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Assessment of Metal (loid)s in Tap Water from Schools in the Niger Delta: Water Quality and Health Risk Implications for Students

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Abstract

The Niger Delta region of Nigeria faces persistent water quality challenges driven by rapid urbanization, oil-related industrial activity, and aging infrastructure. Despite numerous environmental assessments in the region, drinking water quality within schools—where children represent a highly vulnerable population—remains largely unexplored. This study provides a targeted evaluation of metal(loid) contamination in tap water from 30 primary and secondary schools distributed across urban (Port Harcourt, Warri) and peri-urban/rural communities. Concentrations of Pb, Cd, As, Hg, Cr, Ni, Cu, Zn, Fe, and Mn were determined using atomic absorption spectrometry, with rigorous QA/QC procedures. Samples were collected under flushed conditions and acidified, representing total recoverable metal fractions. Mean concentrations (µg/L) decreased in the order Zn > Fe > Cu > Mn > Pb > Ni > Cr > As > Cd > Hg. Lead exceeded the WHO guideline (10 µg/L) in 47% of schools. Entropy-Weighted Water Quality Index (EWQI) results classified 80% of samples as excellent to good, whereas 20% were medium to poor. Multivariate analyses (PCA with KMO = 0.72; Bartlett's $p < 0.001$) identified two dominant factors: (1) infrastructure-related corrosion (Pb–Zn–Cu–Fe) and (2) geogenic/industrial influences (As–Hg–Cr). Health risk assessment following USEPA guidelines indicated that non-carcinogenic risk was generally below the safety threshold (HI < 1), although exceedances occurred in 10% of schools for children. Carcinogenic risk values for Pb and As surpassed the acceptable limit (1×10^{-4}) in 30% of locations. Although limited by sample size and single-season sampling, the findings highlight infrastructure deterioration as a key determinant of school drinking water quality and underscore the need for systematic monitoring and targeted remediation to protect children's health.

Keywords: Niger Delta, Tap water, Heavy metals, Health risk assessment, Water quality, Source apportionment

1. Introduction

Access to safe and clean drinking water is a fundamental human right and a cornerstone of public health, as enshrined in the United Nations' Sustainable Development Goal 6 (SDG-6) (UN-Water, 2018). Despite global efforts, billions of people, particularly in developing nations, still lack access to safely managed drinking water services. The contamination of water sources with toxic metal(loid)s such as lead (Pb), arsenic (As), cadmium (Cd), and mercury (Hg) represents a formidable and persistent public health crisis (Landrigan et al., 2018). These elements are non-biodegradable, bio-accumulative, and can exert severe toxic effects even at trace concentrations, including neurodevelopmental disorders, renal damage, and various forms of cancer (Jaishankar et al., 2014; Tchounwou et al., 2012).

Children are recognized as a uniquely vulnerable population group. Their higher metabolic rates, greater water intake per unit of body weight, and developing physiological systems make them more susceptible to the adverse effects of toxic metal(loid)s (World Health Organization [WHO], 2006). Exposure to Pb, for instance, is unequivocally linked to irreversible cognitive impairment and reduced IQ in children, even at blood levels previously considered safe (Lanphear et al., 2005). Similarly, chronic As exposure is associated with skin lesions, developmental effects, and cancer, while Cd can lead to skeletal and renal damage (WHO, 2017). Consequently, ensuring the safety of water consumed by children, especially in environments like schools where they spend a significant portion of their day, is of paramount importance.

The Niger Delta region of Nigeria presents a critical case study for environmental and public health challenges. It is one of the world's largest deltas, characterized by a complex network of rivers, creeks, and swamps, and is home to over 30 million people (United Nations Development Programme [UNDP], 2006). For over six decades, the region has been the epicentre of Nigeria's oil and gas industry. While this has driven national economic growth, it has come at a profound environmental cost, including frequent oil spills, gas flaring, and the unregulated disposal of industrial and municipal waste (Bello & Amadi, 2019; Emoyan et al., 2008). These activities have led to widespread contamination of surface water, groundwater, and soil with a cocktail of pollutants, including heavy metals.

