PO_4^{3-}, TH, and TDS point to contributions from agricultural activities. Overall, the results show that the river is impacted by multiple pollution sources, including acid mine drainage (SO_4^{2-}, Fe), dumpsite leachate (Cd, Pb, Cr, BOD), agricultural runoff (NO_3^-, PO_4^{3-}), and urban or industrial waste.

These combined influences raise serious environmental and public health concerns. Metals such as lead and cadmium can accumulate in organisms over time, while high BOD levels reduce dissolved oxygen in the water. In addition, the interaction between acid mine drainage and leachate may enhance the mobility of metals, increasing their availability and potential toxicity.

Table 5: Pearson correlation coefficient matrix for the studied water sample in rainy season

	pH_	Temp	EC	TH	TDS	BOD	NO_3^-	SO_4^{2-}	PO_4^{3-}	Cl^-	Cd	As	Fe	Zn	Cr	Pb	Hg
pH	1																
Temp	-.810	1															
EC	.865	-.407	1														
TH	-.932	.543	-.988	1													
TDS	-.533	-.064	-.886	.803	1												
BOD	.863	-.995	.492	-.621	-.032	1											
NO_3^-	.999*	-.839	.839	-.913	-.490	.887	1										
SO_4^{2-}	.751	-.996	.319	-.461	.158	.982	.783	1									
PO_4^{3-}	-.919	.514	-.993	.999*	.823	-.594	-.899	-.431	1								
Cl	.822	-1.000*	.426	-.560	.043	.997*	.850	.993	-.532	1							
Cd	-.836	.999*	-.448	.580	-.019	-.999*	-.862	-.990	.552	-1.000*	1						
As	.788	-.999*	.373	-.511	.101	.991	.818	.998*	-.482	.998*	-.997	1					
Fe	-.799	1.000*	-.389	.527	-.083	-.993	-.828	-.997*	.498	-.999*	.998*	-1.000*	1				
Zn	-.875	.993	-.514	.640	.057	-1.000*	-.898	-.977	.614	-.995	.997*	-.988	.990	1			
Cr	-.176	.720	.341	-.192	-.739	-.650	-.225	-.782	-.225	-.705	.688	-.745	.733	.631	1		
Pb	.890	-.988	.542	-.665	-.089	.998*	.912	.969	-.639	.991	-.994	.982	-.985	-.999*	-.605	1	
Hg	-.719	.175	-.971	.922	.971	-.268	-.683	-.081	.934	-.195	.219	-.138	.156	.292	-.558	-.323	1

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Table 6: Pearson correlation coefficient matrix for the water sample in dry season

	pH	Temp	EC	TH	TDS	BOD	NO_3^-	SO_4^{2-}	PO_4^{3-}	Cl^-	Cd	As	Fe	Zn	Cr	Pb	Hg
pH	1	.															
Temp	.954	1															
EC	-.349	-.614	1														
TH	-.836	-.632	-.223	1													
TDS	-.759	-.529	-.345	.992	1												
BOD	-.909	-.992	.708	.530	.418	1											
NO_3^-	-.618	-.353	-.522	.948	.981	.233	1										
SO_4^{2-}	.953	1.000**	-.616	-.630	-.527	-.992	-.351	1									
PO_4^{3-}	-.896	-.721	-.105	.993	.970	.628	.903	-.719	1								
Cl	.977	.996	-.540	-.700	-.603	-.977	-.436	.996	-.780	1							
Cd	.004	-.297	.936	-.552	-.654	.414	-.789	-.299	-.448	-.209	1						
As	.997*	.973	-.417	-.793	-.709	-.937	-.558	.973	-.860	.990	-.070	1					
Fe	-.247	.055	-.822	.739	.818	-.180	.915	.057	.652	-.035	-.970	-.175	1				
Zn	.533	.254	.607	-.910	-.955	-.131	-.995	.252	-.854	.340	.848	.469	-.952	1			
Cr	-.180	-.467	.985	-.390	-.503	.574	-.662	-.469	-.276	-.385	.983	-.252	-.909	.737	1		
Pb	-.040	-.339	.951	-.515	-.620	.454	-.761	-.341	-.408	-.252	.999*	-.114	-.958	.824	.990	1	
Hg	.756	.918	-.877	-.272	-.147	-.960	.048	.918	-.385	.878	-.652	.802	.448	-.152	-.780	-.685	1

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Source–Pathway–Process–Impact (S–P–P–I) Conceptual Model

The results in Tables 3 and 4 indicate that river contamination arises from multiple sources and is strongly influenced by seasonal hydrological changes. To explain these interactions clearly, a Source–Pathway–Process–Impact (S–P–P–I) conceptual model was developed, as presented in Figure 2. The model groups pollution dynamics into four connected components: sources, pathways, processes, and impacts.

Three major pollution sources were identified from the spatial patterns and geochemical characteristics of the study area. The upstream coal mining zone contributes acid mine drainage (AMD), marked by high sulphate (SO_4^{2-}), elevated iron (Fe), and acidic pH conditions. The waste dump site introduces heavy metals such as Cd, Pb, and Cr, together with organic pollutants reflected in high biochemical oxygen demand (BOD), chloride (Cl^-), and increased electrical conductivity (EC). Agricultural runoff contributes nutrients, mainly nitrate (NO_3^-) and phosphate (PO_4^{3-}). This combination of mining, waste disposal, and agricultural

inputs reflects the mixed-source contamination commonly observed in multi-land-use catchments.

Pollutants enter and move through the river via several pathways, including surface runoff during the rainy season, direct discharge, subsurface flow, downstream transport, and sediment adsorption–desorption processes. Sediment interaction is especially important because contaminants can remain stored in sediments and be released gradually even after source inputs decline.

The main controlling processes include oxidation, mineral dissolution, contaminant mixing, seasonal dilution during rainfall, and concentration during dry periods. These processes create clear seasonal patterns, with lower contaminant concentrations in the wet season due to dilution and higher concentrations in the dry season because of reduced flow and pollutant accumulation. However, dilution may not fully reduce ecological risks, especially for sediment-bound heavy metals.

