Open Access Library Journal
2026, Volume 13, e15692
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Index Based Water Quality Appraisal and Metal Driven Health Risk of Water Sources near Industrial Dumpsites in Makurdi, Nigeria

Barnabas Orngu Mnenga[1*], Adams Udoji Itodo[2], Isaq Shaibu Eneji[1], Nguamo Surma[1], Mark Aondoakaa Tseen[1]

[1]Department of Chemistry, Joseph Sarwuan Tarka University, Makurdi, Nigeria
[2]Department of Industrial Chemistry, Joseph Sarwuan Tarka University, Makurdi, Nigeria
Email: *Banzy30@yahoo.com

How to cite this paper: Mnenga, B.O., Itodo, A.U., Eneji, I.S., Surma, N. and Tseen, M.A. (2026) Index Based Water Quality Appraisal and Metal Driven Health Risk of Water Sources near Industrial Dumpsites in Makurdi, Nigeria. *Open Access Library Journal*, **13**: e15692.
https://doi.org/10.4236/oalib.1115692

Received: June 25, 2026
Accepted: August 10, 2026
Published: August 13, 2026

Abstract

Industrial dumpsites can impose complex pressure on nearby water sources through dissolved ions, oxygen demanding substances, microbial inputs and toxic metals. This study assessed the physicochemical quality, Water Quality Index, toxic metal burden and human health risk of water sources around fertilizer, dye, battery and paint dumpsite vicinities in Makurdi, Nigeria. Water categories comprised fertilizer dumpsite water sample (FDWS), dye dumpsite water sample (DDWS), battery dumpsite water sample (BDWS), paint dumpsite water sample (PDWS), and a comparison water sample (Comp) collected from a site removed from the industrial dumpsite vicinities, representing regional background conditions rather than an uncontaminated reference. Physicochemical variables, Fe, Pb, Cr, Cd, Zn, Mn and Cu concentrations, Water Quality Index values, chronic daily intake, hazard quotient, hazard index, carcinogenic risk and integrated site ranking were evaluated. The physicochemical profile showed strong site variation, with DDWS recording the highest electrical conductivity (1434 ± 1.21 μS/cm), total dissolved solids (758 ± 0.45 ppm), chloride (875 ± 5.67 mg/L) and chemical oxygen demand (176 ± 0.06 mg/L). Water Quality Index (WQI) values classified all water categories as excellent, ranging from 0.549 in FDWS to 1.230 in BDWS. This classification contrasted sharply with the toxic metal profile, where Pb exceeded the WHO guideline by factors of 825.0, 793.0, 888.0 and 718.0 in FDWS, DDWS, BDWS and PDWS, respectively. Cr and Cd also exceeded guideline values across the dumpsite water categories. Child ingestion hazard index (HI) values were consistently higher than adult values, and BDWS recorded the highest child ingestion carcinogenic risk (1.15214×10^{-5}). The health risk assessment employed USEPA-derived exposure parameters for adult (BW: 70 kg, IR: 2.0 L/day) and child

(BW: 15 kg, IR: 1.0 L/day) receptors. Each dumpsite category included both surface water (streams/rivers) and groundwater (wells) samples, pooled to reflect integrated water quality in each industrial vicinity. Integrated ranking placed BDWS first, followed by DDWS, PDWS and FDWS. The findings show that WQI alone is insufficient for classifying dumpsite adjacent water safety when metal exceedance and receptor specific health risk are present.

Subject Areas

Environmental Sciences

Keywords

Water Quality Index, Toxic Metals, Industrial Dumpsites, Lead Exceedance, Hazard Index, Carcinogenic Risk, Makurdi, Nigeria

1. Introduction

Industrial dumpsites represent chemically active interfaces where discarded materials, rainfall infiltration and waste decomposition can generate leachate capable of altering nearby surface water and groundwater quality [1] [2]. In water bodies close to such disposal environments, deterioration is often expressed through elevated dissolved solids, chloride enrichment, turbidity shifts, oxygen demand changes, nutrient loading, microbial indicators and toxic metal accumulation [3] [4]. The scientific importance of these variables lies in the fact that each group describes a different component of water stress, with conductivity and total dissolved solids reflecting ionic enrichment, chloride indicating conservative leachate movement, and chemical oxygen demand (COD) or biological oxygen demand (BOD) reflecting oxygen consuming chemical and biological loads [1]. Particularly in rapidly urbanising settings, open waste disposal may create a mixed contaminant reservoir because industrial residues, domestic waste, battery materials, dye residues, paint components and nutrient bearing wastes can coexist within poorly controlled disposal spaces [5] [6]. Heavy metals are especially important within this mixture because Pb, Cr, Cd, Fe, Mn, Cu and Zn can persist in aquatic environments and remain relevant to chronic exposure even when routine physical parameters appear acceptable. Consequently, water quality assessment around dumpsite vicinities requires a design that captures both general physicochemical condition and contaminant-focused risk information [5] [7].

Water Quality Index (WQI) is valuable because it condenses multiple water quality variables into an accessible score that can communicate overall status to scientists, regulators and non-specialist stakeholders [8] [9]. However, the same compression can become a limitation where toxic metals are present, because a favourable aggregate score may coexist with exceedance of low guideline thresholds for metals such as Pb, Cr and Cd. This limitation is not a failure of WQI as a screening tool, but a reminder that WQI was designed to summarize broad quality

patterns rather than replace metal resolved exceedance assessment and receptor-based health risk modelling [6] [10].

Recent water quality studies increasingly combine WQI with heavy metal pollution indices, hazard quotient, hazard index and carcinogenic risk because each metric answers a different question about water acceptability [5] [10]. WQI answers whether the combined physicochemical profile appears favourable, whereas exceedance factors identify which metal crosses a guideline threshold and health risk outputs estimate the potential consequence of exposure for adults and children [5] [10]. Such integration is particularly important in dumpsite adjacent water because metal contamination may be spatially uneven, chemically persistent and toxicologically significant even when bulk water quality indicators remain within an apparently acceptable range [7]. A stronger introductory framework therefore treats WQI as one layer of evidence and pairs it with toxic metal exceedance and human health risk assessment before water safety is inferred [6].

Human health risk assessment provides the exposure-based layer needed when toxic metals occur in water intended for domestic or community contact [11] [12]. Chronic daily intake (CDI) estimates the normalized dose received by a receptor through a defined exposure route, while hazard quotient compares that dose with a reference dose for an individual metal [11]. Hazard index (HI) then aggregates hazard quotients (HQ) across metals or pathways to represent cumulative non carcinogenic risk, and carcinogenic risk estimates lifetime cancer probability for metals with available cancer slope factors [6]. In dumpsite affected water, receptor separation is methodologically essential because adults and children do not share the same body weight, intake relationship or exposure vulnerability [10]. Recent water risk studies show that children often record higher normalized hazard estimates than adults because smaller body mass can magnify dose per kilogram under comparable water exposure assumptions [6] [11]. Ingestion and dermal contact also require separate treatment because oral intake generally transfers dissolved metals more directly into systemic exposure equations, whereas dermal uptake depends on skin area, permeability and contact duration. Therefore, CDI, HQ, HI and carcinogenic risk form a complementary framework for translating measured Pb, Cr, Cd, Fe, Mn, Cu and Zn concentrations into receptor relevant health risk evidence [13] [14].

Despite the wide use of WQI in water classification, fewer dumpsite water studies integrate WQI, metal exceedance factors, adult and child health risk indices, carcinogenic risk and ranked site prioritisation within one water focused analytical framework [5] [6]. This gap is important for industrial dumpsite vicinities because a favourable aggregate water score may not adequately communicate the toxicological relevance of Pb, Cr and Cd when guideline exceedance and receptor-based risk indicators are examined separately. The present study addresses this gap by evaluating physicochemical quality, WQI classification, toxic metal exceedance, CDI, HQ, HI, carcinogenic risk and integrated site ranking for water sources around fertilizer, dye, battery and paint dumpsite vicinities in Makurdi,

Nigeria. Its original scope lies in treating WQI as one interpretive layer rather than the final safety verdict, thereby positioning metal resolved exceedance and receptor specific risk outputs as decisive evidence for water safety appraisal.

2. Materials and Methods

2.1. Study Area and Sampling Design

The study was conducted in Makurdi, Benue State, Nigeria, using water sources located near four industrial dumpsite categories and one control category for structured comparison. The sampling framework comprised fertilizer dumpsite water sample (FDWS), dye dumpsite water sample (DDWS), battery dumpsite water sample (BDWS), paint dumpsite water sample (PDWS), and a comparison water sample (Comp), with the four dumpsite categories each represented by three reported sampling points in the site coordinate register. Each category included a mixture of surface water sources (streams and rivers) and groundwater sources (wells) located in the vicinity of the respective industrial dumpsites. These sources were pooled within each category to provide an integrated assessment of water quality in the dumpsite-affected area, recognizing that both surface and groundwater pathways contribute to potential human exposure in these communities. The comparison site was selected to represent regional background conditions within the Makurdi metropolitan area. While this site is not pristine—reflecting the urban background contamination common to the region—it serves as a relative reference point for comparing physicochemical characteristics and contaminant levels against the dumpsite-impacted waters. This approach acknowledges that truly uncontaminated control sites are often unavailable in rapidly urbanizing industrial settings. The design was arranged to support integrated assessment of physicochemical quality, microbiological status, toxic metal burden, water quality index calculation, and human health risk modelling, rather than a single parameter description of water condition. [15] similarly applied a dumpsite groundwater framework for heavy metal and health risk evaluation in Nigeria. The coordinate structure was retained as reported visually in **Figure 1**, showing the sampling site coordinates and boundaries. This arrangement ensured that sampling identity, analytical processing and interpretive endpoints remained connected throughout the methodological workflow. **Table 1** clearly details the coordinates used and the parameters for analysis fully covered for each sample.

The three water samples reported for each dumpsite category were collected from three spatially distinct points within that dumpsite's vicinity, as shown by the separate coordinate pairs listed for each category in **Table 1**, and therefore represent independent field sampling locations rather than repeated draws from a single source or repeated laboratory analyses of one sample. Among these three sampling points per category, some represented surface water sources (streams/rivers) while others represented groundwater sources (wells), reflecting the diversity of water sources accessed by local communities in each dumpsite vicinity. One com-

parison water sample was collected from a single reference location set apart from all four dumpsite vicinities. While this site is not pristine, reflecting the regional background contamination common to Makurdi, it serves as a relative reference point for comparing physicochemical characteristics and contaminant levels against the dumpsite-impacted waters. This comparison sample was analysed under the same sample handling and analytical sequence as the dumpsite samples. The decision to pool surface and groundwater sources within each dumpsite category was based on the local community water usage patterns, where residents in each vicinity rely on multiple water sources for domestic purposes. This pooling strategy an integrated assessment of potential exposure rather than source-specific characterization.

Acknowledging the hydrological differences between surface water and groundwater, the study was designed to report aggregated results by dumpsite category to reflect the total water quality burden in each industrial vicinity. This approach is consistent with community-based exposure assessments, which focus on overall contamination risk rather than source-specific attribution. However, the variability in water quality between surface and groundwater sources within each category represents a limitation that is addressed in the discussion.