The population of the Niger Delta relies on a patchwork of water sources, including municipal supplies, private boreholes, and, in many rural areas, untreated surface water. Municipal water infrastructure, where it exists, is often old and poorly maintained, creating a high potential for contaminants to leach from corroding pipes into the water supply (Adesuyi et al., 2015). Despite numerous studies on the general environmental pollution in the Niger Delta (Ogundele et al., 2019; Ordinioha & Brisibe, 2013), there is a significant research gap concerning the quality of tap water specifically within educational institutions and the direct health risks posed to students. This is a critical oversight, as schools represent a key point of exposure for a large and vulnerable demographic.

Access to safe drinking water in educational institutions remains insufficiently studied in many developing regions, despite growing evidence that children represent one of the most vulnerable subpopulations to chronic metal(loid) exposure. Numerous investigations in the Niger Delta have evaluated heavy metals in rivers, groundwater, and household boreholes (e.g., Ogundele et al., 2019; Emoyan et al., 2008), yet none have specifically targeted school tap water as a discrete exposure microenvironment. This distinction is critical because schools differ from households in plumbing age, water stagnation patterns, student density, and daily consumption behaviors.

Previous regional studies have primarily focused on surface water impacted by oil exploration or groundwater from private boreholes. However, metal(loid) concentrations in point-of-use tap water may differ substantially due to distribution-system corrosion, stagnation effects, and infrastructure deterioration. Furthermore, most prior investigations have emphasized concentration-based comparisons with standards, with limited application of risk-based frameworks tailored to school-aged children.

The novelty of this study lies in:
(1) the exclusive focus on tap water within educational institutions;
(2) simultaneous analysis of ten metal(loid)s representing both geogenic and anthropogenic signatures;
(3) integration of entropy-weighted water quality assessment with probabilistic health risk evaluation; and
(4) multivariate source discrimination specifically linked to infrastructure age and urbanization patterns.
By addressing this underexplored exposure pathway, the present study provides a more targeted understanding of drinking water safety within a high-risk population in the Niger Delta.

2. Methodology and Data

2.1. Study Area

The study was conducted in the Niger Delta, a vast deltaic plain located in the southern part of Nigeria, covering an area of approximately 70,000 km². The region is characterized by a hot, humid tropical climate with distinct wet (April-October) and dry (November-March) seasons, and an average annual rainfall exceeding 3,000 mm (UNDP, 2006). Its hydrogeology is dominated by a complex system of rivers, with the Niger River branching into numerous distributaries before emptying into the Atlantic Ocean. The geology of the region is composed of three main Tertiary sedimentary formations (Fig. 1): the basal Akata Formation (marine shales), the overlying Agbada Formation (alternating sandstones and shales, which host the region's hydrocarbon reservoirs), and the topmost Benin Formation (coastal plain sands) (Short & Stauble, 1967). This Benin Formation, comprising unconsolidated sands and gravels, is the primary aquifer system providing groundwater for domestic, industrial, and agricultural use across the region.

The investigation covered two major urban centers—Port Harcourt (Rivers State) and Warri (Delta State)—and ten surrounding peri-urban and rural communities distributed across the eastern and central Niger Delta sub-basins. All sampled schools rely primarily on groundwater abstracted from the Benin Formation aquifer, either via state-managed municipal supply networks or private borehole systems.

The Benin Formation consists predominantly of unconsolidated coastal plain sands with minor clay intercalations, characterized by high permeability and shallow water tables. Iron and manganese enrichment in groundwater has been previously associated with reductive dissolution processes within this aquifer. Conversely, trace elements such as As and Cr may originate from weathering of underlying Agbada shales or from industrial emissions associated with oil refining and gas flaring.

To avoid overgeneralization, we did not assume direct geological sources for individual metals without statistical support. Instead, source attribution was based on combined hydrogeological context, spatial distribution, and multivariate loadings.