The combined impacts include elevated EC, TDS, and total hardness (TH), heavy metal levels above permissible limits, deterioration of aquatic ecosystems, reduced macroinvertebrate diversity, and increased human health risks through drinking water and irrigation exposure.

The model also provides important diagnostic, mechanistic, and seasonal insights. Specific contaminants can be linked to particular pollution sources: sulphate and iron indicate AMD, Cd–Pb–Cr identify waste dump contamination, while nitrate and phosphate suggest agricultural runoff. Such source identification improves pollution management and prevents misattribution of contamination to a single source.

In addition, the framework explains seasonal pollution behaviour by integrating processes such as oxidation, dissolution, mixing, and dilution–concentration dynamics. Similar seasonal trends have been reported in AMD-affected rivers by Guerrero et al. and Abrahams and Carranza, who observed dilution during peak rainfall and concentration during dry periods.

Overall, the S–P–P–I model converts individual pollutant measurements into a clear, seasonal, and management-focused framework for understanding river pollution. It is valuable because it identifies pollution sources, explains seasonal contaminant behaviour, highlights intervention points, and supports monitoring, remediation planning, and future predictive modelling

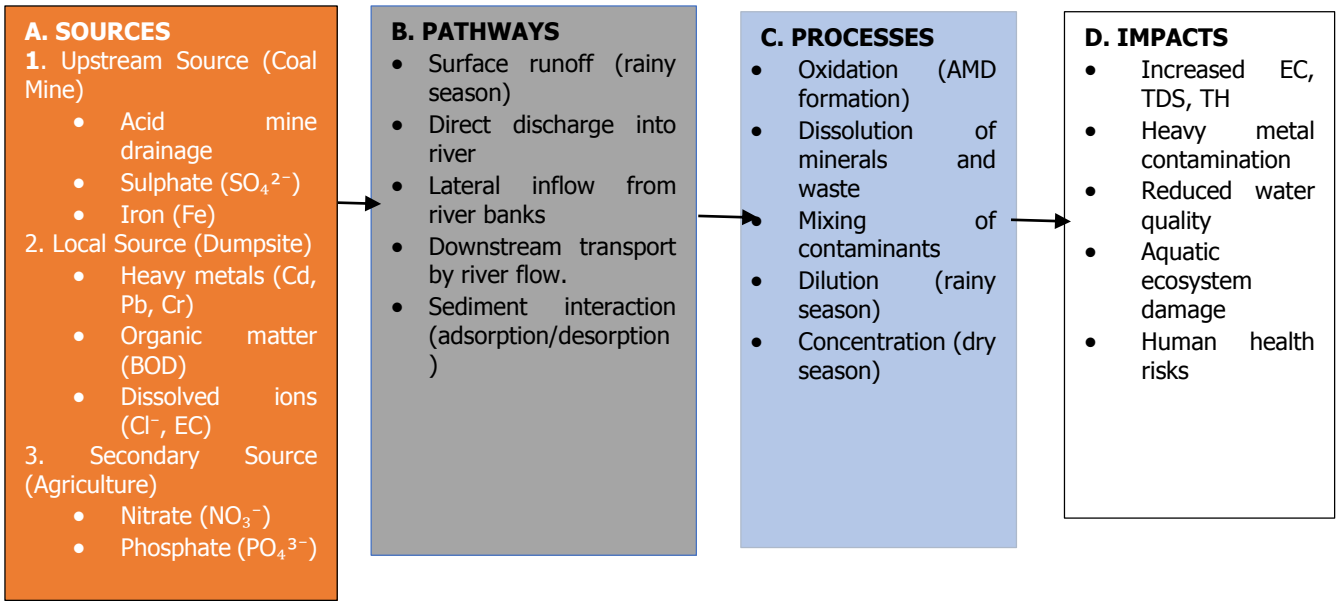

Figure 2: Conceptual model of the River Contamination System

WATER QUALITY INDICES (WQIS)

Water Quality Index

By combining several water quality criteria into a single score, the water quality index (WQI) of the examined river was evaluated using the weighted arithmetic technique to determine its overall acceptability for consumption (Shweta *et al.,* 2013; Wekesa and Otieno, 2022). According to the results, WQI values >100, or grade E, indicate that the water is unsafe for human consumption because of anthropogenic activities and needs to be treated before use. In particular, during the rainy season, WQI values varied from 124.08 to 133.43, while during the dry season, they varied from 136.94 to 184.90 (Tables 7–12). The results emphasize the necessity of properly treating water before use by indicating that trash disposal, agricultural activities, and residential effluents are the primary sources of pollution.

Table 7: The water quality index result for Station A in rainy season

$Parameters$	Sn	$K = 1/\sum 1/S_n$	$W_{n=K/S_n}$	Qn	$Wn * Qn$	WQI
pH	7.5	0.001380692	0.000184092	14.7	0.002706	133.43
Temperature	25	0.001380692	5.52277E-05	103.7468	0.00573	
EC	1000	0.001380692	1.38069E-06	18.65533	2.58E-05	
TH	300	0.001380692	4.60231E-06	47.5555667	0.000219	
TDS	500	0.001380692	2.76138E-06	34.04066	9.4E-05	
BOD	5	0.001380692	0.000276138	32.734	0.009039	
Nitrates	50	0.001380692	2.76138E-05	120.64	0.003331	
Sulphates	250	0.001380692	5.52277E-06	7.7893332	4.3E-05	
Phosphates	5	0.001380692	0.000276138	0.948	0.000262	
Chloride	250	0.001380692	5.52277E-06	22.428	0.000124	
Cadmium	0.003	0.001380692	0.460230769	15.5666667	7.164259	
Arsenic	0.01	0.001380692	0.138069231	316.67	43.72238	
Iron	0.3	0.001380692	0.004602308	58.4443333	0.268979	
Zinc	3	0.001380692	0.000460231	5.35556667	0.002465	
Chromium	0.05	0.001380692	0.027613846	205.734	5.681107	
Lead	0.01	0.001380692	0.138069231	457.33	63.1432	
Mercury	0.006	0.001380692	0.230115384	58.3333333	13.4234	
			1		133.4274	

