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Potentially Harmful Elements in Mine Pond Water from Derelict Tin and Columbite Workings in Barkin-Ladi, Jos Plateau, Nigeria: Contamination Status and Human Health Risk

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ABSTRACT

Derelict tin and columbite mine ponds are a defining feature of the Jos Plateau landscape, yet many continue to be used by rural communities for drinking, domestic chores, livestock watering, and crop irrigation long after active mining has ceased. This study assessed the concentrations of twelve potentially harmful elements (PHEs: As, Cu, Pb, Cr, Fe, Zn, Mn, Cd, Ni, Se, Mo and Hg) in water from twenty georeferenced abandoned and active mine ponds in Barkin-Ladi Local Government Area, Plateau State, north-central Nigeria, and evaluated the associated contamination status and human health risk. Samples were analysed by Atomic Absorption Spectrometry and interpreted against WHO drinking-water guidelines using the Contamination Factor (CF) and Pollution Load Index (PLI), together with non-carcinogenic health risk indices (Estimated Daily Intake, Hazard Quotient and Hazard Index) for adult and child receptors. Arsenic and lead exceeded WHO guidelines at fourteen and sixteen of sixteen detection sites respectively (means 7.7 and 7.7 times the guideline value), cadmium exceeded its guideline at thirteen of sixteen sites, and mercury reached contamination factors in the hundreds to low thousands at several locations (peaking at approximately 1,500 at site W13), a signature consistent with historical gold amalgamation practice associated with artisanal small-scale mining rather than tin ore weathering alone. A discrete, spatially isolated chromium detection at site W9 (2.1 times the guideline) pointed to a localised rather than basin-wide source. Every sampled location returned a Pollution Load Index above unity, and the cumulative adult Hazard Index exceeded the safety threshold of 1.0 at all twenty sites (range 1.20 to 18.02), rising to 2.81-42.05 for children, with the most severe contamination concentrated in a spatially coherent upper cluster of ponds (W11-W20) accounting for every value exceeding HI = 10. These findings, benchmarked against comparable studies from Thailand, southwest Nigeria, and northern Nigeria, place this site among the more severely contaminated legacy mining water resources reported in the recent literature, identify mine pond water as the principal, and most urgent, exposure pathway in this legacy mining landscape, and support prioritizing arsenic, lead, cadmium and mercury for regulatory attention and remedial intervention ahead of any further domestic or agricultural use of these waters.

Keywords: potentially harmful elements; mine pond water; artisanal mining; hazard index; contamination factor; Jos Plateau

INTRODUCTION

Abandoned and active small-scale mine workings leave behind more than a scarred landscape. Across the tin and columbite fields of the Jos Plateau, decades of alluvial and hard-rock extraction have carved thousands of open pits into the terrain, many of which have since filled with water and been absorbed, almost invisibly, into the daily life of the surrounding communities. These mine ponds are used for drinking, bathing, laundry, swimming, livestock watering, block-moulding, and, increasingly, the irrigation of nearby vegetable gardens.

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What is rarely visible to the people who rely on them is the geochemical legacy locked into the water itself: residual sulphide minerals continuing to oxidise, tailings leaching slowly into standing water, and, in places, a lingering imprint of historical mercury amalgamation used to recover fine gold alongside cassiterite.

Mine drainage of this kind is a well-documented global problem. The oxidative weathering of sulphide minerals such as arsenopyrite, galena, sphalerite, and pyrite releases arsenic, lead, cadmium, and a suite of associated trace elements into solution, frequently under acidic, chemically reactive conditions that keep these elements mobile for decades after mining activity ends (Gray, 1997; Nordstrom, 2011). Where artisanal small-scale gold mining (ASGM) has historically overlapped with tin extraction, as is common across the Nigerian basement complex, liquid mercury used in amalgamation adds an additional, highly persistent contaminant to this mixture (Hentschel et al., 2002; UNEP, 2013). The consequences for human health are not speculative: chronic ingestion of arsenic is causally linked to skin, bladder, lung, and kidney cancers as well as peripheral neuropathy (IARC, 2012; Naujokas et al., 2013), lead exposure in children produces measurable, irreversible reductions in IQ at any detectable blood level (Lanphear et al., 2005; Bellinger, 2008), cadmium accumulates in the renal cortex over a ten-to-thirty-year biological half-life (Järup, 2003), and inorganic mercury is nephrotoxic and neurotoxic even at comparatively low chronic doses (Bernhoft, 2012).