School characteristics were recorded during sampling, including:

Urban vs rural classification
Public vs private ownership
Year of establishment
Water source type (municipal vs borehole)
Approximate student population

Older schools (>30 years) were predominantly connected to aging galvanized or mixed copper plumbing systems, whereas newer schools used PVC-based distribution.

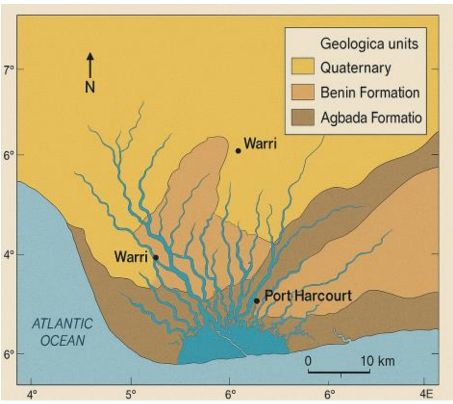

Fig. 1. Simple map of the Niger Delta region, Nigeria, indicating major urban centers and the complex river network. Sampling locations were conducted in and around the cities of Port Harcourt and Warri.

2.2. Sample Collection and Preparation

A total of 30 composite tap water samples were collected from 30 different educational institutions (18 primary and 12 secondary schools) during the dry season (January 2025) to minimize the influence of seasonal rainfall dilution. The schools were selected to represent a cross-section of the region, including densely populated urban areas (Port Harcourt, n=12; Warri, n=8) and surrounding rural communities (n=10). The selection also included a mix of public and private schools of varying ages of establishment to account for potential differences in infrastructure. Sample collection followed stringent protocols to prevent contamination, adapted from United States Environmental Protection Agency (USEPA, 2009) guidelines. High-density polyethylene (HDPE) bottles (1 L) were pre-cleaned by soaking in 10% nitric acid (HNO_3) for 24 hours, followed by thorough rinsing with deionized water and air-drying. At each sampling site, the tap was allowed to run for 3-5 minutes to flush the line and ensure the sample was representative of the water in the distribution system. The sample bottle was then rinsed three times with the tap water before being filled. To create a composite sample representative of typical school-day usage, three separate aliquots were collected from the same tap at 15-minute intervals and combined in the bottle. Immediately after collection, samples were acidified to a pH < 2 with ultra-pure concentrated HNO_3 (2 mL/L) to preserve the metals in solution and prevent adsorption to the container walls. The bottles were sealed, labeled, and transported in a cooler with ice packs to the laboratory, where they were stored at 4 °C before analysis.

Handling of values below the detection limit followed substitution at LOD/2 to minimize statistical bias.

QA/QC included:

- Field blanks (n=3)
- Laboratory duplicates (10%)
- Spike recovery (92–107%)
- Triplicate analysis

2.3. Analytical Procedures

The concentrations of ten metal(loid)s—Lead (Pb), Cadmium (Cd), Arsenic (As), Mercury (Hg), Chromium (Cr), Nickel (Ni), Copper (Cu), Zinc (Zn), Iron (Fe), and Manganese (Mn)—were determined using Atomic

Absorption Spectrometry (AAS). A Varian AA240FS/GTA120 system was employed for the analyses. Flame AAS (F-AAS) was used for Fe, Mn, Zn, and Cu. Graphite Furnace AAS (GF-AAS) was used for Pb, Cd, Cr, Ni, and As. Mercury (Hg) was analyzed using a dedicated Cold Vapour AAS (CV-AAS) system (VGA-77). Instrument calibration was performed using multi-element standard solutions prepared by serial dilution of certified stock solutions (1000 mg/L, AccuStandard). Quality assurance and quality control (QA/QC) measures were rigorously implemented. For every batch of 10 samples, a procedural blank, a duplicate sample, and a spiked sample were analyzed. The spike recovery across all elements remained within the acceptable range of 92–107%. The analytical detection limits (µg/L) were: Fe (1.5), Mn (0.5), Zn (0.8), Cu (0.6), Pb (0.1), Cd (0.05), Cr (0.2), Ni (0.3), As (0.1), and Hg (0.02). All analyses were performed in triplicate, and the mean values are reported.