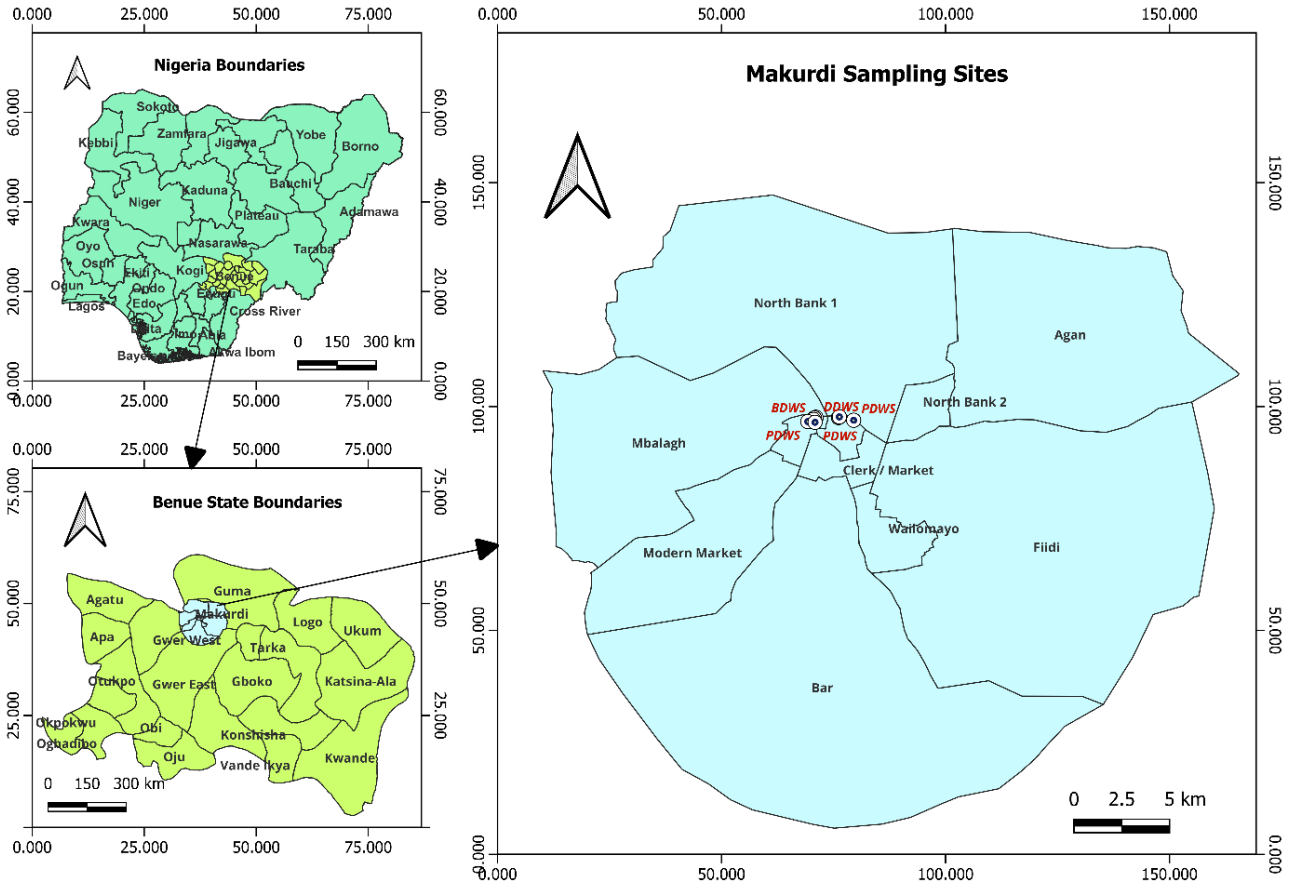

Figure 1. Country, state and local government boundaries showing the study water sampling sites.

2.2. Water Sample Collection, Preservation and Preparation

Water samples were collected from streams, rivers or wells located close to the selected industrial dumpsite categories using labelled plastic containers previously washed with distilled water and aqueous nitric acid solution. After collection, the containers were sealed, labelled, transported to the laboratory in an icebox, and stored at 4˚C before analysis to minimize avoidable alteration of water chemistry during handling. For metal preparation, 20 mL aliquots of each water sample were digested with aqua regia prepared from hydrochloric acid and nitric acid in a 3:1 mixture, with 30 mL of the acid mixture added to each aliquot in a 250 mL beaker. Digestion was conducted on a hot plate inside a fume cupboard for 2.5 h at 120˚C, after which the cooled digest was filtered into a 50 mL volumetric flask and diluted to volume with deionized water. The prepared digest was retained for subsequent toxic metal determination, while the broader sample set supported physicochemical, microbiological, WQI and health risk data generation under a consistent sample handling sequence. Total dissolved solids and total suspended solids were each determined in triplicate per sample in the laboratory, while the remaining physicochemical parameters and toxic metal determinations were carried out as single analytical measurements on each of the field samples described in **Table 1** [11] [16].

All glassware and plasticware used in sample preparation were thoroughly cleaned by soaking in 10% nitric acid for 24 hours, followed by rinsing with deionized water (resistivity ≥ 18.2 MΩ·cm) and air-drying in a clean environment to prevent cross-contamination.

Table 1. Sampling framework, site codes and analytical dataset.

Site category	Code	Number of representative water samples	Water source type	Latitude range, decimal degrees	Longitude range, decimal degrees	Analytical domains used
Fertilizer dumpsite water sample	FDWS	3	Nearby stream, river or well	7.74579 to 7.74610	8.52570 to 8.52613	Physicochemical parameters, microbiology, WQI, toxic metals, CDI, HQ, HI and carcinogenic risk
Dye dumpsite water sample	DDWS	3	Nearby stream, river or well	7.74535 to 7.74589	8.51425 to 8.51495	Physicochemical parameters, microbiology, WQI, toxic metals, CDI, HQ, HI and carcinogenic risk
Battery dumpsite water sample	BDWS	3	Nearby stream, river or well	7.44891 to 7.74487	8.51380 to 8.51381	Physicochemical parameters, microbiology, WQI, toxic metals, CDI, HQ, HI and carcinogenic risk

Continued

Paint dumpsite water sample	PDWS	3	Nearby stream, river or well	7.74352 to 7.74449	8.51113 to 8.53288	Physicochemical parameters, microbiology, WQI, toxic metals, CDI, HQ, HI and carcinogenic risk
Comparison water category	Comp	1 Comparison category	Water source away from dumpsite sampling points	-	-	Physicochemical parameters, microbiology, WQI, toxic metals, CDI, HQ, HI and carcinogenic risk

2.3. Physicochemical Water Quality Analysis

The physicochemical assessment was designed to characterize the basic chemical, ionic, oxygen demand and suspended matter conditions of water collected from the four dumpsite vicinity categories and the control category. The measured variables comprised pH, electrical conductivity, turbidity, temperature, total dissolved solids, total suspended solids, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, sulphate, phosphate, nitrate, chloride, calcium, magnesium and total hardness, which are widely used as diagnostic indicators of water quality alteration in polluted aquatic settings [17]. The analytical sequence followed standard laboratory procedures in which pH was measured using a calibrated pH meter, electrical conductivity was measured using a conductivity meter at controlled temperature, and turbidity was determined using a turbidity meter [17] [18]. Dissolved oxygen was measured by titration with sodium thiosulphate after starch indicator development, while total dissolved solids and total suspended solids were determined through filtration, oven drying, cooling and repeated weighing to constant mass. Calcium and magnesium measurements were retained for hardness estimation, while chloride, nitrate, phosphate and sulphate were included to capture ionic enrichment associated with wastewater and leachate influence [17] [19].

2.4. Toxic Metal Determination and Analytical Quality Control

For toxic metal analysis, water aliquots were digested before instrumental determination to place dissolved and acid extractable metal fractions into a measurable solution phase. Each 20 mL water aliquot was treated with 30 mL freshly prepared aqua regia, using hydrochloric acid and nitric acid in a 3:1 ratio, then heated on a hot plate in a fume cupboard for 2.5 h at 120˚C. After cooling, each digest was filtered into a 50 mL volumetric flask and made to volume with deionized water before instrumental analysis. Concentrations of Fe, Pb, Cr, Cd, Zn, Mn and Cu were determined by atomic absorption spectrophotometry, a method routinely applied for trace and heavy metal determination in water matrices [20]. Calibration was performed with working standard solutions prepared from stock standards, and blank readings were recorded so that instrumental background contri-

butions could be corrected during concentration calculation. [21] emphasized that blanks, reference materials and calibration-based checks strengthen precision and accuracy during AAS based metal determination in environmental water studies. The detailed QA/QC procedures, including method detection limits, replicate precision, spike recoveries, and reference material verification, are described in Section 2.4.1.

Analytical Quality Assurance and Quality Control

Rigorous quality assurance and quality control (QA/QC) procedures were implemented throughout sample preparation, instrumental analysis and data processing to ensure reliable toxic metal determinations. The AAS was calibrated using serial dilutions of 1000 ppm stock standards (PerkinElmer, USA) with five-point calibration curves ($R^2 \geq 0.995$) verified against an independent check standard every ten samples; samples exceeding the calibration range (Pb samples 007, 008, 011 and 012) were diluted and reanalyzed. Method detection and quantification limits, derived from seven replicate blanks (LOD = 3 × SD_blank, LOQ = 10 × SD_blank; [22]), ranged from 0.003 - 0.015 mg/L (LOD) and 0.010 - 0.050 mg/L (LOQ) across the seven metals, and all sample concentrations exceeded these limits. Reagent and method blanks were processed with each batch (maximum 20 samples) and subtracted from sample readings to correct for background contamination. Duplicate analyses (10% of samples, n = 5) gave mean relative percent differences of 2.8–5.6% across metals, within the [23] acceptance limit of ≤ 20%. Matrix spike recoveries (n = 4, ~50% above ambient concentration) averaged 94.8% - 98.1%, within the USEPA 80% - 120% acceptance range. Analysis of NIST SRM 1643f (n = 3 batches) showed measured Pb, Cr and Cd concentrations within 96.2% - 102.1% of certified values. Calibration check standards, run every ten samples, remained within ± 10% of expected concentrations throughout, confirming stable instrument performance.

2.5. Water Quality Index Calculation

Water Quality Index was calculated using the weighted arithmetic indexing procedure, which converts water quality variables with different units into a single comparative score suitable for site level interpretation [8]. Parameter selection followed the measured physicochemical suite and included pH, electrical conductivity, turbidity, temperature, total dissolved solids, total suspended solids, dissolved oxygen, chemical oxygen demand, sulphate, phosphate, nitrate, chloride and total hardness. The unit weight assigned to each parameter was calculated using Equation (1), so that parameters with lower permissible limits had proportionally greater influence on the index. The quality rating for each parameter was then calculated using Equation (2), based on the measured value, the guideline value and the ideal value in pure water. The weighted subindex for each parameter was obtained using Equation (3), after which the final WQI was derived by aggregating the weighted subindices using Equation (4).

$$W_i = \frac{K}{S_i} \tag{1}$$

$$Q_i = \left[\frac{(V_i - V_0)}{S_i - V_0}\right] \times 100 \tag{2}$$

$$SI_i = W_i \times Q_i \tag{3}$$

$$WQI = \sum\left(\frac{SI_i}{W_i}\right) \tag{4}$$

where, W_i is the unit weight of parameter *i*, K is the proportionality constant, S_i is the standard permissible value of parameter *i*, Q_i is the quality rating of parameter *i*, V_i is the measured value of parameter *i*, V_0 is the ideal value of parameter i in pure water, SI_i is the weighted subindex of parameter *i*, and Σ is the summation across all selected water quality parameters [6] [8] [14].