The Jos Plateau Younger Granite Complex has been mined for tin and associated columbite-tantalite ore since the early twentieth century, first through large-scale alluvial dredging and later through a proliferation of small-scale and artisanal operations that continued long after the major mining companies withdrew. The result is a landscape pockmarked with thousands of disused pits of widely varying depth and age, many of which have naturally filled with rainwater and shallow groundwater to form what local communities refer to simply as mine ponds. Unlike engineered tailings dams in large-scale operations, these features were never designed, lined, or capped, and their geochemical behaviour is governed almost entirely by the mineralogy of the surrounding host rock and the residual waste material left in and around each pit. Where these ponds sit atop or adjacent to sulphide-bearing zones, principally arsenopyrite, galena, and sphalerite associated with the tin-columbite mineralisation, continued weathering under humid tropical conditions sustains a slow but persistent release of arsenic, lead, cadmium, and other trace elements into the standing water column, a process that can continue for decades after mining ceases (Gray, 1997; Nordstrom, 2011).

Despite the scale of derelict mining across the Jos Plateau, and despite the fact that many of these ponds are in continuous, informal domestic and agricultural use, comprehensive, multi-element water quality and health-risk data for this specific setting remain limited. Existing regional studies have tended to focus on either soil or crop contamination in isolation (Adamu et al., 2023; Adie et al., 2018), leaving the water pathway itself comparatively under-characterised even though it is frequently the pathway of highest and most direct exposure. The present study addresses this gap by presenting a systematic, twelve-element geochemical and health-risk assessment of mine pond water across the derelict tin and columbite workings of Barkin-Ladi and its environs. The specific objectives were to: (i) quantify the concentrations of twelve PHEs (As, Cu, Pb, Cr, Fe, Zn, Mn, Cd, Ni, Se, Mo, Hg) across twenty sampling locations; (ii) evaluate the degree of contamination relative to natural geochemical background using the Contamination Factor and Pollution Load Index; and (iii) quantify the non-carcinogenic health risk to adult and child consumers using the Estimated Daily Intake, Hazard Quotient, and Hazard Index framework. In doing so, this study provides the first integrated contamination-and-risk picture of the mine pond water pathway in this specific derelict mining landscape, and offers an evidence base for prioritising remedial intervention.

The public health relevance of this pathway is amplified by the fact that these communities typically have no access to piped, treated alternative water supplies, meaning the mine ponds are frequently the only readily available source of water within walking distance for both domestic and agricultural use. Rural health facilities serving these communities rarely have the diagnostic capacity to link chronic, low-grade symptoms such as fatigue, cognitive difficulty, or gastrointestinal disturbance back to long-term trace-element exposure, meaning that a contamination problem of this scale can persist for years, even generations, without being formally recognised as an environmental health issue by either the affected population or the health system serving them. Establishing a clear, quantitative evidence base for the scale and nature of this contamination is

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therefore a necessary first step toward any future intervention, whether that intervention takes the form of alternative water provision, active remediation, or targeted community health screening.

MATERIALS AND METHODS

Study Area

The study was carried out in Barkin-Ladi Local Government Area and its environs, on the Jos Plateau in Plateau State, north-central Nigeria, a region underlain by the Jos Plateau Younger Granite Complex and associated basement rocks that have historically hosted extensive alluvial and lode tin-columbite mining. Twenty sampling locations were established across a network of abandoned and, in a small number of cases, still-active mine ponds, ranging from long-disused pits with no current activity to ponds actively used for irrigation, swimming, livestock watering, and block-moulding. Sampling locations were georeferenced using a handheld GPS receiver (Garmin GPSMAP 62) and ranged in elevation from approximately 4,150 to 4,425 feet above sea level.

Table 1 summarises the twenty sampling locations, their approximate elevation, and their principal current use, illustrating the diversity of informal domestic and agricultural activity these ponds continue to support.