Table 8: The water quality index result for Station B in rainy season

$Parameters$	Sn	$K = 1/\sum 1/S_n$	$W_{n=K/S_n}$	Qn	$Wn * Qn$	WQI
pH	7.5	0.001380692	0.000184092	6	0.001105	124.38
Temperature	25	0.001380692	5.52277E-05	105.5868	0.005831	
EC	1000	0.001380692	1.38069E-06	19.23067	2.66E-05	
TH	300	0.001380692	4.60231E-06	47.6666667	0.000219	
TDS	500	0.001380692	2.76138E-06	33.30934	9.2E-05	
BOD	5	0.001380692	0.000276138	31.4	0.008671	
Nitrates	50	0.001380692	2.76138E-05	115.36666	0.003186	
Sulphates	250	0.001380692	5.52277E-06	5.44	3E-05	
Phosphates	5	0.001380692	0.000276138	0.84866	0.000234	
Chloride	250	0.001380692	5.52277E-06	21.66	0.00012	
Cadmium	0.003	0.001380692	0.460230769	147.766667	68.00677	
Arsenic	0.01	0.001380692	0.138069231	26.67	3.682306	
Iron	0.3	0.001380692	0.004602308	83	0.381992	
Zinc	3	0.001380692	0.000460231	9.1889	0.004229	
Chromium	0.05	0.001380692	0.027613846	393.4	10.86329	
Lead	0.01	0.001380692	0.138069231	204.67	28.25863	
Mercury	0.006	0.001380692	0.230115384	57.2166667	13.16644	
			1		124.3832	

Table 9: The water quality index result for Station C in rainy season

$Parameters$	Sn	$K = 1/\sum 1/S_n$	$W_{n=K/S_n}$	Qn	$Wn * Qn$	WQI
pH	7.5	0.001380692	0.000184092	-7.3	-0.00134	124.08
Temperature	25	0.001380692	5.52277E-05	105.6	0.005832	
EC	1000	0.001380692	1.38069E-06	14.92767	2.06E-05	
TH	300	0.001380692	4.60231E-06	50.6666667	0.000233	
TDS	500	0.001380692	2.76138E-06	34.58666	9.55E-05	
BOD	5	0.001380692	0.000276138	31.134	0.008597	
Nitrates	50	0.001380692	2.76138E-05	108.59334	0.002999	
Sulphates	250	0.001380692	5.52277E-06	5.6386668	3.11E-05	
Phosphates	5	0.001380692	0.000276138	34.246	0.009457	
Chloride	250	0.001380692	5.52277E-06	21.624	0.000119	
Cadmium	0.003	0.001380692	0.460230769	156.766667	72.14884	
Arsenic	0.01	0.001380692	0.138069231	33.33	4.601847	
Iron	0.3	0.001380692	0.004602308	83.2223333	0.383015	
Zinc	3	0.001380692	0.000460231	9.84443333	0.004531	
Chromium	0.05	0.001380692	0.027613846	262.734	7.255096	
Lead	0.01	0.001380692	0.138069231	148.33	20.47981	
Mercury	0.006	0.001380692	0.230115384	83.3333333	19.17628	
			1		124.0755	

Table 10: The water quality index result for Station A in dry season

$Parameters$	Sn	$K = 1/\sum 1/S_n$	$W_{n=K/S_n}$	Qn	$Wn * Qn$	WQI
pH	7.5	0.001380692	0.000184092	-47	-0.00865	136.94
Temperature	25	0.001380692	5.52277E-05	112.3068	0.006202	
EC	1000	0.001380692	1.38069E-06	35.48367	4.9E-05	
TH	300	0.001380692	4.60231E-06	61.2222333	0.000282	
TDS	500	0.001380692	2.76138E-06	55.13334	0.000152	
BOD	5	0.001380692	0.000276138	40.334	0.011138	
Nitrates	50	0.001380692	2.76138E-05	72.89334	0.002013	
Sulphates	250	0.001380692	5.52277E-06	13.78	7.61E-05	
Phosphates	5	0.001380692	0.000276138	15.53334	0.004289	
Chloride	250	0.001380692	5.52277E-06	17.4906668	9.66E-05	
Cadmium	0.003	0.001380692	0.460230769	160	73.63692	
Arsenic	0.01	0.001380692	0.138069231	93.33	12.886	
Iron	0.3	0.001380692	0.004602308	85.8333333	0.395031	
Zinc	3	0.001380692	0.000460231	13.3555667	0.006147	
Chromium	0.05	0.001380692	0.027613846	472.666	13.05213	
Lead	0.01	0.001380692	0.138069231	245	33.82696	
Mercury	0.006	0.001380692	0.230115384	13.5666667	3.121899	
			1		136.9407	

Table 11: The water quality index result for Station B in dry season

$Parameters$	Sn	$K = 1/\sum 1/S_n$	$W_{n=K/S_n}$	Qn	$Wn * Qn$	WQI
pH	7.5	0.001380692	0.000184092	-35	-0.00644	151.44
Temperature	25	0.001380692	5.52277E-05	112.3332	0.006204	
EC	1000	0.001380692	1.38069E-06	31.12733	4.3E-05	
TH	300	0.001380692	4.60231E-06	60.4444333	0.000278	
TDS	500	0.001380692	2.76138E-06	55	0.000152	
BOD	5	0.001380692	0.000276138	37.334	0.010309	
Nitrates	50	0.001380692	2.76138E-05	73.68	0.002035	
Sulphates	250	0.001380692	5.52277E-06	18.6093332	0.000103	
Phosphates	5	0.001380692	0.000276138	15.06666	0.00416	
Chloride	250	0.001380692	5.52277E-06	26.036	0.000144	
Cadmium	0.003	0.001380692	0.460230769	126.666667	58.2959	
Arsenic	0.01	0.001380692	0.138069231	146.67	20.25061	
Iron	0.3	0.001380692	0.004602308	99.2223333	0.456652	
Zinc	3	0.001380692	0.000460231	13.1555667	0.006055	
Chromium	0.05	0.001380692	0.027613846	246.666	6.811397	
Lead	0.01	0.001380692	0.138069231	121.7	16.80303	
Mercury	0.006	0.001380692	0.230115384	212.05	48.79597	
			1		151.4366	