2.6. Human Health Risk Assessment

Human health risk assessment was performed for toxic metals in water using adult and child receptor categories, because exposure dose is influenced by body weight, exposure duration and contact assumptions. The exposure pathways were limited to ingestion and dermal contact because these pathways were represented in the analytical dataset and are commonly used in water related metal risk assessment. Chronic daily intake through ingestion was calculated using Equation (5), while chronic daily intake through dermal contact was calculated using Equation (6). The hazard quotient for each metal and exposure route was calculated using Equation (7), and the cumulative hazard index was calculated using Equation (8) by summing the relevant hazard quotients. Carcinogenic risk was calculated for eligible metals using Equation (9), based on chronic daily intake and the corresponding cancer slope factor.

$$CDI_{ing} = \frac{(C \times IR \times EF \times ED)}{(BW \times AT)} \tag{5}$$

$$CDI_{derm} = \frac{(C \times SA \times Kp \times ET \times ED \times CF)}{(BW \times AT)} \tag{6}$$

$$HQ = \frac{CDI}{RfD} \tag{7}$$

$$HI = \sum HQ_i \tag{8}$$

$$CR = CDI\ x\ SF \tag{9}$$

where, CDI_{ing} is chronic daily intake through ingestion, CDI_{derm} is chronic daily intake through dermal contact, C is the metal concentration in water, IR is ingestion rate, EF is exposure frequency, ED is exposure duration, BW is body weight, AT is averaging time, SA is exposed skin area, Kp is dermal permeability coefficient, ET is exposure time, CF is conversion factor, HQ is hazard quotient, CDI is chronic daily intake, RfD is reference dose, HI is hazard index, HQ_i is the

hazard quotient for metal *i*, *CR* is carcinogenic risk, and *SF* is cancer slope factor [11] [24]. The specific values assigned to each parameter are presented in Table 2 (Section 2.6.1), with sources including the USEPA Exposure Factors Handbook [25], USEPA IRIS database [26], and peer-reviewed literature [11] [24].

Exposure Parameters and Risk Model Inputs

The human health risk assessment was conducted using exposure parameters derived from USEPA guidance and relevant literature. Table 2 presents the complete set of input parameters used for chronic daily intake (CDI), hazard quotient (HQ), hazard index (HI), and carcinogenic risk (CR) calculations for both adult and child receptor groups.

Table 2. Exposure parameters and reference values used in health risk assessment.

Parameter	Symbol	Unit	Adult Value	Child Value	Source
Ingestion Rate	IR	L/day	2.0	1.0	[25], Exposure Factors Handbook
Exposure Frequency	EF	days/year	365	365	[25]
Exposure Duration	ED	years	30	6	[25]
Body Weight	BW	kg	70	15	[11] [25]
Averaging Time (Non-carcinogenic)	AT	days	ED × 365	ED × 365	[25]
Averaging Time (Carcinogenic)	AT	days	70 × 365	70 × 365	[25]
Skin Surface Area	SA	cm^2	18,000	6,600	[25]
Dermal Permeability Coefficient (Pb)	Kp	cm/h	0.001	0.001	[27]
Dermal Permeability Coefficient (Cr)	Kp	cm/h	0.002	0.002	[27]
Dermal Permeability Coefficient (Cd)	Kp	cm/h	0.001	0.001	[27]
Dermal Permeability Coefficient (others)	Kp	cm/h	0.001	0.001	[27]
Exposure Time (Dermal)	ET	h/day	0.58	1.0	[25]
Conversion Factor	CF	L/cm^3	0.001	0.001	[25]

Reference Doses (RfD) Used for Non-Carcinogenic Risk

Metal	Ingestion RfD (mg/kg/day)	Dermal RfD (mg/kg/day)	Source
Fe	0.700	0.700	[26], IRIS
Pb	0.00350	0.000525*	[26], IRIS; *dermal = ingestion × 0.15
Cr	0.00300	0.000060*	[26], IRIS; *dermal RfD from [27]
Cd	0.00100	0.000050*	[26], IRIS; *dermal = ingestion × 0.05
Zn	0.300	0.300	[26], IRIS
Mn	0.046	0.046	[26], IRIS
Cu	0.040	0.040	[26], IRIS

Cancer Slope Factors (SF) Used for Carcinogenic Risk

Metal	Ingestion SF $(mg/kg/day)^{-1}$	Dermal SF $(mg/kg/day)^{-1}$	Source
Pb	0.00850	0.00850	[26], IRIS (Oral Slope Factor)
Cr	0.500	0.500	[26], IRIS (Oral Slope Factor)
Cd	0.380	0.380	[26], IRIS (Oral Slope Factor)

Note: Dermal RfD values were calculated by multiplying ingestion RfD by appropriate gastrointestinal absorption fractions as recommended by [27] and the Risk Assessment Guidance for Superfund (RAGS), Part E. Dermal cancer slope factors were assumed equivalent to oral slope factors as per USEPA guidance when specific dermal values are unavailable.

Metals Included in Carcinogenic Risk Assessment: Carcinogenic risk assessment was conducted exclusively for Pb, Cr, and Cd based on the following criteria:

1) Pb (Lead): Classified as a probable human carcinogen (Group B2) by [26]. The International Agency for Research on Cancer (IARC) classifies inorganic lead compounds as probably carcinogenic to humans (Group 2A). Lead has been associated with stomach cancer, lung cancer, and brain tumors in epidemiological studies [26] [28]. An oral slope factor of 0.0085 $(mg/kg/day)^{-1}$ is available for lead in the IRIS database.

2) Cr (Chromium): Hexavalent chromium [Cr(VI)] is classified as a known human carcinogen (Group A) by USEPA and IARC (Group 1). Inhalation exposure to Cr(VI) is associated with lung cancer, and oral exposure has been linked to stomach tumors in animal studies [26]. An oral slope factor of 0.5 $(mg/kg/day)^{-1}$ for chromium (total) is available in IRIS. Although the AAS method does not speciate Cr (III) vs Cr (VI), the conservative approach assumes all chromium is in the carcinogenic Cr (VI) form for risk assessment purposes.

3) Cd (Cadmium): Classified as a known human carcinogen (Group A) by USEPA and IARC (Group 1). Cadmium exposure is associated with lung cancer, prostate cancer, and renal cancer [28]. An oral slope factor of 0.38 $(mg/kg/day)^{-1}$ for cadmium is available in the IRIS database.

Exclusion of Other Metals from Carcinogenic Risk Assessment: The remaining metals (Fe, Zn, Mn, and Cu) were not included in the carcinogenic risk assessment for the following reasons:

1) Fe (Iron): Not classified as a human carcinogen by USEPA, IARC, or NTP. Iron is an essential nutrient and does not have an established cancer slope factor. Excess iron is associated with oxidative stress but is not considered a direct carcinogen.

2) Zn (Zinc): Not classified as a human carcinogen. Zinc is an essential trace element with no established cancer slope factor in USEPA IRIS.

3) Mn (Manganese): Not classified as a human carcinogen. Manganese is an essential nutrient; chronic exposure is associated with neurotoxicity (manganism)

but not cancer. No cancer slope factor is available.

4) Cu (Copper): Not classified as a human carcinogen. Copper is an essential trace element with no established cancer slope factor in USEPA IRIS.

This approach is consistent with USEPA guidance, which specifies that carcinogenic risk should only be calculated for metals with established cancer slope factors and known carcinogenic potential [26] [29].

2.7. Statistical and Graphical Synthesis

Statistical synthesis was performed to convert the validated water dataset into reproducible descriptive, comparative and visual outputs suitable for manuscript level interpretation. Site wise descriptive statistics were generated for physicochemical variables, toxic metals, WQI components and health risk indices, with coefficient of variation retained where dispersion assessment was supported by the available fields. Guideline based interpretation was conducted by calculating metal exceedance factors against the adopted WHO and NESREA limits, because exceedance factors provide a transparent way to compare measured concentrations with regulatory thresholds. WQI class confirmation was performed from the computed WQI summary and component files, while Spearman correlation was used only as a non-parametric association screen across selected physicochemical, metal, WQI and risk variables. Integrated risk ranking combined normalized evidence from physicochemical deviation, metal exceedance, WQI status, human health risk outputs, and microbiological counts using a reproducible multi-criteria scoring framework described below:

Normalization Rule: Each indicator variable was normalized to a 0–1 scale using min-max normalization:

$$\text{Normalized\_Score} = \left(X_i - X_{\min}\right) / \left(X_{\max} - X_{\min}\right)$$

where X_i is the observed value, $X_{\min}$ and $X_{\max}$ are the minimum and maximum values across all sites for that indicator. For indicators where lower values represent better quality (e.g., metal concentrations, HI, WQI deviation), the complement was taken:

$$\text{Score} = 1 - \text{Normalized\_Score}$$

Weighting Scheme: Equal weighting (1/5 per domain) was applied across five domains:

1) Physicochemical deviation (z-score sum of EC, TDS, COD, chloride).

2) Metal exceedance burden (sum of WHO exceedance factors for Pb, Cr, Cd).

3) WQI class penalty (0 for Excellent, 0.25 for Good, 0.50 for Poor, 0.75 for Very Poor, 1.0 for Unsuitable).

4) Human health risk (child ingestion HI + child ingestion carcinogenic risk, combined and normalized).

5) Microbiological contamination (total coliform count normalized; E. coli presence scored 1.0, absence 0.0).

Final Score Calculation:

$$\text{Integrated\_Score} = \sum_{j=1}^{5} \left(\text{Score}_j \times 0.20\right) \times 100$$

Scores range from 0 - 100, with higher scores indicating greater integrated concern. Classification: 0 - 20 (Low), 21 - 40 (Moderate), 41 - 60 (High), 61 - 80 (Very High), 81 - 100 (Critical).

Microbiological Contribution: Microbial data were incorporated as the fifth domain. Total coliform CFU counts from water samples were normalized, with E. coli presence treated as a binary indicator (presence = 1.0). This domain reflects the additional health burden from pathogenic contamination, though the aggregated ranking is primarily driven by metal and HI values due to the magnitude of metal exceedance.

3. Results

3.1. Physicochemical Profile of Dumpsite Adjacent Water Sources

The results presented in this section are aggregated by dumpsite category, combining surface water samples (streams and rivers) and groundwater samples (wells) collected from each industrial vicinity. This aggregation reflects the integrated water quality burden affecting communities in each area, where residents may access multiple water sources. The standard deviations reported for each parameter capture the variability between sampling points within each category, which may partly reflect differences between surface and groundwater sources.