2.4. Water Quality Assessment

To provide a holistic assessment of the water's suitability for drinking, the Entropy-Weighted Water Quality Index (EWQI) was calculated. The EWQI is a robust method that assigns objective weights to each parameter based on the information entropy of its concentration data, thus avoiding the subjectivity of expert-assigned weights (Namdari et al., 2016). The calculation involved constructing an eigenvalue matrix, normalizing it, calculating information entropy (e_j) and entropy weight (ω_j) for each parameter, and then calculating a quality rating scale (q_j) for each parameter by comparing its concentration (C_j) to the standard permissible limit (S_j) from WHO guidelines (WHO, 2017). Finally, the EWQI for each sample was calculated as $EWQI = \Sigma(\omega_j * q_j)$. The water quality was then classified into five categories based on the calculated EWQI value: Excellent (<25), Good (25–50), Medium (50–100), Poor (100–150), and Extremely Poor (> 150) (Siddique et al., 2021).

2.5. Health Risk Assessment

A human health risk assessment was conducted following the USEPA framework (USEPA, 2004, 2011) to estimate the potential non-carcinogenic and carcinogenic risks for students (children) and, for comparison, adults. Exposure via two primary pathways was considered: direct ingestion and dermal absorption.

2.5.1. Exposure Dose Calculation

The average daily dose (ADD) for ingestion (ADDing) and dermal contact (ADDderm) was calculated using the equations: ADDing(mg/kg/day) = (Cw× IR × EF × ED) / (BW × AT) and ADDderm(mg/kg/day) = (Cw× SA × Kp× ET × EF × ED × CF) / (BW × AT). The parameters are defined in Table 1.

Table 1. Exposure Factors Used for Health Risk Assessment

Parameter	Symbol	Unit	Child	Adult	Reference
Concentration in Water	Cw	mg/L	Measured	This Study	
Ingestion Rate	IR	L/day	1.0	2.2	USEPA (2011)
Body Weight	BW	kg	15	70	USEPA (2011)
Exposure Frequency	EF	days/year	350	350	USEPA (2023)
Exposure Duration	ED	years	12	30	USEPA (2023)
Skin Surface Area	SA	cm^2	2800	5700	USEPA (2023)
Dermal Exposure Time	ET	hours/day	0.6	0.6	USEPA (2023)
Dermal Permeability Coeff.	Kp	cm/hr	Element-specific		USEPA (2023)
Conversion Factor	CF	-	0.001		USEPA (2023)
Averaging Time (non-carcinogen)	ATnc	days	ED × 365	ED × 365	USEPA (2011)
Averaging Time (carcinogen)	ATc	days	70 × 365		USEPA (2011)

2.5.2. Non-Carcinogenic Risk

The non-carcinogenic risk was evaluated by calculating the Hazard Quotient (HQ) for each metal and exposure pathway (HQ = ADD / RfD). The Hazard Index (HI) was then calculated as the sum of all HQs (HI = ΣHQing+ ΣHQderm). An HI value greater than 1 suggests a potential for adverse health effects. RfD (chronic reference dose) values were obtained from the USEPA's Integrated Risk Information System (IRIS) (USEPA, 2023).

2.5.3. Carcinogenic Risk

The carcinogenic risk (CR), or the incremental probability of an individual developing cancer over a lifetime as a result of exposure, was calculated for known or probable human carcinogens (As, Cr, Cd, Pb) using the formula: CR = ADD × CSF. The Cancer Slope Factor (CSF) was obtained from the IRIS database (USEPA, 2023). A CR value between 1×10^{-6} and 1×10^{-4} is generally considered the acceptable or tolerable range.