Table 12: The water quality index result for Station C in dry season

$Parameters$	Sn	$K = 1/\sum 1/S_n$	$W_{n=K/S_n}$	Qn	$Wn * Qn$	WQI
pH	7.5	0.001380692	0.000184092	-30	-0.00552	184.9
Temperature	25	0.001380692	5.52277E-05	112.32	0.006203	
EC	1000	0.001380692	1.38069E-06	34.83767	4.81E-05	
TH	300	0.001380692	4.60231E-06	56.6666667	0.000261	
TDS	500	0.001380692	2.76138E-06	51.6	0.000142	
BOD	5	0.001380692	0.000276138	37.934	0.010475	
Nitrates	50	0.001380692	2.76138E-05	69.19334	0.001911	
Sulphates	250	0.001380692	5.52277E-06	18.5946668	0.000103	
Phosphates	5	0.001380692	0.000276138	13.86666	0.003829	
Chloride	250	0.001380692	5.52277E-06	26.9813332	0.000149	
Cadmium	0.003	0.001380692	0.460230769	168.9	77.73298	
Arsenic	0.01	0.001380692	0.138069231	164.33	22.68892	
Iron	0.3	0.001380692	0.004602308	74.889	0.344662	
Zinc	3	0.001380692	0.000460231	13.9111	0.006402	
Chromium	0.05	0.001380692	0.027613846	481.334	13.29148	
Lead	0.01	0.001380692	0.138069231	299	41.2827	
Mercury	0.006	0.001380692	0.230115384	128.35	29.53531	
			1		184.9	

Heavy Metal Pollution Index (HPI)

The Heavy Metal Pollution Index (HPI) results in Table 13 showed clear seasonal and spatial differences in the level of heavy metal contamination across the sampled stations of the Mmili Ocha River. HPI is commonly used to assess the overall effect of heavy metals on water quality by combining the concentrations of different metals into a single value (Mohan *et al.,* 1996). According to Kabir *et al.,* (2020), HPI values below 100 indicate relatively safe water conditions, while values above 100 suggest serious heavy metal pollution.

During the rainy season, all stations recorded HPI values below the critical limit of 100. Station A had the highest value of 97.89, followed by Station C (89.21) and Station B (88.36) (Table 13). Although these values were still within the acceptable range, the result from Station A was very close to the pollution threshold, indicating increasing heavy metal pressure in the river.

The relatively high HPI values during this season may be linked to runoff carrying contaminants from dumpsites, domestic wastes, agricultural activities, and mine-related sources into the river system. Similar findings have been reported in polluted freshwater environments where rainfall runoff increases metal contamination (Etim *et al.,* 2013).

A higher level of contamination was observed during the dry season. Station A recorded an HPI value of 97.52, which remained slightly below the critical limit, whereas Stations B and C recorded values of 112.07 and 135.22 respectively, exceeding the permissible limit of 100. This indicates significant heavy metal pollution, especially at Station C. The increase in HPI during the dry season may be due to reduced water volume and higher evaporation, which can concentrate dissolved heavy metals in the river. Pollution from urban runoff, waste disposal, and leachates from nearby dumpsites may have also contributed to the elevated values. Similar seasonal increases in heavy metal levels during dry periods have been reported in other tropical rivers and urban water bodies (Majolagbe *et al.,* 2023; Nwosu *et al.,* 2021).

The elevated HPI values correspond with the high concentrations of toxic metals detected in the river water. Cadmium concentrations ranged from 0.0005–0.0051 mg/L, chromium from 0.103–0.241 mg/L, lead from 0.0148–0.046 mg/L, and mercury from 0.00343–0.0123 mg/L, with several values exceeding the permissible limits recommended by WHO (2022) and NSDWQ (2015). Chromium consistently exceeded the recommended limit of 0.05 mg/L across both seasons, while lead and cadmium also exceeded acceptable limits in some stations. These elevated concentrations contributed greatly to the increased HPI values recorded, particularly during the dry season.

Overall, the HPI results indicate that the Mmili Ocha River is under increasing heavy metal pollution pressure, with contamination becoming more severe during the dry season. Although some stations recorded values slightly below the critical limit, their closeness to the threshold suggests possible future deterioration if pollution sources are not properly controlled. The findings highlight the need for regular monitoring and improved environmental management practices to reduce heavy metal contamination and protect public health.

Metal Index (MI)

The Metal Index (MI) results presented in Table 14 revealed a high level of heavy metal contamination in the Mmili Ocha River across all sampling stations during both seasons. The Metal Index is commonly used to evaluate the degree of heavy metal pollution in water by comparing the concentration of each metal with its maximum permissible limit for drinking water (Tamasi & Cini, 2004). According to Caeiro *et al.,* (2005) and Bakan *et al.,* (2010), MI values greater than 6 indicate that water is seriously affected by heavy metal pollution.

The results obtained in this study showed that all stations recorded MI values far above the acceptable limit, with values ranging from 7.73 to 13.27 (Table 14). During the rainy season, Station A recorded the highest MI value of 11.31, followed by Station B (9.18) and Station C (7.73). In the dry season, the contamination level increased further, especially at Station C which recorded the highest value of 13.27, while Stations A and B recorded 10.78 and 9.54 respectively. These findings indicate that the river is heavily polluted by heavy metals throughout the year.