The physicochemical profile showed clear variation across the four dumpsite-adjacent water categories and the comparison water category. Table 3 presents the compact summary of pH, electrical conductivity, turbidity, temperature, total dissolved solids, total suspended solids, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, sulphate, phosphate, nitrate, chloride and total hardness. The pH values ranged from 6.00 ± 0.06 in FDWS to 7.40 ± 0.03 in the comparison sample, with DDWS, BDWS and PDWS recording 7.01 ± 0.07, 7.20 ± 0.06 and 7.24 ± 0.06, respectively. Electrical conductivity was highest in DDWS at 1434 ± 1.21 µS/cm, followed by BDWS at 864 ± 0.91 µS/cm, PDWS at 856 ± 0.58 µS/cm, the comparison site at 615 ± 0.58 µS/cm and FDWS at 183 ± 0.37 µS/cm.

Table 3. Physicochemical characteristics of water samples from industrial dumpsite vicinities.

Parameter	Unit	FDWS	DDWS	BDWS	PDWS	Comparison	Guideline value	Main interpretation
pH	Unitless	6.00 ± 0.06	7.01 ± 0.07	7.20 ± 0.06	7.24 ± 0.06	7.40 ± 0.03	8.5	No exceedance flagged
Electrical conductivity	µS/cm	183 ± 0.37	1434 ± 1.21	864 ± 0.91	856 ± 0.58	615 ± 0.58	1000	Above guideline in DDWS
Turbidity	NTU	3.95 ± 0.41	3.83 ± 0.40	3.51 ± 0.25	3.45 ± 0.57	4.27 ± 0.54	10	No exceedance flagged

Continued

Temperature	˚C	28.1 ± 0.20	26.7	29.3	28.8 ± 0.21	28.8 ± 0.004	25	Above guideline in all sites
Total dissolved solids	ppm	87.4 ± 0.17	758 ± 0.45	409 ± 0.58	445 ± 0.58	201 ± 0.58	500	Above guideline in DDWS
Total suspended solids	mg/L	0.292 ± 0.001	0.477 ± 0.001	0.478 ± 0.001	0.422 ± 0.001	0.270 ± 0.002	250	No exceedance flagged
Dissolved oxygen	mg/L	7.07 ± 0.01	9.43 ± 0.08	4.57 ± 0.02	3.83 ± 0.02	4.31 ± 0.02	8	Below guideline in FDWS, BDWS, PDWS and Control
Biochemical oxygen demand	mg/L	9.15 ± 0.01	5.56 ± 0.07	7.37 ± 0.02	8.56 ± 0.02	9.48 ± 0.01	NA	Guideline value not available in WQI component table
Chemical oxygen demand	mg/L	94.0 ± 0.05	176 ± 0.06	103 ± 0.08	74.7 ± 0.05	104 ± 0.01	75	Above guideline in FDWS, DDWS, BDWS and Control
Sulphate	mg/L	2.48 ± 1.14	2.61 ± 0.09	2.59 ± 0.13	2.48 ± 0.09	2.33 ± 0.05	400	No exceedance flagged
Phosphate	mg/L	3.62 ± 0.08	11.9 ± 0.22	14.0 ± 0.12	16.0 ± 0.15	15.5 ± 0.23	5	Above guideline in DDWS, BDWS, PDWS and Control
Nitrate	mg/L	0.808 ± 0.13	1.41 ± 0.01	5.28 ± 0.00	4.84 ± 0.01	0.485 ± 0.01	5	Above guideline in BDWS
Chloride	mg/L	47.3 ± 1.24	875 ± 5.67	363 ± 4.87	409 ± 4.87	60.5 ± 3.27	250	Above guideline in DDWS, BDWS and PDWS
Calcium	mg/L	4.67 ± 0.07	5.79 ± 0.16	6.42 ± 0.12	6.42 ± 0.18	3.76 ± 0.24	NA	Guideline value not available in WQI component table
Magnesium	mg/L	2.14 ± 0.07	1.69 ± 0.19	6.00 ± 0.13	1.87 ± 0.18	0.800 ± 0.24	NA	Guideline value not available in WQI component table

Continued

Total hardness as Ca plus Mg	mg/L	6.81 ± 0.14	7.48 ± 0.35	12.4 ± 0.25	8.28 ± 0.18	4.56 ± 0.24	NA	Guideline value not available in WQI component table

Note: Samples within each category include a mixture of surface water (streams/rivers) and groundwater (wells) sources. Values represent the mean ± standard deviation of all sampling points within each category, reflecting integrated water quality in each dumpsite vicinity.

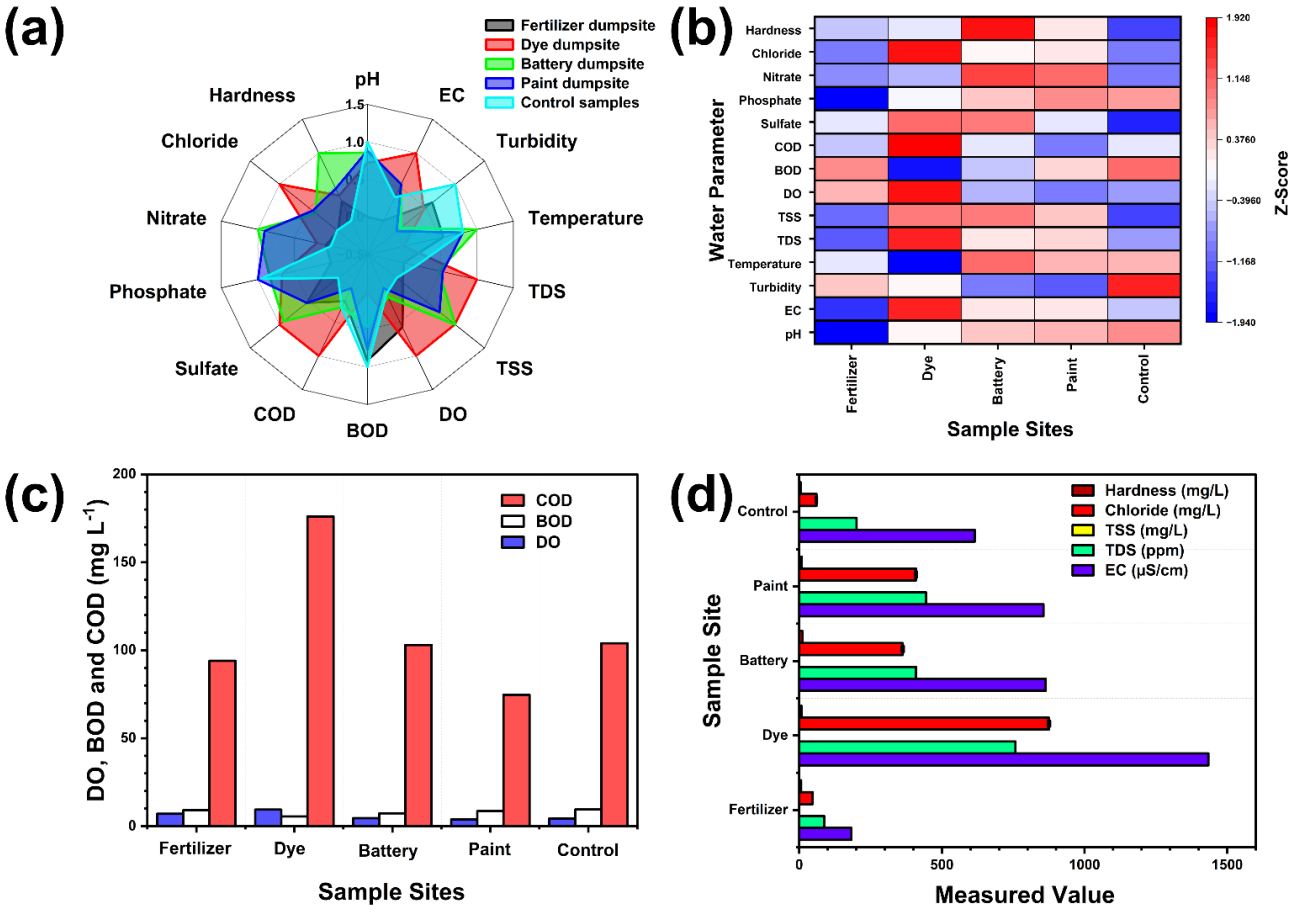

Figure 2. Physicochemical water quality signatures across industrial dumpsite water categories. (a) normalized physicochemical profiles, (b) the z score heatmap of site level physicochemical deviation, (c) DO, BOD and COD with error bars, and (d) EC, TDS, TSS, chloride and hardness with error bars.

Turbidity ranged from 3.45 ± 0.57 NTU in PDWS to 4.27 ± 0.54 NTU in the control. Temperature values were between 26.7˚C in DDWS and 29.3˚C in BDWS, with FDWS, PDWS and the control recording 28.1 ± 0.20˚C, 28.8 ± 0.21˚C and 28.8 ± 0.004˚C, respectively. Total dissolved solids followed the order DDWS at 758 ± 0.45 ppm, PDWS at 445 ± 0.58 ppm, BDWS at 409 ± 0.58 ppm, control at 201 ± 0.58 ppm and FDWS at 87.4 ± 0.17 ppm. Total suspended solids were narrowly distributed, from 0.270 ± 0.002 mg/L in the comparison site to 0.478 ± 0.001 mg/L in BDWS. Oxygen related variables showed site specific spread. Dissolved

oxygen ranged from 3.83 ± 0.02 mg/L in PDWS to 9.43 ± 0.08 mg/L in DDWS. Biochemical oxygen demand ranged from 5.56 ± 0.07 mg/L in DDWS to 9.48 ± 0.01 mg/L in the comparison site, while chemical oxygen demand ranged from 74.7 ± 0.05 mg/L in PDWS to 176 ± 0.06 mg/L in DDWS. Sulphate remained between 2.33 ± 0.05 and 2.61 ± 0.09 mg/L. Phosphate ranged from 3.62 ± 0.08 mg/L in FDWS to 16.0 ± 0.15 mg/L in PDWS, nitrate from 0.485 ± 0.01 mg/L in the comparison site to 5.28 ± 0.00 mg/L in BDWS, and chloride from 47.3 ± 1.24 mg/L in FDWS to 875 ± 5.67 mg/L in DDWS. **Figure 2(a)** presents the normalized physicochemical profiles, **Figure 2(b)** shows the z score heatmap, **Figure 2(c)** compares DO, BOD and COD, and **Figure 2(d)** displays EC, TDS, TSS, chloride and hardness.

3.2. Water Quality Index Pattern and Classification

The calculated Water Quality Index (WQI) values showed a narrow numerical spread across the dumpsite adjacent water categories and the comparison category. **Table 4** presents the Water Quality Index calculation summary and quality class for each sampling category, with the associated dominant contributing parameters, apparent water quality status and metal risk flag. The lowest WQI value was recorded for FDWS at 0.549, followed by DDWS at 0.944, the comparison site at 0.994, PDWS at 1.150 and BDWS at 1.230. On the basis of the rating scheme used for the WQI calculation, all five water categories were classified as excellent. The dominant WQI contributing parameters differed across the site categories. FDWS was mainly represented by phosphate, chemical oxygen demand and dissolved oxygen, while DDWS was represented by phosphate, dissolved oxygen and pH. BDWS showed dominant contributions from phosphate, nitrate and total dissolved solids. PDWS was represented by phosphate, nitrate and pH, whereas the control category was represented by phosphate, chemical oxygen demand and chloride. Although all water categories were assigned an excellent WQI class, the WQI status did not match the metal risk flag recorded in the integrated table. All dumpsite categories and the comparison category carried a metal exceedance flag. Pb was the dominant metal risk driver in each category, with maximum WHO exceedance factors of 825.0 in FDWS, 793.0 in DDWS, 888.0 in BDWS, 718.0 in PDWS and 162.0 in the comparison site. The apparent WQI status therefore remained excellent across the dataset, while the paired metal risk field recorded metal exceedance presence for all five water categories.