2.6. Statistical Analysis

All statistical analyses were performed using the R software environment (version 4.3.1). Descriptive statistics (mean, median, standard deviation, min, max) were calculated for all metal(loid) concentrations. To identify the sources of contamination, multivariate statistical techniques were employed. Principal Component Analysis (PCA) with Varimax rotation was used to reduce the dimensionality of the dataset and identify groups of covarying elements. Before PCA, data normality was assessed using Shapiro–Wilk tests. Non-normally distributed variables were log-transformed to reduce skewness. Kaiser–Meyer–Olkin (KMO) measure (0.72) and Bartlett's test of sphericity ($p < 0.001$) confirmed suitability for PCA. Variance inflation factors (VIF < 5) indicated absence of severe multicollinearity. Given sample size constraints (n=30), PCA interpretation was restricted to components with eigenvalues >1 and loadings >0.60 to minimize overinterpretation.

Hierarchical Cluster Analysis (CA) using Ward's method with Euclidean distance was applied to both the elemental data and the sampling sites. Pearson's correlation matrix was also generated to examine the inter-element relationships.

3. Results and Discussion

3.1. Metal(loid) Concentrations in Tap Water

The concentrations of the ten measured metal(loid)s in the 30 tap water samples from schools in the Niger Delta are summarized in Table 2. The results reveal a wide range of concentrations for all elements, indicating significant spatial variability in water quality across the study area. The mean concentrations (in µg/L) followed the descending order: Zn (1150) > Fe (480) > Cu (255) > Mn (95) > Pb (18.5) > Ni (15.3) > Cr (7.2) > As (4.8) > Cd (2.1) > Hg (0.9). When compared with the World Health Organization (WHO, 2017) guidelines and the Nigerian Standard for Drinking Water Quality (NSDWQ) (Standards Organisation of Nigeria, 2015), several exceedances were noted. The mean concentration of Pb (18.5 µg/L) is nearly double the WHO and NSDWQ limit of 10 µg/L, with 47% of schools exceeding this limit. The mean Cd concentration (2.1 µg/L) was below the 3 µg/L limit, but 17% of schools exceeded it. The mean Fe concentration (480 µg/L) surpassed the 300 µg/L limit in 40% of samples. Concentrations of As and Hg were generally low and below their respective limits. The high levels of Zn and Cu are strong indicators of leaching from galvanized and copper plumbing.

Table 2. Descriptive Statistics of Metal(loid) Concentrations (µg/L) in Tap Water Samples (n=30) and Comparison with Drinking Water Standards

Parameter	Mean	Median	SD	Min	Max	WHO Limit (2017)	NSDWQ (2015)	% Exceedance (WHO)
Pb	18.5	15.1	14.2	1.8	65.2	10	10	47%
Cd	2.1	1.5	1.9	0.2	7.8	3	3	17%
As	4.8	4.2	2.5	0.9	9.5	10	10	0%
Hg	0.9	0.6	0.8	<0.02	3.1	6	1	10% (NSDWQ)
Cr (Total)	7.2	6.5	4.1	1.5	18.9	50	50	0%
Ni	15.3	12.8	9.8	2.4	45.1	70	20	7% (NSDWQ)
Cu	255	180	210	25	950	2000	1000	0%
Zn	1150	850	1020	150	5200	-	3000	3% (NSDWQ)

Parameter	Mean	Median	SD	Min	Max	WHO Limit (2017)	NSDWQ (2015)	% Exceedance (WHO)
Fe	480	350	390	55	1850	300	300	40%
Mn	95	70	115	12	510	400	200	3%

3.2. Water Quality Assessment using EWQI

The Entropy-Weighted Water Quality Index (EWQI) provided a composite score for each water sample. The EWQI values ranged from 18.5 (classified as 'Excellent') to 125.7 ('Poor'). The distribution of water quality classes was as follows: Excellent (37%), Good (43%), Medium (13%), and Poor (7%) (see Figure 2). Overall, 80% of the schools had water of 'Excellent' or 'Good' quality. However, the 20% of samples falling into the 'Medium' and 'Poor' categories are a cause for concern. These samples were characterized by high concentrations of multiple elements, particularly Pb, Fe, and Zn. The entropy weight (ω_j) calculation identified Pb, Fe, Zn, and Cd as the parameters with the highest weights, indicating they were the primary drivers of water quality degradation in this study. Spatially, the 'Poor' and 'Medium' quality samples were predominantly located in the older, more industrialized parts of Port Harcourt, corroborating the link between aging infrastructure and water contamination.