Location	Approx. elevation (ft)	Current use / description
W1	4,229	Abandoned mine pond, used for block-moulding industry
W2	4,239	Pepper farm irrigated from abandoned mine pond
W3	4,241	Abandoned open mine pond used for farming
W4	4,193	Open mine pond used for irrigation and mixed farming
W5	4,152	Abandoned mine pond
W6	4,183	Yellow pepper farm irrigated from abandoned mine pond
W7	4,183	Garden egg and pepper farm
W8	4,182	Abandoned flooded mine pond
W9	4,192	Abandoned mine pond
W10	4,424	Abandoned mine pond used for farming and swimming
W11	4,261	Active mining pond with crops farmed around it
W12	4,276	Abandoned mine pond, no farming
W13	4,273	Active mining along the bank
W14	4,232	Active mining within the mine pond
W15	4,205	Abandoned mine pond
W16	4,221	Abandoned mine pond
W17	4,214	Abandoned mine pond

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W18	4,234	Abandoned mine pond used for farming
W19	4,234	Abandoned mine pond used for swimming
W20	4,237	Abandoned mine pond, no current activity

Figure 1 presents the spatial distribution of the twenty water sampling locations plotted from their recorded GPS coordinates, classified by adult Hazard Index severity tier as determined in Section 3.3.

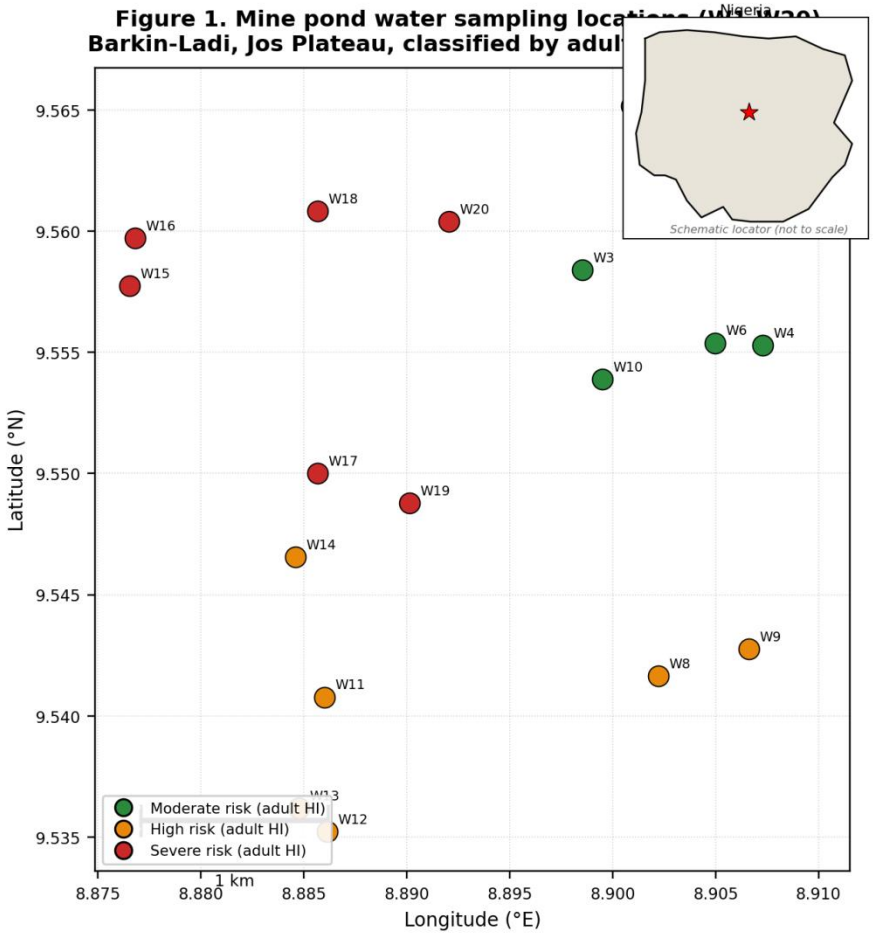


Figure 1. Spatial distribution of mine pond water sampling locations (W1-W20) in Barkin-Ladi, Jos Plateau, Nigeria, classified by adult non-carcinogenic Hazard Index severity tier. Coordinates plotted from field GPS records (Garmin GPSMAP 62). Inset shows the approximate location of the study area within Nigeria.

Sample Collection

Twenty water samples were collected during the dry season, when reduced dilution typically produces peak trace-element concentrations in standing surface water. Samples were collected in pre-cleaned 250 mL polyethylene bottles that had been soaked in a 75% distilled water/25% HNO_3 mixture, rinsed with distilled water, and oven dried. Bottles were rinsed with the sample water prior to collection to minimise cross-contamination, then capped, stored at 4°C, and transported to the laboratory within the standard holding time.