The consistently high MI values suggest continuous discharge of pollutants into the river from human activities such as indiscriminate waste disposal, urban runoff, dumpsite leachates, and possible contamination from the abandoned Onyeama coal mine located upstream. The higher MI values recorded during the dry season may be due to lower water volume and increased evaporation, which tend to increase the concentration of dissolved heavy metals in the river water. Station C appeared to be the most affected area, likely because of downstream accumulation of contaminants and increased surrounding human activities.

The elevated MI values correspond with the high concentrations of toxic metals detected in the river water. Chromium concentrations ranged from 0.103–0.241 mg/L and consistently exceeded the WHO (2022) permissible limit of 0.05 mg/L. Cadmium, lead, arsenic, and mercury also exceeded recommended limits at some sampling stations. These elevated metal concentrations contributed significantly to the high MI values observed in the river.

Overall, the MI results indicate that the Mmili Ocha River is seriously contaminated with heavy metals and may pose environmental and public health concerns to communities that depend on the river for domestic and other uses. The findings emphasize the need for regular monitoring, improved waste management practices, and effective pollution control measures to reduce further contamination of the river system.

Table 13: The result on the heavy metal pollution index of the analysed river

Season	Location	HPI Value	Class	Water Quality Status
Raining	Station A	97.89	HPI < 100	Safe for drinking and free from heavy metal pollution.
	Station B	88.36	HPI < 100	Safe for drinking and free from heavy metal pollution.
	Station C	89.21	HPI < 100	Safe for drinking and free from heavy metal pollution.
Dry	Station A	97.52	HPI < 100	Safe for drinking and free from heavy metal pollution.
	Station B	112.07	HPI > 100	Indicates contamination by heavy metals.
	Station C	135.22	HPI > 100	Indicates contamination by heavy metals.

Table 14: The result on the metal index of the analysed river

Season	Location	MI Value	Range	Water Quality Status	Description
Raining	Station A	11.31	MI > 1	Seriously affected	Severe heavy metal contamination.
	Station B	9.18	MI > 1	Seriously affected	Severe heavy metal contamination.
	Station C	7.73	MI > 1	Seriously affected	Severe heavy metal contamination
Dry	Station A	10.78	MI > 1	Seriously affected	Severe heavy metal contamination
	Station B	9.54	MI > 1	Seriously affected	Severe heavy metal contamination
	Station C	13.27	MI > 1	Seriously affected	Severe heavy metal contamination

HUMAN HEALTH RISK ASSESSMENT

The Human Health Risk Assessment (HHRA) results presented in Table 15 were used to evaluate the potential non-carcinogenic health risks associated with exposure to heavy metals in the Mmili Ocha River through ingestion, inhalation, and dermal contact. The assessment was based on average daily dose (ADD), reference dose (RfD), hazard quotient (HQ), and total hazard index (THI). According to the U.S. Environmental Protection Agency (USEPA, 1989; 2011), HQ and THI values below 1 indicate that adverse health effects are unlikely. The computed ADD, HQ, and THI values are summarized in Table 15. The results showed that all HQ values for Cd, As, Fe, Zn, Cr, Pb, and Hg were below the recommended safety limit for both children and adults. This suggests that the heavy metals currently pose low non-carcinogenic health risks to the residents of the study area. However, children recorded higher ADD and HQ values than adults across all exposure pathways. This is expected because children are usually more vulnerable to environmental pollutants due to their lower body weight, higher intake rates, and developing body systems (WHO, 2017).

Among the different exposure routes, ingestion contributed the highest risk compared to inhalation and dermal contact. For example, chromium (Cr) recorded an ingestion HQ of 5.24×10^{-4} in children, which was higher than the inhalation and dermal values. A similar trend was observed for arsenic (As), where ingestion exposure was also higher than the other pathways. This indicates that contaminated water, food, and accidental ingestion of polluted particles may be the major routes through which residents are exposed to heavy metals. Similar observations have been reported by Wu et al. (2009) and Tchounwou et al. (2012), who identified ingestion as the main pathway of heavy metal exposure in contaminated environments.

Cadmium (Cd) recorded the highest inhalation HQ value in children (2.03×10^{-1}), although the value was still below the safety threshold. The relatively higher Cd exposure may be linked to human activities such as waste disposal, mining-related inputs, and airborne particulates. Long-term exposure to cadmium has been associated with kidney damage and bone-related diseases (Jarup, 2003).

Chromium and arsenic also showed relatively higher ingestion HQ values compared to the other metals. This is important because both metals are known for their toxic effects on human health. Prolonged exposure to arsenic has been linked to skin diseases, cardiovascular problems, and cancer, while chromium toxicity may affect the liver, kidneys, and respiratory system (ATSDR, 2007; WHO, 2018).

Lead (Pb) and mercury (Hg) showed relatively low exposure levels across all pathways, suggesting limited immediate health risks. Nevertheless, these metals remain a concern because they can accumulate in the body over time and may affect the nervous system, especially in children. Previous studies have shown that even low levels of lead exposure can impair learning ability and cognitive development (WHO, 2010).

The total hazard index (THI) values for both children and adults were also below 1, confirming that the combined exposure to these heavy metals is unlikely to cause immediate non-carcinogenic health effects. However, children recorded higher THI values than adults, indicating that they are more susceptible to environmental contamination.

Overall, the findings suggest that heavy metal contamination in Abakpa currently poses low non-carcinogenic health risks to residents. Despite this, the continuous presence of toxic metals such as Cd, Cr, As, Pb, and Hg highlights the need for regular environmental monitoring, proper waste management, and pollution control measures to prevent long-term health and environmental problems.