The elevated Pb at the comparison site (162 × WHO guideline) is notable and indicates that Makurdi's water sources may face diffuse contamination from multiple sources including urban runoff, atmospheric deposition, and aging infrastructure. The comparison site therefore reflects the regional baseline contamination burden rather than a pristine environmental condition, strengthening the study's ability to demonstrate that industrial dumpsites introduce additional contamination above and beyond the already-elevated background

levels.

Table 4. Water quality index calculation summary and quality class for each sampling category.

Site code	WQI value	WQI class	Dominant contributing parameters	Apparent water quality status	Metal risk flag	Dominant metal risk driver	Maximum WHO exceedance factor
FDWS	0.549	Excellent	Phosphate, chemical oxygen demand, dissolved oxygen	Excellent	Metal exceedance present	Pb	825.0
DDWS	0.944	Excellent	Phosphate, dissolved oxygen, pH	Excellent	Metal exceedance present	Pb	793.0
BDWS	1.230	Excellent	Phosphate, nitrate, total dissolved solids	Excellent	Metal exceedance present	Pb	888.0
PDWS	1.150	Excellent	Phosphate, nitrate, pH	Excellent	Metal exceedance present	Pb	718.0
Comp	0.994	Excellent	Phosphate, chemical oxygen demand, chloride	Excellent	Metal exceedance present	Pb	162.0

Note: The comparison site (Comp) represents regional background conditions within the Makurdi metropolitan area and is not a pristine or uncontaminated reference site. Its elevated Pb concentration (1.62 mg/L; 162 × WHO guideline) indicates diffuse urban contamination, making it suitable as a relative comparison point rather than an absolute control.

3.3. Toxic Metal Concentrations and Guideline Exceedance Pattern

The toxic metal dataset comprised Fe, Pb, Cr, Cd, Zn, Mn and Cu across FDWS, DDWS, BDWS, PDWS and the comparison category. Table 5 presents mean ± standard deviation concentrations together with WHO and NESREA guideline limits, site level exceedance factors and priority pollutant status for the four dumpsite adjacent water categories. Across the concentration table, Pb occurred at 8.25 ± 0.004 mg/L in FDWS, 7.93 ± 0.002 mg/L in DDWS, 8.88 ± 0.003 mg/L in BDWS, 7.18 ± 0.004 mg/L in PDWS and 1.62 ± 0.001 mg/L in the comparison site. The corresponding WHO exceedance factors for Pb were 825.0, 793.0, 888.0 and 718.0 in FDWS, DDWS, BDWS and PDWS, respectively, while the comparison site recorded 162.0. The NESREA exceedance factors for the dumpsite categories were 82.5, 79.3, 88.8 and 71.8, respectively. Cr concentrations were 1.24 ± 0.001 mg/L in FDWS, 2.06 ± 0.001 mg/L in DDWS, 1.58 ± 0.001 mg/L in BDWS, 1.68 ± 0.001 mg/L in PDWS and 0.098 ± 0.001 mg/L in the comparison site. Cr exceeded both WHO and NESREA limits by factors of 24.8, 41.2, 31.6 and 33.6 across FDWS, DDWS, BDWS and PDWS, respectively. Cd was recorded at 0.038

± 0.001 mg/L in FDWS, 0.081 ± 0.001 mg/L in DDWS, 0.056 ± 0.001 mg/L in BDWS, 0.076 ± 0.001 mg/L in PDWS and 0.034 ± 0.001 mg/L in the comparison site. The WHO and NESREA exceedance factors for Cd were 12.7, 27.0, 18.7 and 25.3 across the four dumpsite water categories.

Fe concentrations ranged from 0.235 ± 0.001 mg/L in BDWS to 0.982 ± 0.002 mg/L in FDWS. The WHO exceedance factors for Fe were 3.27 in FDWS, 2.18 in DDWS, 0.783 in BDWS and 1.06 in PDWS, whereas all Fe values remained below the NESREA limit. Mn, Cu and Zn remained below both guideline limits in all dumpsite water categories, with WHO exceedance factors below 1.0. Figure 3(a) compares the seven metal concentrations with error bars, Figure 3(b) presents the WHO exceedance factors on a log scale, Figure 3(c) displays the site by metal concentration heatmap, and Figure 3(d) summarizes the priority pollutant contribution of Pb, Cr and Cd.

All dumpsite metal concentrations exceeded the method quantification limits by wide margins (Pb, Cr and Cd by at least 40-fold), consistent with the precision and accuracy confirmed by the QA/QC checks in Section 2.4.1.

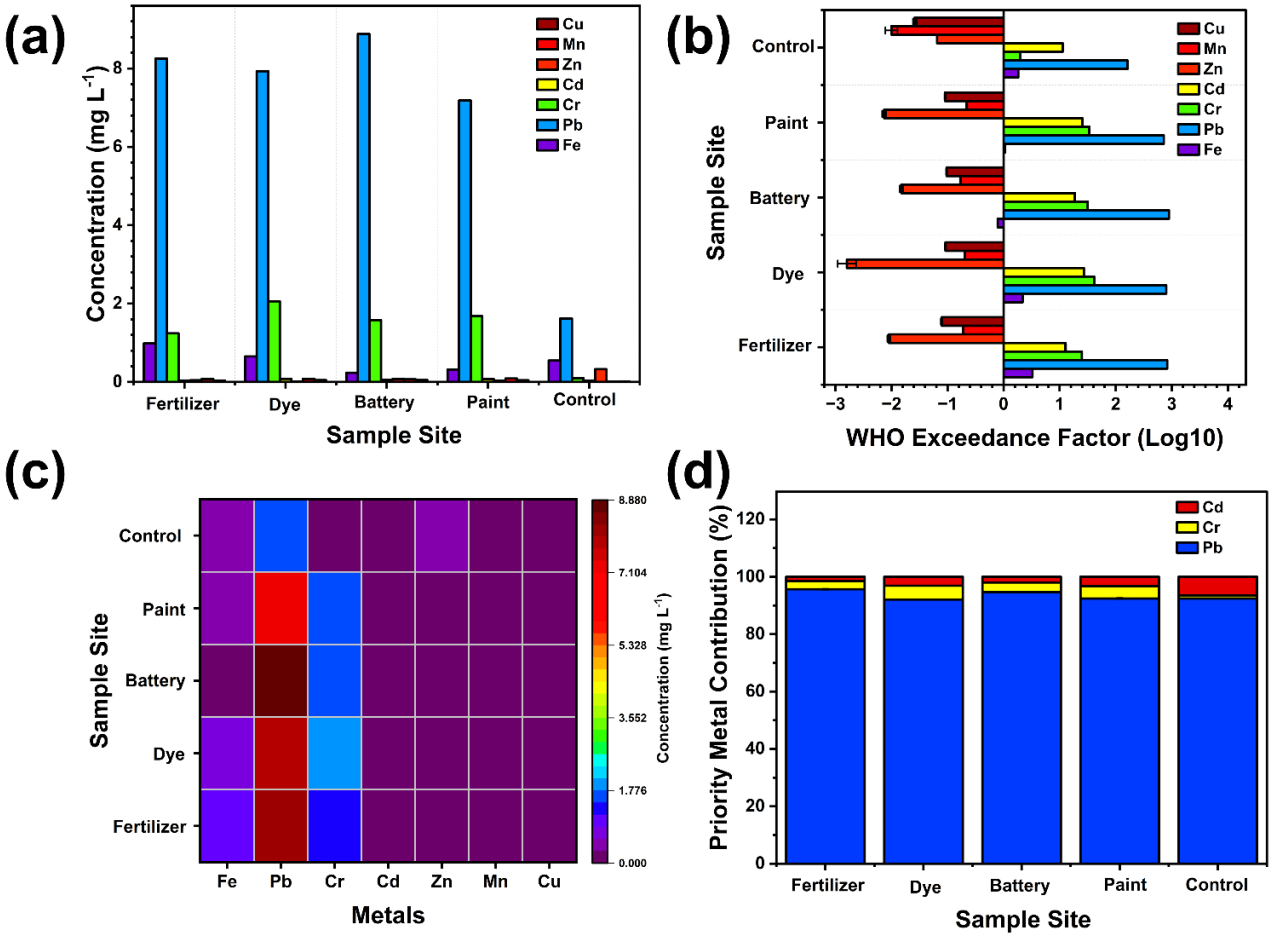

Figure 3. Toxic metal concentration and guideline exceedance architecture in water samples; (a) Fe, Pb, Cr, Cd, Zn, Mn and Cu concentrations across sites with error bars, (b) WHO exceedance factors on a log scale, (c) the site by metal concentration heatmap, and (d) the priority pollutant contribution of Pb, Cr and Cd.

Table 5. Toxic metal concentrations, guideline exceedance factors and priority pollutants in water samples.

Metal	WHO limit, mg/L	NESREA limit, mg/L	FDWS exceedance factor	DDWS exceedance factor	BDWS exceedance factor	PDWS exceedance factor	Priority status
Pb	0.010	0.100	825.00	793.00	888.00	718.00	High exceedance
Cr	0.050	0.050	24.80	41.20	31.60	33.60	Moderate exceedance
Cd	0.003	0.003	12.67	27.00	18.67	25.33	Moderate exceedance
Fe	0.300	1.000	3.27	2.18	0.78	1.06	Low exceedance
Mn	0.400	0.400	0.19	0.21	0.17	0.22	No exceedance
Cu	0.500	1.000	0.08	0.09	0.10	0.09	No exceedance
Zn	5.000	3.000	0.009	0.002	0.015	0.007	No exceedance

Note: Metal concentrations represent pooled results from surface and groundwater sources within each dumpsite category. The standard deviation reflects variability between sampling points, which may include differences between water source types.

3.4. Non Carcinogenic Health Risk across Receptor Groups

The non carcinogenic health risk profile was organized by site category, receptor group and exposure pathway. Across all site categories, ingestion produced higher total HI values than dermal contact for both adult and child receptor groups. For children, ingestion HI followed the order BDWS, 0.080488, DDWS, 0.077859, FDWS, 0.071540, PDWS, 0.068188, and Comp, 0.020451. The adult ingestion HI values followed a similar numerical sequence, with BDWS at 0.008291, DDWS at 0.008120, FDWS at 0.007851, PDWS at 0.007686, and Comp at 0.002124.