Laboratory Analysis

Water samples were analysed for twelve elements (As, Cu, Pb, Cr, Fe, Zn, Mn, Cd, Ni, Se, Mo, and Hg) by Atomic Absorption Spectrometry (AAS, model AA210 VGP), following acid digestion where required. Analytical quality was checked against certified reference material recovery and replicate analyses, with outliers identified using boxplots and the ±3 standard deviation criterion (Khan et al., 2016).

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Contamination Assessment

The Contamination Factor (CF) was calculated for each element as CF = C_m / C_ref, where C_m is the measured concentration and C_ref is the natural background concentration in freshwater, taken from Reimann and Caritat (1998) and cross-validated against WHO (2011) values (As = 0.001, Cu = 0.003, Pb = 0.001, Cr = 0.001, Fe = 0.050, Zn = 0.005, Mn = 0.005, Cd = 0.0001, Ni = 0.002, Se = 0.0002, Mo = 0.001, Hg = 0.00001 mg/L). Following Hakanson (1980), CF values were classified as low (< 1), moderate (1-3), considerable (3-6), or very high (≥ 6) contamination. The Pollution Load Index (PLI), the geometric mean of all element-specific CF values at a given location, was used to give an integrated, site-level contamination picture, with PLI < 1 indicating no meaningful deviation from background and PLI > 1 indicating a recognisable anthropogenic footprint (Tomlinson et al., 1980; Abrahim and Parker, 2008).

Human Health Risk Assessment

Non-carcinogenic health risk was quantified using the standard USEPA exposure framework (USEPA, 1989, 2002, 2011). The Estimated Daily Intake (EDI, mg/kg body weight/day) was calculated as EDI = (C × IR × EF × ED) / (BW × AT), where C is the mean element concentration, IR is the water ingestion rate, EF is exposure frequency, ED is exposure duration, BW is body weight, and AT is averaging time. Separate parameter sets were applied for adult (IR = 2.0 L/day, ED = 30 years, BW = 70 kg) and child (IR = 1.0 L/day, ED = 6 years, BW = 15 kg) receptors, with EF = 350 days/year for both groups. The Hazard Quotient (HQ = EDI/RfD) was calculated using USEPA IRIS (2023) oral reference doses, and the Hazard Index (HI = ΣHQ) summed the twelve element-specific HQ values at each site to estimate cumulative non-carcinogenic risk, with HI or HQ ≥ 1.0 indicating a potential for adverse health effects (USEPA, 1989; Zheng et al., 2010).

Quality Assurance and Statistical Treatment

Prior to statistical analysis, all data were checked for outliers, inconsistencies, and missing values, with outliers identified using boxplots and the ±3 standard deviation threshold from the mean (Khan et al., 2016). Analytical accuracy was validated by comparison with certified reference material recovery values and replicate analyses. Concentrations below the method detection limit were treated as non-detects (ND) and excluded from mean calculations rather than substituted with an arbitrary fraction of the detection limit, in order to avoid artificially inflating or deflating site means for elements with low detection frequency, such as chromium and nickel. Where element concentrations spanned several orders of magnitude, values were log-transformed for descriptive summary purposes to improve interpretability, consistent with standard practice in mine-impacted environmental datasets (Yuan et al., 2020).

RESULTS

Element Concentrations

Twelve PHEs were detected across the twenty sampled ponds at widely varying frequencies and concentrations, summarised in Table 1.

Element	Detection frequency	Range (mg/L)	Mean (mg/L)	WHO (2017) guideline (mg/L)	Sites exceeding guideline
Arsenic (As)	16/20	0.00345-0.1649	0.0766	0.01	14
Lead (Pb)	16/20	0.02107-0.1507	0.0768	0.01	16
Cadmium (Cd)	16/20	0.00125-0.00662	0.00451	0.003	13
Mercury (Hg)	18/20	0.002-0.015	-	0.006	7
Chromium (Cr)	20-Feb	0.00918-0.1051	-	0.05	1
Iron (Fe)	18/20	ND-0.3617	-	0.3	1
Manganese (Mn)	20/20	0.00158-0.4738	-	0.4	1

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Copper (Cu)	18/20	ND-0.3073	-	2	0
Zinc (Zn)	18/20	ND-0.03927	-	3	0
Nickel (Ni)	20-May	ND-0.03668	-	0.07	0
Selenium (Se)	20/20	0.004-0.027	-	0.04	0
Molybdenum (Mo)	20/20	0.003-0.027	-	0.07	0