Table 15: Health Risk Assessment of the Heavy Metals on the Residents of Abakpa

Metals	Metal Conc.	Age group	Inhalation			Ingestion			Dermal		
			ADD	RfD	HQ	ADD	RfD	HQ	ADD	RfD	HQ
Cd	0.0039 ±0.0017	Children	$1.35E^{-12}$	$6.67E^{-6}$	$2.03\ E^{-1}$	$3.56E^{-8}$	$1.00\ E^{-3}$	$3.56E^{-5}$	$9.97E^{-11}$	$2.50\ E^{-5}$	$3.98\ E^{-5}$
		Adult	$5.79E^{-13}$	$2.86E^{-6}$	$2.03\ E^{-7}$	$3.82E^{-9}$		$3.82E^{-6}$	$8.82E^{-12}$		$3.53\ E^{-7}$
As	0.013 ± 0.011	Children	$4.51E^{-12}$	$2.00E^{-5}$	$2.26\ E^{-7}$	$1.19E^{-7}$	$3.00\ E^{-4}$	$3.96E^{-4}$	$3.32E^{-10}$	$2.85\ E^{-4}$	$1.16\ E^{-6}$
		Adult	$1.93E^{-12}$	$8.57\ E^{-6}$	$2.26\ E^{-7}$	$1.27E^{-8}$		$4.24E^{-5}$	$2.94E^{-11}$		$1.03\ E^{-7}$
Fe	0.242 ± 0.041	Children	$8.39E^{-11}$			$2.21E^{-6}$	$7.00\ E^{-1}$	$3.16E^{-6}$	$6.19E^{-9}$	$7.00\ E^{-2}$	$8.84\ E^{-8}$
		Adult	$3.59E^{-11}$			$2.37E^{-7}$		$3.38E^{-7}$	$5.47E^{-10}$		$7.81\ E^{-9}$
Zn	0.324 ± 0.099	Children	$1.12E^{-10}$	$2.00E^{-4}$	$5.62\ E^{-7}$	$2.96E^{-6}$	$3.00\ E^{-1}$	$9.86E^{-6}$	$8.29E^{-9}$	$9.00\ E^{-2}$	$9.21\ E^{-8}$
		Adult	$4.82E^{-11}$	$8.57\ E^{-5}$	$5.62\ E^{-7}$	$3.17E^{-7}$		$1.06E^{-6}$	$7.32E^{-10}$		$8.13\ E^{-9}$
Cr	0.172 ± 0.060	Children	$5.97E^{-11}$	$6.67E^{-5}$	$8.95\ E^{-7}$	$1.57E^{-6}$	$3.00\ E^{-3}$	$5.24E^{-4}$	$4.39E^{-9}$	$7.50\ E^{-5}$	$5.85\ E^{-5}$
		Adult	$2.56E^{-11}$	$2.86\ E^{-5}$	$8.95E^{-7}$	$1.68E^{-7}$		$5.61E^{-5}$	$3.88E^{-10}$		$5.17\ E^{-6}$
Pb	0.0246 ± 0.0122	Children	$8.54E^{-12}$			$2.25E^{-7}$			$6.29E^{-10}$		
		Adult	$3.l66E^{-12}$			$2.41E^{-8}$			$5.56E^{-11}$		
Hg	0.0055 ± 0.0042	Children	$1.91E^{-12}$	$2.00E^{-4}$	$9.54\ E^{-9}$	$5.02E^{-8}$	$3.00\ E^{-4}$	$1.67E^{-4}$	$1.41E^{-10}$	$2.10\ E^{-5}$	$6.71\ E^{-6}$
		Adult	$8.18E^{-13}$	$8.57E^{-5}$	$9.54\ E^{-9}$	$5.38E^{-9}$		$1.79E^{-5}$	$1.24E^{-11}$		$5.90\ E^{-7}$
THI		Children			0.203			$1.14E^{-3}$			$1.06E^{-4}$
		Adult			$1.90E^{-6}$			$1.21E^{-4}$			$6.23E^{-6}$

CONCLUSION

Anthropogenic activities have a major impact on the Mmili Ocha River at Abakpa Nike, making the water unfit for human consumption without treatment. In order to safeguard the aquatic ecosystem and public health in this densely populated region of Enugu State, Nigeria, the results highlight the critical need for integrated environmental management strategies that address both legacy pollution from past mining operations and current contamination from inappropriate waste disposal practices.

Competing Interest:

The authors affirm that the work presented in this paper was not influenced by any known financial or non-financial competing interests.

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Author's contributions:

Ezechi, Ejikeme C. was in charge of the study's idea, methodology, data analysis, and initial draft.

Iyioku M.U. also wrote the first draft, analyzed the data, reviewed and edited the manuscript, and offered general assistance all along the way.

REFERENCES

Abrahams, J.-L. R., & Carranza, E. J. M. (2024). Geochemical characterization of an AMD-affected stream: Detection of associated trace metal contamination using element 'dilution factors'. *Mine Water and the Environment*. Advance online publication. https://doi.org/10.1007/s10230-024-00982-6

Ademoroti, C. M. A. (1996). *Standard methods for waste and effluent analysis* (pp. 55–70). Foludex Press Ltd.

Amadi, B. A., Agomuo, E. N., & Ibegbulem, C. O. (2004). *Research methods in biochemistry* (pp. 90–115). Supreme Publishers.

AOAC. (2004). *Official methods of analysis of the Association of Official Analytical Chemists* (15th ed.). AOAC.

APHA. (2015). *Standard methods for the examination of water and wastewater* (21st ed.). American Public Health Association.

ATSDR. (2007). *Toxicological profile for arsenic*. Agency for Toxic Substances and Disease Registry, U.S. Department of Health and Human Services. https://www.atsdr.cdc.gov/toxprofiles/tp2.pdf

Bakan, G., Özkoç, H. B., Tülek, S., & Cüce, H. (2010). Integrated environmental quality assessment of Kızılırmak River and its coastal environment. *Turkish Journal of Fisheries and Aquatic Sciences, 10*(4), 453–462.

Bernhard, A. (2010). The nitrogen cycle: Processes, players, and human impact. *Nature Education Knowledge, 3*(10), 25.

Caeiro, S., Costa, M. H., Ramos, T. B., Fernandes, F., Silveira, N., Coimbra, A., Medeiros, G., & Painho, M. (2005). Assessing heavy metal contamination in Sado Estuary sediment: An index analysis approach. *Ecological Indicators, 5*(2), 151–169. https://doi.org/10.1016/j.ecolind.2005.02.001

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, 8(3), 559-568.