A narrower value range was recorded for dermal contact. Child dermal HI values were 0.000722 for DDWS, 0.000600 for BDWS, 0.000599 for PDWS, 0.000492 for FDWS, and 0.000072 for the comparison site. Adult dermal HI values were 0.000182 for DDWS, 0.000152 for PDWS, 0.000151 for BDWS, 0.000124 for FDWS, and 0.000018 for the comparison site. Across matched exposure pathways, child HI values were consistently higher than adult HI values, and the largest receptor difference occurred under the ingestion pathway. Figure 4(a) presents the paired adult and child Hazard Index comparison used to display this receptor level pattern. The individual HQ records showed that Pb and Cr accounted for the largest non-carcinogenic values in the ingestion and dermal datasets. Under ingestion exposure for children, the highest Pb HQ values were 0.033 in BDWS, 0.030 in FDWS, 0.029 in DDWS, 0.026 in PDWS, and 0.00957 in the comparison site. The corresponding adult Pb HQ values were 0.00349 in BDWS, 0.00323 in FDWS, 0.00306 in DDWS, 0.00281 in PDWS, and 0.00103 in the comparison site. For dermal exposure in children, the highest Cr HQ occurred in DDWS at 2.95×10^{-4}, followed by PDWS, 2.40×10^{-4}, BDWS, 2.27×10^{-4}, and FDWS, 1.78×10^{-4}.

3.5. Carcinogenic Risk Profile

Carcinogenic risk was calculated for Pb, Cr, and Cd only, as these metals have established cancer slope factors in the USEPA IRIS database and are classified as

known or probable human carcinogens. Fe, Zn, Mn, and Cu were excluded from the carcinogenic risk assessment due to their lack of established carcinogenic classification and absence of USEPA cancer slope factors [26] [28].

The carcinogenic risk dataset contained Pb, Cr and Cd records for adult and child receptors under ingestion and dermal exposure pathways. **Figure 4(b)** displays the receptor and site level comparison for total carcinogenic risk. Across all site categories, ingestion produced higher carcinogenic risk values than dermal contact in both receptor groups. For child ingestion exposure, total carcinogenic risk followed the order BDWS, 1.15×10^{-5}, DDWS, 1.10×10^{-5}, FDWS, 1.04×10^{-5}, PDWS, 9.79×10^{-6}, and Comp, 3.01×10^{-6}. Adult ingestion values followed the same general site sequence, with BDWS at 5.14×10^{-6}, DDWS at 4.93×10^{-6}, FDWS at 4.67×10^{-6}, PDWS at 4.37×10^{-6}, and Comp at 1.34×10^{-6}. In both adult and child ingestion records, BDWS recorded the highest total carcinogenic risk value, whereas the comparison category recorded the lowest total value.

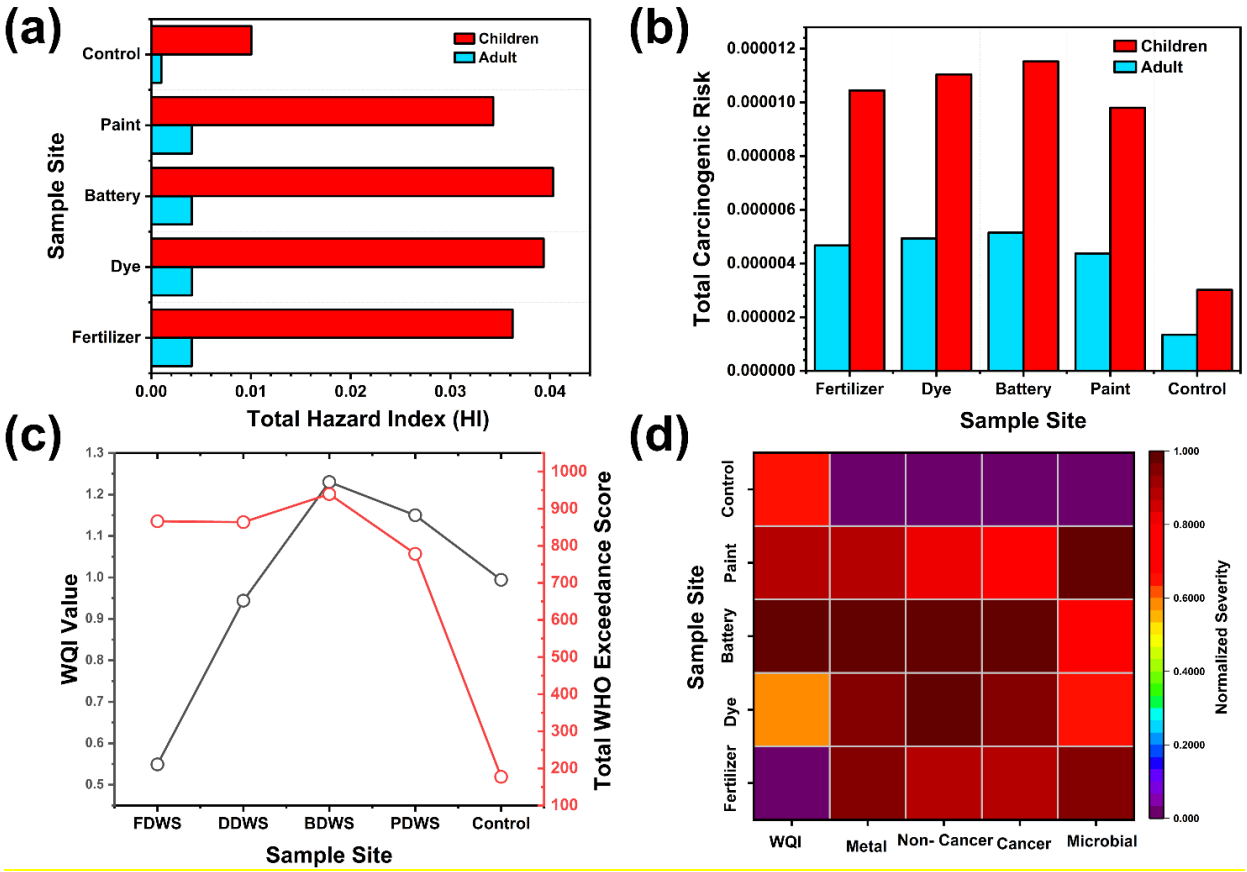

Figure 4. Integrated water quality and human health risk synthesis for dumpsite adjacent water sources; (a) WQI to total metal exceedance and metal risk mismatch plot, (b) adult and child Hazard Index risk, (c) carcinogenic risk and, (d) the integrated risk ranking matrix. The comparison site (Comp) is shown for reference; it represents regional background conditions rather than pristine conditions.

The dermal pathway produced markedly smaller values across all categories.

Adult dermal total carcinogenic risk was highest in DDWS at 4.69×10^{-9}, followed by BDWS at 4.68×10^{-9}, FDWS at 4.17×10^{-9}, PDWS at 4.11×10^{-9}, and Comp at 1.11×10^{-9}. The corresponding child dermal values were DDWS, 4.47×10^{-9}, BDWS, 4.45×10^{-9}, FDWS, 3.97×10^{-9}, PDWS, 3.91×10^{-9}, and Comp, 1.05×10^{-9}. Metal specific records showed Pb as the largest individual contributor in the ingestion pathway. For child ingestion, Pb risk values were 9.73×10^{-6} in BDWS, 9.04×10^{-6} in FDWS, 8.69×10^{-6} in DDWS, 7.87×10^{-6} in PDWS, and 2.87×10^{-6} in the comparison site. Cr formed the next largest ingestion component, while Cd produced the smallest carcinogenic risk values among the three eligible metals.

3.6. Integrated Site Ranking and Risk Triangulation

Integrated site ranking combined five normalized domains using the workflow described in Section 2.7: physicochemical deviation, total WHO metal exceedance score, WQI class penalty, child ingestion HI, and microbiological contamination (total coliform counts with E. coli presence as a binary factor). The final integrated scores ranged from 9.80 in the comparison category to 98.43 in BDWS. Among the dumpsite adjacent water categories, BDWS ranked first with an integrated score of 98.43, followed by DDWS at 88.29, PDWS at 85.28 and FDWS at 77.30. The four dumpsite categories were classified as very high integrated concern, while the comparison category was classified as low integrated concern. The site ranking separated the apparent WQI class from the broader risk matrix as illustrated in **Figure 4(c)** relating WQI to total metal exceedance and the total WHO exceedance score. BDWS recorded the highest WQI value, 1.230, together with the highest total WHO exceedance score, 939.331, the highest maximum WHO exceedance factor, 888.0, the highest maximum total HI, 0.040, and the highest total carcinogenic risk, 0.000017. DDWS recorded a WQI value of 0.944, a total WHO exceedance score of 863.675, a maximum WHO exceedance factor of 793.0, a maximum total HI of 0.039, and a total carcinogenic risk of 0.000016. PDWS recorded a WQI value of 1.150, a total WHO exceedance score of 778.314, a maximum WHO exceedance factor of 718.0, a maximum total HI of 0.034, and a total carcinogenic risk of 0.000014. FDWS recorded the lowest WQI value among dumpsite categories, 0.549, but retained a total WHO exceedance score of 866.017 and a maximum WHO exceedance factor of 825.0. The comparison site, despite having the lowest integrated score (9.80), still showed the background Pb contamination discussed in Section 4.2. **Figure 4(d)** presents the integrated risk ranking matrix visualized as a heatmap. Spearman correlation analysis showed that total WHO exceedance score correlated with child ingestion HI at rho = 0.90 and with child ingestion carcinogenic risk at rho = 0.90.

Microbiology in the ranking: Although microbiological results are not developed in the main results section, they were included in the integrated ranking to reflect the additional health burden from pathogenic contamination. The microbial counts (CFU counts from tables 28 - 29) showed FDWS and PDWS with the

highest contamination levels (70 - 75 CFU) and the presence of *E. coli* in both water and soil at these sites. This domain contributes to the integrated score but does not dominate the ranking, as the magnitude of metal exceedance and health risk indices exerts a stronger influence on the overall prioritization.

4. Discussion

4.1. Dumpsite Associated Chemical Loading Effect on Water Quality

A chemically uneven water quality pattern was apparent across the dumpsite adjacent categories, with DDWS presenting the clearest dissolved ion signal through electrical conductivity of 1434 ± 1.21 µS/cm, total dissolved solids of 758 ± 0.45 ppm and chloride of 875 ± 5.67 mg/L, consistent with the ionic loading typical of dumpsite leachate [30]. Electrical conductivity correlated strongly with total dissolved solids ($\rho = 0.900$, $p = 0.037$), and total dissolved solids correlated perfectly with chloride ($\rho = 1.000$, $p = 1.40 \times 10^{-24}$), consistent with the leachate migration effects reported in similar dumpsite groundwater studies [4].

A more irregular oxygen demand pattern was also observed: DDWS recorded the highest chemical oxygen demand (176 ± 0.06 mg/L), while PDWS had the lowest dissolved oxygen (3.83 ± 0.02 mg/L), indicating that oxidizable load, biological oxygen balance and dilution did not vary uniformly across sites [31]. Nutrient and hardness variables added a further layer of differentiation, with phosphate peaking in PDWS (16.0 ± 0.15 mg/L), nitrate in BDWS (5.28 ± 0.00 mg/L), and hardness also highest in BDWS (12.4 ± 0.25 mg/L), consistent with the independent variation of nutrient species and major ions reported in other dumpsite leachate studies [32] [33]. Overall, the evidence indicates heterogeneous chemical loading, with DDWS dominated by ionic and COD signals, BDWS by nitrate and hardness, and PDWS by phosphate enrichment and lower oxygen availability.

A methodological consideration is the pooling of surface water and groundwater samples within each dumpsite category; groundwater moves more slowly and is buffered differently than the more dynamic surface pathways [3] [4], which partly explains the standard deviations in **Table 3** for hydrology-sensitive parameters such as turbidity, dissolved oxygen and total suspended solids. This aggregation reflects community-level exposure but limits source-specific attribution, a limitation discussed further in Section 4.6.