3.1.1 Arsenic. Arsenic was detected at sixteen of twenty locations, ranging from 0.00345 mg/L (W2) to 0.1649 mg/L (W17), with a mean of 0.0766 mg/L, more than seven times the WHO (2017) guideline of 0.01 mg/L. Fourteen of the sixteen detection sites exceeded the guideline, with the most extreme values recorded at W17 (16.5 times the guideline), W18 (16.5 times), W20 (13.7 times), and W19 (13.2 times). The highest concentrations clustered consistently at W11 to W20, a pattern consistent with proximity to primary waste-rock or tailings material, or with reductive dissolution of iron oxyhydroxides along a shared groundwater flow path (Smedley and Kinniburgh, 2002; Nordstrom, 2011).

3.1.2 Lead. Lead was detected at sixteen locations and exceeded the WHO (2017) limit of 0.01 mg/L at every one of them, ranging from 0.02107 mg/L (W3) to 0.1507 mg/L (W12), with a mean of 0.0768 mg/L, 7.7 times the guideline value. The highest values, at W12 (15.1 times the guideline), W13 (13.1 times), W20 (10.0 times), and W9 (9.9 times), are consistent with galena (PbS) dissolution from residual mine waste (Nriagu, 1988; Gray, 1997). The spatial separation of the highest lead readings from the highest arsenic readings at the westerly locations (W3-W5) suggests distinct galena-dominated versus arsenopyrite-dominated weathering zones within the same broad catchment.

3.1.3 Cadmium. Cadmium was detected at sixteen locations (0.00125-0.00662 mg/L), exceeding the WHO (2017) guideline of 0.003 mg/L at thirteen sites. The highest exceedances occurred at W20 (2.21 times), W14 (2.17 times), and W16 and W17 (both 2.14 times), with a mean of 0.00451 mg/L, 1.5 times the guideline. Cadmium most plausibly derives from sphalerite dissolution and iron oxyhydroxide desorption under changing pH conditions (Gray, 1997; Satarug et al., 2010).

3.1.4 Mercury. Mercury was detected at eighteen locations (0.002-0.015 mg/L), equalling or exceeding the WHO (2017) guideline of 0.006 mg/L at seven sites. The highest concentration, at W13 (0.015 mg/L, 2.5 times the guideline), and the clustering of exceedances at W13-W19, are spatially consistent with former amalgamation processing areas or cinnabar (HgS) mineralisation associated with the gold-bearing vein systems of the Nigerian basement complex (Hentschel et al., 2002; Bose-O'Reilly et al., 2010).

3.1.5 Chromium. Chromium was detected at only two locations, W9 (0.1051 mg/L, 2.1 times the WHO guideline) and W11 (0.00918 mg/L), indicating a discrete, spatially isolated source rather than a basin-wide signal. Because total chromium analysis cannot distinguish the less toxic trivalent form, Cr(III), from the considerably more toxic hexavalent form, Cr(VI), the health significance of the W9 detection cannot be fully resolved without dedicated speciation analysis (Kotas and Stasicka, 2000).

3.1.6 Iron, manganese, and the remaining elements. Iron was detected at eighteen locations and exceeded the WHO (2017) aesthetic guideline of 0.3 mg/L only at W3 (0.3617 mg/L). Manganese was detected at all twenty locations (0.00158-0.4738 mg/L) and exceeded the WHO health guideline of 0.4 mg/L at W12. Copper, zinc, nickel, selenium, and molybdenum were detected widely but remained below their respective WHO guideline values throughout the study area; their universal or near-universal detection nonetheless confirms active sulphide mineral weathering throughout the system, encompassing chalcopyrite, sphalerite, and molybdenite (Adriano, 2001).

Across all twelve elements, the most severe contamination consistently clustered in the upper-numbered sampling locations (W11-W20), while the lower-numbered cluster (W1-W10) showed comparatively, though still frequently guideline-exceeding, lower concentrations. This spatial pattern was most pronounced for arsenic, lead, and mercury.

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Contamination Factor and Pollution Load Index

Table 2 summarises the Contamination Factor classification and dominant hotspot locations for each of the twelve elements assessed.