Chandra, S. D., Asadi, S. S., & Raju, M. V. S. (2017). Estimation of water quality index by weighted arithmetic water quality index method: A model study. *International Journal of Civil Engineering and Technology, 8*(4), 1215–1222.

Dewangan, S. K., Shrivastava, S. K., Tigga, V., Lakra, M., Namrata, & Preeti. (2023). *Review paper on the role of pH in water quality implications for aquatic life, human health, and environmental sustainability*. International Advanced Research Journal in Science, Engineering and Technology (IARJSET), 10(6), 215–220. https://doi.org/10.17148/IARJSET.2023.10633

Etim, E. E., Odoh, R., Itodo, A. U., Umoh, S. D., & Lawal, U. (2013). Water quality index for the assessment of water quality from different sources in the Niger Delta region of Nigeria. *Frontiers in Science, 3*(3), 89–95. https://doi.org/10.5923/j.fs.20130303.02

Ezechi, E. C., & Diara, C. I. (2025). Assessment of water quality index of Ogbanokwute spring water in Enugu North Local Government Area of Enugu State, Nigeria. *ChemSearch Journal, 16*(2), 47–57.

Guerrero, J. L., Gutiérrez-Álvarez, I., Hierro, A., Pérez-Moreno, S. M., Olías, M., & Bolívar, J. P. (2021). Seasonal evolution of natural radionuclides in two rivers affected by acid mine drainage and phosphogypsum pollution. *Catena*, 197, 104978.

Ihedioha, J. N., Ukoha, P. O., & Ekere, N. R. (2017). Ecological and human health risk assessment of heavy metal concentration in soil of a municipal solid waste dump in Uyo, Nigeria. *Environmental Geochemistry and Health, 39*, 497–515. https://doi.org/10.1007/s10653-016-9830-8

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology, 7*(2), 60–72. https://doi.org/10.2478/intox-2014-0009

Jarup, L. (2003). Hazards of heavy metal contamination. *British Medical Bulletin, 68*(1), 167–182. https://doi.org/10.1093/bmb/ldg032

Kabir, M. H., Islam, M. S., Hoq, M. E., Tusher, T. R., & Islam, M. S. (2020). Appraisal of heavy metal contamination in sediments of the Shitalakhya River in Bangladesh using pollution indices, geo-spatial, and multivariate statistical analysis. *Arabian journal of geosciences*, *13*(21), 1135.

Kalagbor, I. A., Echem, O. G., & Banwo, E. (2021). Water quality assessment of Ntawogba Stream in Port Harcourt metropolis, Rivers State, Nigeria. *International Journal of Water Resources and Environmental Engineering, 13*(1), 76–87.

Kaushal, S., Mon, A., Grant, S., Mayer, P. M., Porter, A. J., Sekellick, A. J., Chase, J., Bhide, S., Jastram, J. D., Newcomer-Johnson, T., Shelton, S. A., Yaculak, A. M., Malin, J. T., Maas, C. M., Salanitri, N., Silberstein, D. J., Hohman, S. P., Dann, A. B., Slaughter, W. M., Rippy, M. A., Monofy, A., Shatkay, R. R., Reimer, J. E., Seppi, M., Noel, R., Mussa, J., Kellmayer, B., Sivirichi, G., Grese, M., Boger, W. L., Chanat, J. G., Duan, S., & Belt, K. T. (2026). Watershed Continuum Monitoring Approach: Combining multiple water quality patterns along stream and river flowpaths to track sources, pathways, and processing of pollutants. *Ecological Engineering*, 229, 107971. https://doi.org/10.1016/j.ecoleng.2026.107971

Ken-Onukuba, D. N., Okeke, O. C., Amadi, C. C., Akaolisa, C. C. Z., Okonkwo, S. I., Offoh, J. I., & Nwachukwu, H. G. O. (2021). Water quality assessment of Ekulu and Asata Rivers in Enugu Area, Southeastern Nigeria using physico-chemical and bacteriological parameters. *Journal of Environment and Earth Science, 11*(4), 70–92.

Khan, N., Kumar, A., Sharma, V., & Farooq, U. (2015). Effect of temperature and distance on physico-chemical and biological parameters of Ghaggar River water, India. *International Journal of Current Microbiology and Applied Sciences, 4*(1), 614–624.

Kumar, V., Arya, S., Dhaka, A., Minakshi, & Chanchal. (2011). *A study on physico-chemical characteristics of Yamuna River around Hamirpur (U.P.), Bundelkhand region, central India*. *International Multidisciplinary Research Journal, 1*(5), 14–16.

Majolagbe, A. O., Adeyi, A., & Osibanjo, O. (2014). Hydrochemical characterization and quality assessment of groundwater in the vicinities of a major active dumpsite in Lagos, Nigeria: the use of multivariate analytical technique and water quality indices. *Europe Water48*, 29-42

Majolagbe, A. O., Anko, S. O., Onwordi, C. T., Sobola, A. O., & Wusu, O. E. (2023). Physicochemical and trace metals characterisation: An impact assessment of Badagry Creek on groundwater quality in Ojo Community, Lagos, Nigeria. *ChemSearch Journal, 14*(2), 107–117.

Man, K., Ma, Z. M., & Xu, X. J. (2014). Research on the mechanism of sulfate pollution of groundwater in Jiaozuo area. *Applied Mechanics and Materials, 665*, 436–439. https://doi.org/10.4028/www.scientific.net/AMM.665.436

Manavi Yadav, Radhika Gupta, Rakesh Kumar Sharma (2019). Advances in Water Purification Techniques: Meeting the Needs of Developed and Developing Countries. Chapter 14 - Green and Sustainable Pathways for Wastewater Purification. Journal of science direct, Copyright © 2019 Elsevier Inc. Edited by Satinder Ahuja. Ahuja Consulting, Calabash, NC, United States Pages 355-383. https://doi.org/10.1016/B978-0-12-814790-0.00014-4 OR https://doi.org/10.1016/C2017-0-01909-2

Mbae, M., Hansen, P., Way, C., Mills, F., Willetts, J., Foster, T., & Evans, B. (2024). Onsite sanitation systems and contamination of groundwater: A systematic review of the evidence for risk using the source-pathway-receptor model. *PLOS Water*, 3 (7), e0000167.

Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A., Idris, A. M., Khandaker, M. U., Osman, H., Alhumaydhi, F. A., & Simal-Gandara, J. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. Journal of King Saud University – Science, 34(3), 101865. https://doi.org/10.1016/j.jksus.2022.101865

Mohan, S. V., Nithila, P., & Reddy, S. J. (1996). Estimation of heavy metals in drinking water and development of heavy metal pollution index. *Journal of Environmental Science and Health, Part A, 31*(2), 283–289. https://doi.org/10.1080/10934529609376357

NSDWQ (2015). Nigerian Standards for Drinking Water Quality, Nigerian Industrial Standards NIS-554- 2015 Approved by the Standard Society of Nigeria (SON).

Nwabunike, M. O. (2016). Monthly variation in physicochemical parameters of Ebonyi River system. *Global Journal of Fisheries and Aquaculture, 4*(1), 270–280.

Nwosu, T. V., Nwaiwu, C. J., & Egboka, N. T. (2021). Analysis of water quality deterioration in Nworie River, Owerri, Imo State, Southeast Nigeria. *Journal Clean WAS, 5*(2), 58–61. https://doi.org/10.26480/jcleanwas.02.2021.58.61

Otero, N., Canals, À., & Soler, A. (2007). Using dual-isotope data to trace the origin and processes of dissolved sulphate: A case study in Calders Stream (Llobregat Basin, Spain). *Aquatic Geochemistry, 13*, 109–126. https://doi.org/10.1007/s10498-007-9010-3

Phyllis, K. W., & Lawrence, K. D. (2007). Effects of total dissolved solids on aquatic organisms: A review of literature and recommendation for salmonid species. American Journal of Environmental Sciences, 3(1), 1-6.

Raid Al-Khateeb (2014). Influence of Chloride Concentration on Water Quality. International Journal of Applied Engineering Research and Development. 4(1): 63-68

Rajkumar, S., Velmurugan, P., Shanthi, K., Ayyasamy, P. M., & Lakshmanaperumalasamy, P. (2004). Water quality of Kodaikanal Lake in relation to physicochemical and bacteriological characteristics. *Lake 2004 Proceedings*, 339–346.

Rubel, M. D., Shahidul, I., Sheikh, M. A., & Mohammad, H. U. (2019). Assessment of dissolved oxygen and solids in industrial effluents and their impact on public health. *American Journal of Biomedical Science and Research, 5*(5), 382–390.

Sawyer, C. N., McCarty, P. L., & Parkin, G. F. (2003). *Chemistry for environmental engineering and science* (Vol. 5, p. 587590). New York: McGraw-Hill.

Shweta T, Bhavtosh S, Prashant S, Rajendra D. (2013). Water Quality Assessment in Terms of Water Quality Index, American Journal of Water Resources. 1 (3): 34-38

Tamasi, G., & Cini, R. (2004). Heavy metals in drinking water from Mount Amiata (Tuscany, Italy). *Science of the Total Environment, 327*(1–3), 41–51. https://doi.org/10.1016/j.scitotenv.2003.10.011

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *EXS, 101*, 133–164. https://doi.org/10.1007/978-3-7643-8340-4_6

U.S. Environmental Protection Agency. (1989). *Risk assessment guidance for Superfund (RAGS), Volume I: Human health evaluation manual (Part A)*. Office of Emergency and Remedial Response.

U.S. Environmental Protection Agency. (2011). *Exposure factors handbook: 2011 edition*. https://www.epa.gov/expobox/exposure-factors-handbook

UNEP. (2021). *Progress on freshwater ecosystem management*. United Nations Environment Programme.

UNESCO. (2009). *The United Nations world water development report 3: Water in a changing world*. UNESCO.

UNESCO. (2020). *The United Nations world water development report 2020: Water and climate change*. UNESCO.

USEPA. (2011). *Risk assessment guidance for Superfund (RAGS)*. U.S. Environmental Protection Agency.

Wekesa, A. M., & Otieno, C. (2022). Assessment of groundwater quality using water quality index. *Scientific World Journal*, 2022, Article 3498394. https://doi.org/10.1155/2022/3498394

WHO (World Health Organization), 2017. *Guidelines for Drinking-water Quality: Fourth Edition Incorporating the First Addendum* WHO, Geneva

World Health Organization. (1996). *Total dissolved solids in drinking water*. WHO.

World Health Organization. (2007). *pH in drinking-water*. WHO.

World Health Organization. (2009). *Calcium and magnesium in drinking water: Public health significance*. WHO.

World Health Organization. (2010). *Childhood lead poisoning*. WHO Press. https://www.who.int/publications/i/item/9789241500333

World Health Organization. (2011). *Hardness in drinking water*. WHO.

World Health Organization. (2017). *Guidelines for drinking-water quality* (4th ed., incorporating 1st addendum). WHO Press. https://www.who.int/publications/i/item/9789241549950

World Health Organization. (2018). *Arsenic fact sheet*. https://www.who.int/news-room/fact-sheets/detail/arsenic

World Health Organization. (2022). *Guidelines for drinking-water quality* (4th ed.). WHO.

Wufem, B. M., Ibrahim, A. Q., Gin, N. S., Shibdawa, M. A., Adamu, H. M., & Agya, P. J. (2009). Levels of heavy metals in Gubi dam water Bauchi, Nigeria. *Global journal of environmental sciences*, *8*(2).

Zeyneb Kilic(2020). The importance of water and conscious use of water. International journal of hydrology. 4(5):239-241. DOI:10.15406/ijh.2020:04:00250