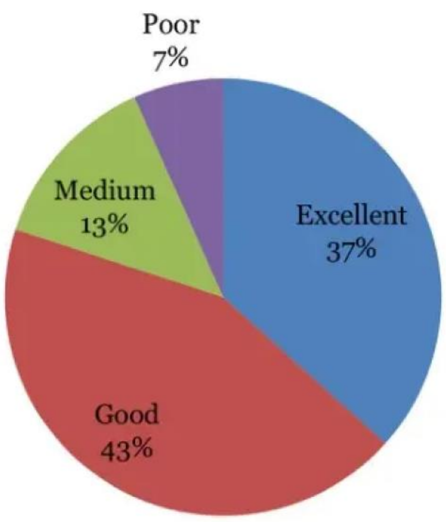

Fig. 2. Distribution of Water Quality Classes Based on EWQI Values.

3.3. Source Apportionment of Metal(loid)s

Multivariate statistical analyses were instrumental in elucidating the origins of the metal(loid)s. The Principal Component Analysis (PCA) extracted three significant principal components (PCs) that collectively explained 78.6% of the total variance in the dataset. PC1 (41.2% of variance) showed strong positive loadings for Zn, Cu, Fe, and Pb, a classic signature of corrosion from plumbing systems, and was labeled the 'Pipe Corrosion/Infrastructure' factor. PC2 (22.5% of variance) was strongly loaded with As, Hg, and Cr, suggesting a 'Geogenic/Industrial' factor related to regional geology and industrial atmospheric deposition. PC3 (14.9% of variance) had a strong loading for Mn and a moderate loading for Fe, suggesting a 'Geogenic/Redox' factor representing the natural occurrence of these metals in the Benin Formation aquifer. The Cluster Analysis (CA) of the sampling sites reinforced these findings, producing two main clusters. Cluster A comprised mainly newer schools and those in rural areas with lower metal concentrations. Cluster B consisted almost exclusively of older schools (established before 1990) in urban centers, which exhibited significantly higher mean concentrations for the 'Pipe Corrosion' elements (Pb, Zn, Cu, Fe), confirming that the age and condition of plumbing infrastructure are primary determinants of tap water quality.

Elevated Zn and Cu concentrations were statistically associated with Pb and Fe ($r > 0.65$, $p < 0.01$) and strongly loaded in PC1. This grouping, combined with higher concentrations observed in older urban schools, is consistent with corrosion-related inputs. While direct pipe material analysis was not conducted, the co-occurrence pattern supports infrastructure influence rather than purely geogenic sources.

3.4. Health Risk Assessment

Exposure parameters were adopted from the USEPA Exposure Factors Handbook (2011, 2023). Although region-specific Nigerian exposure factors are limited, applied values represent conservative assumptions for children. Sensitivity analysis using ±20% variation in ingestion rate showed proportional HI variation but did not change exceedance classification for high-risk schools.

Risk thresholds (HI >1; CR 10^{-6}–10^{-4}) follow USEPA (2004) and WHO risk management guidance.

Mercury and nickel were excluded from carcinogenic risk due to absence of established oral cancer slope factors for the detected exposure form; however, their potential toxicity is acknowledged.

3.4.1. Non-Carcinogenic Risk

The Hazard Index (HI) was calculated for both children and adults. The mean HI for children was 0.58, while for adults it was 0.15. For all 30 samples, the HI for adults remained below the 1 threshold. However, for children, the HI exceeded 1 in three schools (10% of samples), with a maximum value of 1.45. These exceedances were driven primarily by the high HQ values for Pb and, to a lesser extent, Cu and Fe. An HI > 1 indicates that the combined exposure to these metals could potentially lead to non-carcinogenic adverse health effects. The results clearly demonstrate that children are at a significantly higher risk than adults, with their average risk being nearly four times that of adults.