Element	CF range (approx.)	Classification	Peak site(s)
Mercury (Hg)	200-1,500	Very high	W13
Cadmium (Cd)	20-65	Very high	W4, W9, W10, W13, W14
Lead (Pb)	up to 150.7	Very high	W12, W13, W9
Arsenic (As)	3.5-165	Moderate to very high	W15-W19
Copper (Cu)	up to 102.4	Very high (site-specific)	W5
Selenium (Se)	3-135	Considerable to very high	W6, W11, W14
Manganese (Mn)	~1-94.8	Low to very high (site-specific)	W12
Molybdenum (Mo)	27-Mar	Moderate to considerable	W14, W13, W2
Chromium (Cr)	9.2-105.1	Considerable to very high	W9
Nickel (Ni)	5.5-18.3	Moderate to considerable	W11, W18-W20
Zinc (Zn)	<3 (spike 7.9)	Low to moderate	W6
Iron (Fe)	0.1-7.3	Low to considerable	W3

Cadmium and mercury returned the highest Contamination Factor values recorded in the entire dataset, a direct mathematical consequence of their extremely low natural freshwater backgrounds. Cadmium CF values at W4, W9, W10, W13, and W14 ranged from approximately 20 to 65 (very high contamination class), while mercury reached CF = 200 at its lowest detectable concentration (W2) and CF ≈ 1,500 at its highest (W13, Hg = 0.015 mg/L), with additional very high values clustering at W4, W5, W12, W16, and W17, a pattern characteristic of artisanal small-scale gold mining, where liquid mercury amalgamation discharges Hg^{2+} directly into surface water (Hentschel et al., 2002; UNEP, 2013).

Selenium CF escalated progressively toward the upper cluster, reaching considerable-to-very-high levels (CF 3-135) with hotspots at W6 (135), W11 (45), and W14 (15), consistent with diffuse agricultural selenium loading from phosphate fertiliser and irrigation return flow, overlaid with point sources such as coal combustion or smelter emissions (Reimann and de Caritat, 1998). Arsenic CF was modest at W1 (11.7) and W2 (3.5) but rose steeply downstream, with W15-W19 recording CF values of 95-165, a progressive downstream accumulation pattern implying a source somewhere upstream of W11, consistent with reductive release from iron oxyhydroxides or legacy mineral-processing effluent (Smedley and Kinniburgh, 2002).

Lead reached its highest CF values at W12 (150.7), W13 (130.6), and W9 (98.7), all classified very high, with concentrations ten to fifteen times the WHO guideline, a clustering that points to a discrete contamination source consistent with corroded infrastructure or concentrated waste-rock leaching (WHO, 2011). Copper produced the single most extreme location-specific CF value in the entire dataset at W5 (102.4), plausibly reflecting an industrial discharge or concentrated mining drainage input, while the wider Cu CF range (4-45) elsewhere indicates chronic, diffuse background enrichment across the study area (Adriano, 2001). Molybdenum, nickel, and zinc fell mostly in the moderate-to-considerable range, while iron and manganese were harder to attribute to a single source given their natural occurrence in tropical lateritic terrain, although manganese reached CF = 94.8 at W12, a value too extreme to be purely geogenic and suggestive of an additional anthropogenic input.

Every one of the twenty sampled locations returned a Pollution Load Index well above 1, with the majority above 3 and several approaching or exceeding 10, meaning no location in the study area could be considered within natural geochemical background once all twelve metals were combined. The highest PLI values

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clustered at W12 (driven by manganese and arsenic), W13 (lead, arsenic, mercury, molybdenum), W16-W19 (arsenic, copper, mercury, lead), and W5 (copper), a pattern indicating multiple, overlapping contamination sources rather than a single point of origin, with the W12-W19 cluster in particular suggesting either a major localised source or the progressive accumulation of inputs along a shared watercourse.

Non-Carcinogenic Health Risk

The exposure parameters applied in the Estimated Daily Intake calculation for both receptor groups are summarised in Table 3.

Parameter	Adult	Child	Unit
Water ingestion rate (IR)	2	1	L/day
Body weight (BW)	70	15	kg
Exposure frequency (EF)	350	350	days/year
Exposure duration (ED)	30	6	years
Averaging time (AT)	ED x 365	ED x 365	days