4.2. Index Classification and Metal Specific Risk Evidence

A striking feature of the dataset is that excellent WQI classifications coexisted with substantial metal exceedance, especially for Pb, Cr and Cd, showing that a composite score can mask contaminant-specific hazards [5] [6]. Pb produced the largest exceedance burden (WHO factors of 825.0, 793.0, 888.0 and 718.0 in FDWS, DDWS, BDWS and PDWS), with Cr (24.8 − 41.2×) and Cd (12.67 − 27.0×) reinforcing the same pattern; these three metals are commonly prioritized in water risk assessment owing to persistence, toxicity and chronic exposure relevance [34].

The correlation structure provided additional support, read as a site-level association screen rather than broad population inference. Total WHO exceedance score correlated strongly with child ingestion HI ($\rho = 0.900$, $p = 0.037$) and with child ingestion carcinogenic risk ($\rho = 0.900$, $p = 0.037$), aligning metal exceedance with receptor-based risk more clearly than the general WQI class. The strongest single-metal signal was Pb, whose concentration correlated perfectly with total WHO exceedance score ($\rho = 1.000$, $p = 1.40 \times 10^{-24}$), indicating Pb largely structured the exceedance architecture without implying Cr and Cd were negligible. The WQI classification is therefore best read as a general physicochemical index, while metal exceedance and receptor-based risk metrics provide the sharper safety signal for dumpsite adjacent water appraisal.

A noteworthy finding is the elevated Pb concentration at the comparison site (1.62 mg/L; 162× WHO guideline), indicating that Makurdi's water sources may face diffuse contamination from sources such as urban runoff, atmospheric deposition and aging lead infrastructure, rather than reflecting a pristine baseline. This strengthens the study's central finding that industrial dumpsites add contamination above and beyond this elevated regional background, and confirms the comparison site's role as a relative rather than absolute reference point.

The exceptionally high Pb concentrations (exceedance factors of 793 - 888) were verified by the QA/QC checks in Section 2.4.1, and several samples required dilution and reanalysis after exceeding the initial calibration range, underscoring the magnitude of contamination.

4.3. Child Receptor Risk as a Decisive Public Health Signal

Receptor separation added an important public health dimension because children consistently showed higher non-carcinogenic risk than adults under ingestion: child ingestion HI ranged from 0.020451 to 0.080488 (highest in BDWS), versus 0.002124 - 0.008291 for adults, consistent with body-weight-driven dose amplification reported elsewhere [10] [13]. Ingestion dominated the dermal pathway by several orders of magnitude in both receptor groups, mirroring the pattern typically seen in groundwater and drinking-water risk assessments where oral intake transfers contaminants more directly into systemic exposure [13].

The carcinogenic risk profile followed the same receptor-differentiated structure: child ingestion carcinogenic risk was highest in BDWS (1.15214×10^{-5}) and lowest in the control (3.0143×10^{-6}), while adult values ranged from 1.3445×10^{-6} to 5.1404×10^{-6}, consistent with the prominence of Pb, Cr and Cd among metals of major toxicological concern [28] and with the correlation pattern reported in Section 4.2.

The exposure parameters follow standard USEPA guidelines [25] and comparable Nigerian studies [11] [16]. Higher child risk values are driven by lower body weight (15 kg vs 70 kg) and higher intake per unit body weight (1.0 vs 2.0 L/day), which magnify child CDI estimates—conservative, screening-appropriate assumptions for data-scarce settings [29].

Pb, Cr and Cd were selected for carcinogenic risk assessment based on established USEPA/IARC classification [26] [28]; Fe, Zn, Mn and Cu were excluded as they lack cancer slope factors and carcinogenic classification, keeping the risk estimates scientifically defensible.

4.4. Contextual Industrial Signatures and Contaminant Distribution

A contextual reading of the four dumpsite categories treats the metal distribution as an industrial-vicinity signal rather than definitive source attribution, since mixed waste deposits, hydrological transport and weathering can obscure a single source pathway [35]. BDWS recorded the highest Pb concentration (8.88 ± 0.003 mg/L) and exceedance factor (888.0), consistent with lead's prominence in battery waste; DDWS recorded the highest Cr (2.06 ± 0.001 mg/L) and Cd (0.081 ± 0.001 mg/L), plausibly linked to metal-bearing additives common in textile and dyeing wastewater [36], though this is not conclusive source allocation. The strong site-level association between Cr and Cd ($\rho = 1.000$, $p = 1.40 \times 10^{-24}$) suggests co-movement of these metals but should support, not replace, chemical source verification.

The fertilizer and paint categories carried distinct but non-exclusive signals: FDWS had the highest Fe concentration (0.982 ± 0.002 mg/L), plausibly from phosphate-related impurities, while PDWS showed Pb, Cr and Cd exceedance without being the maximum site for any single metal, consistent with metal-bearing paint formulation residues. The integrated ranking (BDWS, then DDWS, PDWS, FDWS) reflects combined metal exceedance, health risk and water quality evidence rather than site label alone, consistent with contemporary industrial wastewater assessment that interprets contaminant mixtures through converging metrics rather than single-source assumptions.

The pooling of surface and groundwater sources may also affect interpretation of industrial source signatures, since surface contamination more likely reflects recent runoff while groundwater contamination reflects persistent leaching [30] [32]; BDWS's high Pb concentration (8.88 mg/L), for instance, could originate from either pathway. This source-pathway limitation is discussed further in Section 4.6.

4.5. Scientific and Regulatory Implications

A key regulatory implication is that dumpsite water classification should not rely on WQI alone: excellent WQI classes coexisted with Pb exceedance factors of 825.0 - 888.0 across the four dumpsite categories, showing that the composite index and the metal exceedance screen answer different safety questions [8]. This supports the growing practice of combining WQI with metal pollution indices and human health risk models, since regulatory meaning shifts once toxic metals are evaluated through exposure pathways and receptor groups.

Pb, Cr and Cd require explicit regulatory attention given their much larger exceedance factors relative to Fe, Mn, Cu and Zn, since concentration-based screen-

ing alone is insufficient without exposure-based risk assessment—a priority reinforced by the correlation pattern reported in Section 4.2. A defensible surveillance framework should therefore combine WQI classification, metal exceedance factors, child and adult HI, carcinogenic risk and integrated site ranking, consistent with recent Nigerian and African water risk studies [11] [16]. This combined approach offers a stronger basis for site prioritisation, periodic testing and risk communication than any single index alone.

The integrated ranking workflow (Section 2.7) provides a transparent, reproducible method for site prioritization; although microbiological data are included, the limited characterization (presence/absence, CFU counts without species-level pathogenicity assessment) means this domain is a supporting rather than primary driver of the ranking outcome.

4.6. Boundary Conditions and Risk Management Priorities

This evidence should be read as a site-specific risk screening framework rather than a basis for broad regional generalisation, given the compact number of water categories sampled [5]. The absence of seasonal repetition means that dry season dilution, wet season runoff, water table fluctuation and episodic leachate movement could not be separated, and repeated temporal monitoring would strengthen future assessments [37]. Source interpretation also remains constrained: the fertilizer, dye, battery and paint categories identify industrial vicinity contexts rather than verified chemical source allocation, and more definitive attribution would require hydrochemical tracers or isotopic evidence, since metal inputs can arise from interacting natural and anthropogenic pathways [14].

A further boundary condition concerns the comparison site, which does not represent pristine conditions given its elevated Pb concentration (162× WHO guideline)—reflecting the reality that truly uncontaminated control sites are rarely available in rapidly urbanizing industrial settings. Relatedly, streams, rivers and wells differ fundamentally in hydrological behaviour and contaminant residence time [14] [37], and pooling them by category, while intentional for capturing community-level exposure, may mask pathway-specific differences; future studies should analyse surface and groundwater sources separately. The present findings should therefore be read as integrated vicinity-scale assessments rather than source-specific characterizations.

Within those boundaries, the most defensible recommendation is a targeted surveillance programme centred on Pb, Cr and Cd, which dominated the exceedance architecture and carry established neurological, developmental, renal and cardiovascular relevance [10], reinforced by the correlation pattern in Section 4.2. Practical management should combine periodic physicochemical testing, metal-specific exceedance screening, adult and child health risk calculations, risk-based site ranking and precautionary community water advisories where exceedance persists, consistent with integrated water quality and health risk approaches applied elsewhere in Nigeria [16].

This regional background contamination (Section 4.2) reinforces the study's central recommendation that comprehensive risk assessment combining WQI, metal exceedance factors, and receptor-specific health risk modelling be applied across all water sources in the region, not only those immediately adjacent to known pollution sources.

5. Conclusions

This study evaluated the physicochemical quality, toxic metal burden, water quality status and human health risk profile of water sources around fertilizer, dye, battery and paint dumpsite vicinities in Makurdi, Nigeria. The physicochemical results showed marked site variation, with DDWS recording the strongest dissolved ionic signature through electrical conductivity of 1434 ± 1.21 μS/cm, total dissolved solids of 758 ± 0.45 ppm and chloride of 875 ± 5.67 mg/L. Oxygen related variables also varied across the water categories, as chemical oxygen demand peaked in DDWS at 176 ± 0.06 mg/L, while dissolved oxygen was lowest in PDWS at 3.83 ± 0.02 mg/L. The comparison site, while removed from the industrial dumpsites, still exhibited notable contamination with Pb at 1.62 mg/L (162× WHO guideline), reflecting the diffuse urban background contamination in Makurdi.

These patterns confirmed that the water sources were chemically heterogeneous rather than uniformly affected. The Water Quality Index classified all water categories as excellent, with values ranging from 0.549 in FDWS to 1.230 in BDWS. However, this general classification did not sufficiently represent the toxic metal profile. Pb exceeded the WHO guideline by factors of 825.0, 793.0, 888.0 and 718.0 in FDWS, DDWS, BDWS and PDWS, respectively. Cr and Cd also showed repeated exceedance across the dumpsite water categories, whereas Mn, Cu and Zn remained below the adopted guideline limits. The central contribution of this study is therefore the demonstration that favourable WQI classification can coexist with substantial metal exceedance in dumpsite adjacent water. Health risk outputs further clarified the relevance of metal resolved assessment. Child ingestion HI values were consistently higher than adult ingestion HI values, with the maximum child ingestion HI recorded in BDWS at 0.080488. Carcinogenic risk also showed higher ingestion pathway values for children than adults, with BDWS recording the highest child ingestion carcinogenic risk at 0.0000115214. Integrated ranking placed BDWS first, followed by DDWS, PDWS and FDWS, while the comparison category showed the lowest integrated score. This regional background contamination indicates the need for region-wide water quality monitoring. Overall, the findings support a water safety framework that combines WQI, toxic metal exceedance, receptor specific health risk and integrated site ranking before dumpsite adjacent water is described as acceptable for use.