3.4.2. Carcinogenic Risk.

The carcinogenic risk (CR) was calculated for As, Cd, Cr, and Pb. The total CR for children ranged from 2.5×10^{-5} to 3.8×10^{-4}. For adults, the range was 1.1×10^{-5} to 1.6×10^{-4}. The primary contributors to the CR were As and Pb. Critically, in 9 of the 30 schools (30%), the total CR for children exceeded the upper acceptable limit of 1×10^{-4}. The highest calculated risk was 3.8×10^{-4}, implying that for every 10,000 children exposed to this water over their school years, nearly four could potentially develop cancer in their lifetime due to this exposure alone. This level of risk is considered unacceptable by most regulatory agencies. The high CR values were almost entirely driven by the concentrations of Pb and As. This finding underscores the limitation of using only concentration-based guidelines and highlights the necessity of risk-based assessments to fully understand public health implications.

4. Summary and Limitations

This study provides the first targeted assessment of metal(loid) contamination in the tap water of schools in Nigeria's Niger Delta, revealing a significant and previously unquantified health risk to students. While the majority of schools had water that could be classified as 'good' quality, a substantial minority, particularly older urban schools, supplied water contaminated with Pb, Fe, and other metals at levels exceeding safe drinking water standards. Multivariate statistical analysis successfully identified two main contamination pathways: a geogenic/industrial source and a dominant anthropogenic source related to the corrosion of aging plumbing infrastructure. The health risk assessment confirmed the heightened vulnerability of children. While non-carcinogenic risks were generally low, they exceeded the safe threshold in 10% of schools for children. More alarmingly, the carcinogenic risk, driven by Pb and As, surpassed the acceptable limit of 1×10^{-4} in 30% of the schools, indicating an unacceptable long-term cancer risk. This study has some limitations. The sampling was conducted during the dry season only. Furthermore, this study focused on dissolved metals; an analysis of particulate-bound metals could reveal additional exposure risks. Speciation analysis, particularly for As and Cr, would also refine the risk assessment. Despite these limitations, the findings are a clear call to action. We recommend immediate implementation of routine, risk-based water quality monitoring programs in all schools, prioritization of infrastructure renewal, and the installation of point-of-use water treatment systems in high-risk schools as an interim measure. Protecting the health of children in their learning environments must be a public health and policy priority.

5. Conclusion

This study provides the first comprehensive evaluation of metal(loid) contamination in tap water from schools across the Niger Delta, revealing important insights into water safety, contamination pathways, and associated health risks for students. Although most water samples were classified as excellent to good based on the Entropy-Weighted Water Quality Index, a significant proportion of schools—particularly older institutions in urban centers—showed elevated concentrations of Pb, Fe, Zn, and Cu. These exceedances were strongly linked to corrosion of aging plumbing systems, while As, Hg, and Cr were associated with geogenic and industrial influences. Multivariate analyses confirmed two dominant contamination sources: (1) infrastructure-related corrosion and (2) combined geogenic/industrial inputs.

Health risk assessment demonstrated that children are substantially more vulnerable than adults. While non-carcinogenic risks remained within acceptable limits for most schools, 10% of locations exceeded the hazard threshold for children. More critically, carcinogenic risk values driven primarily by Pb and As surpassed the acceptable limit (1×10^{-4}) in 30% of sampled schools, indicating a significant long-term public health concern.

Overall, the findings underscore the urgent need for targeted interventions, including systematic water quality monitoring, replacement of corroding plumbing infrastructure, and implementation of point-of-use treatment technologies, especially in high-risk schools. Ensuring safe drinking water for students in the Niger Delta should be a priority for policymakers, water authorities, and educational stakeholders, given the profound implications of chronic metal(loid) exposure for children's health and development.

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Declarations

Data and code availability

All data generated or analyzed during this study are available from the corresponding author upon reasonable request. No computational code was used in this study.

Conflicts of interest

The authors announced that they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this manuscript.

Ethical approval

The authors declare no ethical issues; the research was carried out in full agreement with ethical standards. Also, this paper is neither under Review nor published elsewhere.

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