The study pooled surface water (streams and rivers) and groundwater (wells) sources within each dumpsite category to reflect community-level water use patterns and integrated exposure risk. While this approach captures the overall con-

tamination burden in each industrial vicinity, it does not differentiate between contaminant pathways in surface versus groundwater. The observed variability (standard deviations) in the results partially reflects these source-type differences. Future research should conduct separate sampling and analysis of surface and groundwater sources to enable pathway-specific risk characterization.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Onu, J., Mustapha Muhammad, R., Bala Maiauduga, T. and Ishaq Dikko, Y. (2024) Effect of Leachate Waste on Groundwater Quality in Bayan-geri, Bauchi Metropolis, Bauchi State, Nigeria. *International Journal of Innovative Environmental Studies Research*, **12**, 18-23. https://www.seahipublications.org/wp-content/uploads/2024/05/IJIESR-J-3-2024.pdf

[2] Wang, J., Zhang, H., Liu, J., Hu, S., Shi, J., Li, X., *et al.* (2025) Distribution Characteristics, Source Identification, and Health Risk Assessment of Heavy Metals in Surface Water and Groundwater: A Case Study in Mining-Affected Areas. *Frontiers in Water*, **7**, Article ID: 1639009. https://doi.org/10.3389/frwa.2025.1639009

[3] Gupta, A., Verma, A. and Rajamani, P. (2024) Impact of Landfill Leachate on Ground Water Quality: A Review. In: Singh, P. and Kumar, R., Eds., *Springer Water*, Springer, 93-107. https://doi.org/10.1007/978-3-031-55513-8_6

[4] Nihalani, S.A., Behede, S.N. and Meeruty, A.R. (2022) Groundwater Quality Assessment in Proximity to Solid Waste Dumpsite at Uruli Devachi in Pune, Maharashtra. *Water Science and Technology*, **85**, 3331-3342. https://doi.org/10.2166/wst.2022.172

[5] Badeenezhad, A., Soleimani, H., Shahsavani, S., Parseh, I., Mohammadpour, A., Azadbakht, O., *et al.* (2023) Comprehensive Health Risk Analysis of Heavy Metal Pollution Using Water Quality Indices and Monte Carlo Simulation in R Software. *Scientific Reports*, **13**, Article No. 15817. https://doi.org/10.1038/s41598-023-43161-3

[6] Nawaz, R., Nasim, I., Irfan, A., Islam, A., Naeem, A., Ghani, N., *et al.* (2023) Water Quality Index and Human Health Risk Assessment of Drinking Water in Selected Urban Areas of a Mega City. *Toxics*, **11**, Article 577. https://doi.org/10.3390/toxics11070577

[7] Hama Aziz, K.H., Mustafa, F.S., Omer, K.M., Hama, S., Hamarawf, R.F. and Rahman, K.O. (2023) Heavy Metal Pollution in the Aquatic Environment: Efficient and Low-Cost Removal Approaches to Eliminate Their Toxicity: A Review. *RSC Advances*, **13**, 17595-17610. https://doi.org/10.1039/d3ra00723e

[8] Chidiac, S., El Najjar, P., Ouaini, N., El Rayess, Y. and El Azzi, D. (2023) A Comprehensive Review of Water Quality Indices (WQIs): History, Models, Attempts and Perspectives. *Reviews in Environmental Science and Bio/Technology*, **22**, 349-395. https://doi.org/10.1007/s11157-023-09650-7

[9] Hsieh, T.-Y. and Chiueh, P.-T. (2025) *Journal of Water and Health*, **23**, 1430-1445. https://doi.org/10.2166/wh.2025.126

[10] Tripathi, P., Varma, K., Srivastava, V., Dlamini, N.S. and Jha, P.K. (2025) Heavy Metal Contamination and Associated Health Risk Assessment in Groundwater of

Mirzapur, Uttar Pradesh. *Frontiers in Water*, **7**, Article ID: 1694963. https://doi.org/10.3389/frwa.2025.1694963

[11] Emmanuel, U.C., Chukwudi, M.I., Monday, S.S. and Anthony, A.I. (2022) Human Health Risk Assessment of Heavy Metals in Drinking Water Sources in Three Senatorial Districts of Anambra State, Nigeria. *Toxicology Reports*, **9**, 869-875. https://doi.org/10.1016/j.toxrep.2022.04.011

[12] Ijioma, U.D., Ijioma, M. and Herd, R. (2025) Assessment of Quality and Health Risks in Drinking Water Sources in Aba, Nigeria. *Water Practice & Technology*, **20**, 937-953. https://doi.org/10.2166/wpt.2025.042

[13] Dimowo, B.O., Gbadebo, A.M., Taiwo, A.M., Sojinu, O.S. and Dimowo, M.O. (2025) Carcinogenic and Non-Carcinogenic Health Risk Assessment of Heavy Metals in Water from Selected Oil Pollution-Prone Communities in the Niger Delta Region. *Journal of Trace Elements and Minerals*, **14**, Article 100266. https://doi.org/10.1016/j.jtemin.2025.100266

[14] Vesković, J. and Onjia, A. (2025) Exposure and Toxicity Factors in Health Risk Assessment of Heavy Metal(Loid)s in Water. *Water*, **17**, Article 2901. https://doi.org/10.3390/w17192901

[15] Barambu, A.U., Maigari, A.U. and Sulaiman, M.B. (2020) Levels of Heavy Metals in Groundwater around a Municipal Solid Waste Dumpsite in Bauchi, Nigeria: Assessing the Health Impact. *Journal of Chemical Society of Nigeria*, **45**, 316-323.

[16] Agboeze, E., Chime, C., Udeozo, P.I., Ofordile, V.A., Nsude, P.O., Eze, C.G., *et al.* (2025) Heavy Metal Contamination and Health Risks from Dumpsite Effluents in Enugu State Southeastern Nigeria. *Environmental Analysis Health and Toxicology*, **40**, e2025023. https://doi.org/10.5620/eaht.2025023

[17] Rahman, A., Jahanara, I. and Jolly, Y.N. (2021) Assessment of Physicochemical Properties of Water and Their Seasonal Variation in an Urban River in Bangladesh. *Water Science and Engineering*, **14**, 139-148. https://doi.org/10.1016/j.wse.2021.06.006

[18] American Public Health Association (APHA) (2012) Standard Methods for the Examination of Water and Wastewater. 22nd Edition, American Public Health Association, American Water Works Association and Water Environment Federation.

[19] Anate, S.G. and Edori, O.S. (2024) Applicability of Water Quality Index in Assessing the Portability of Kaani River in Ogoni Axis of Rivers State, Nigeria. *Faculty of Natural and Applied Sciences Journal of Basic and Environmental Research*, **1**, 9-16. https://www.academia.edu/128415979/

[20] Zangina, T., Idris, M., Ummati, L.M.A., Muazu, A., Saadu, I. and Musa, I.M. (2019) Atomic Absorption Spectroscopy Analysis of Heavy Metals in Water at Mai-Ganga Coal Mining Village, Gombe State, Nigeria. *FUDMA Journal of Sciences*, **3**, 497-500. https://fjs.fudutsinma.edu.ng/index.php/fjs/article/view/1678

[21] Sumary, D.P., Raymond, J., Chacha, M., Banzi, F.P. and Gomezulu, E. (2025) Assessment of Heavy Metals in Soil and Water from Bahi District, Tanzania. *PLOS ONE*, **20**, e0325487. https://doi.org/10.1371/journal.pone.0325487

[22] USEPA (2016) Definition and Procedure for the Determination of the Method Detection Limit, Revision 2. EPA 821-R-16-006, Office of Water.

[23] USEPA (2018) National Functional Guidelines for Inorganic Superfund Data Review. Office of Land and Emergency Management.

[24] Mawari, G., Kumar, N., Sarkar, S., Frank, A.L., Daga, M.K., Singh, M.M., *et al.* (2022) Human Health Risk Assessment Due to Heavy Metals in Ground and Surface Water and Association of Diseases with Drinking Water Sources: A Study from Maharash-

tra, India. *Environmental Health Insights*, **16**, 1-11.

[25] USEPA (2011) Exposure Factors Handbook 2011 Edition (Final). EPA/600/R-09/052F, National Center for Environmental Assessment.

[26] USEPA (2022) Integrated Risk Information System (IRIS) Database. United States Environmental Protection Agency. https://www.epa.gov/iris

[27] USEPA (2004) Risk Assessment Guidance for Superfund (RAGS) Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment). EPA/540/R/99/005, Office of Emergency and Remedial Response.

[28] Khoshakhlagh, A.H., Mohammadzadeh, M. and Gruszecka-Kosowska, A. (2024) The Preventive and Carcinogenic Effect of Metals on Cancer: A Systematic Review. *BMC Public Health*, **24**, Article No. 2079. https://doi.org/10.1186/s12889-024-19585-5

[29] USEPA (2005) Guidelines for Carcinogen Risk Assessment. EPA/630/P-03/001F, Risk Assessment Forum.

[30] Wang, J. and Qiao, Z. (2024) A Comprehensive Review of Landfill Leachate Treatment Technologies. *Frontiers in Environmental Science*, **12**, Article ID: 1439128. https://doi.org/10.3389/fenvs.2024.1439128

[31] Ishaq, A., Said, M.I.M., Azman, S.B., Houmsi, M.R., Isah, A.S., Jagun, Z.T., *et al.* (2024) The Influence of Various Chemical Oxygen Demands on Microbial Fuel Cells Performance Using Leachate as a Substrate. *Environmental Science and Pollution Research*, **32**, 27467-27482. https://doi.org/10.1007/s11356-024-32090-x

[32] Alemayehu, T., Mebrahtu, G., Hadera, A. and Bekele, D.N. (2019) Assessment of the Impact of Landfill Leachate on Groundwater and Surrounding Surface Water: A Case Study of Mekelle City, Northern Ethiopia. *Sustainable Water Resources Management*, **5**, 1641-1649. https://doi.org/10.1007/s40899-019-00328-z

[33] Hariri Asli, K., Falahatkar, S. and Dayemi Gorabi, M. (2024) Water Hammer Stress on Water Transmission Line. *Water Practice & Technology*, **19**, 2399-2418. https://doi.org/10.2166/wpt.2024.148

[34] Zhou, J., Jiang, Z., Qin, X. and Zhang, L. (2024) Heavy Metal Distribution and Health Risk Assessment in Groundwater and Surface Water of Karst Lead-Zinc Mine. *Water*, **16**, Article 2179. https://doi.org/10.3390/w16152179

[35] Oladimeji, T.E., Oyedemi, M., Emetere, M.E., Agboola, O., Adeoye, J.B. and Odunlami, O.A. (2024) Review on the Impact of Heavy Metals from Industrial Wastewater Effluent and Removal Technologies. *Heliyon*, **10**, e40370. https://doi.org/10.1016/j.heliyon.2024.e40370

[36] Gupta, B.G. and Mukhopadhyay, R. (2025) Heavy Metal Contamination from Textile Wastewater and Its Health Impacts: A Case Study from West Bengal with Sustainable Remediation Approaches. *Scientific Reports*, **15**, Article No. 29578. https://doi.org/10.1038/s41598-025-13357-w

[37] Younesi Baneh, P., Ahmadi, B., Salehzadeh, H., Mohammadi, H., Shahmoradi, B. and Ghaderi, B. (2024) Assessment of Heavy Metal Contamination in Groundwater of Rural Areas of Kurdistan Province Iran: A Comprehensive Study. *Heliyon*, **10**, e39833. https://doi.org/10.1016/j.heliyon.2024.e39833