3.3.1 Adult population. Arsenic dominated the risk profile owing to its very low oral reference dose (0.0003 mg/kg/day): of the thirteen sites with detectable arsenic, ten exceeded HQ = 1.0, peaking at approximately 15 at both W17 and W18. Chronic exposure at these levels is linked to peripheral neuropathy, melanosis, keratosis, portal hypertension, cardiovascular dysfunction, and immune suppression (Naujokas et al., 2013; Smedley and Kinniburgh, 2002). Mercury was the second major contributor, with its stringent reference dose producing HQ > 1.0 at twelve sites, peaking at W13 (HQ = 4.11), with chronic exposure linked to nephrotoxicity and neurological effects including tremor and cognitive impairment (Bernhoft, 2012). Lead exceeded the threshold at W12 (HQ = 1.03); cadmium remained sub-threshold overall but contributed meaningfully to the Hazard Index (0.28-0.36) at several sites; chromium at W9 (HQ = 0.96) approached the threshold; and molybdenum and selenium made modest additional contributions. Iron, zinc, and manganese stayed low throughout, except for a manganese spike at W12 (HQ = 0.09). The adult Hazard Index exceeded 1.0 at all twenty sites, ranging from 1.20 (W2) to 18.02 (W17), with six sites exceeding HI = 10 (W15-W20) and a further six exceeding HI = 4 (W8, W9, W11-W14).

3.3.2 Child population. Child HQ and HI values exceeded adult values by approximately 2.33-fold at every site, a direct physiological consequence of children's greater dose per kilogram of body weight, compounded by heightened toxicological sensitivity to lead, arsenic, mercury, and cadmium during critical developmental windows (Lanphear et al., 2005). Arsenic HQ exceeded unity at fifteen sites, reaching approximately 35 at both W17 and W18, among the highest values reported in any African groundwater risk assessment, with sustained childhood exposure linked to IQ reduction, impaired working memory, and stunted growth (Caldwell et al., 2009; Tyler and Allan, 2014). Mercury exceeded threshold at twelve sites, peaking at W13 (HQ = 9.59), of particular concern given the developing nervous system's sensitivity to disrupted neurotransmission and impaired myelination (Clarkson and Magos, 2006). Lead exceeded unity at twelve sites, reaching HQ = 2.41 at W12, consistent with the consensus that no blood lead level is considered safe for children's cognitive and behavioural development (Lanphear et al., 2005; Bellinger, 2008). The cumulative child Hazard Index ranged from 2.81 (W2) to 42.05 (W17), exceeding 1.0 at every site and exceeding 10.0 at seventeen of the twenty sites, with the six worst locations (W15-W20) classified as severe cumulative hazard.

Table 4 summarises the Hazard Index range recorded for both receptor groups across the twenty sampling locations.

Receptor	Minimum HI	Maximum HI	Sites with HI > 1.0	Sites with HI > 10.0
Adult	1.20 (W2)	18.02 (W17)	20/20	20-Jun
Child	2.81 (W2)	42.05 (W17)	20/20	17/20

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Spatial Pattern in Health Risk

The risk burden was not uniform across the study area. The lower-numbered cluster (W1-W5) generally showed lower, though still mostly elevated, Hazard Index values, while the upper cluster (W11-W20) accounted for all of the most extreme scores recorded in the dataset. This pattern is consistent with progressive groundwater chemistry change along a shared aquifer, driving reductive dissolution of iron oxyhydroxides and concurrent release of co-sorbed arsenic and other metals (Smedley and Kinniburgh, 2002; Bhattacharya et al., 2007), or alternatively with increasing proximity to zones historically subject to more intensive mineral processing.

Summary of Priority Contaminants

Table 5 ranks the twelve elements by overall severity, integrating the contamination-factor evidence and the health-risk evidence into a single priority ordering for management purposes.

Rank	Element	Basis for ranking
1	Mercury	Highest CF (up to ~1,500); major HQ/HI contributor; ASGM signature
2	Arsenic	Widespread guideline exceedance; dominant HQ/HI contributor for both age groups
3	Lead	Guideline exceeded at all detection sites; no safe threshold in children
4	Cadmium	Very high CF; long renal half-life; irreversible accumulation
5	Selenium	Very high CF at multiple sites; narrow deficiency-toxicity margin
6	Chromium	Localised very high CF at W9; possible Cr(VI) fraction unresolved
7	Copper	Extreme site-specific CF at W5; sub-threshold health risk
8	Molybdenum	Moderate-considerable CF; sub-threshold health risk
12-Sep	Manganese, Nickel, Zinc, Iron	Low to moderate CF; no guideline or HQ exceedance except isolated sites

This ranking reinforces the case for prioritising mercury, arsenic, lead, and cadmium in any subsequent monitoring or remediation programme targeting this site, while flagging selenium and the localised chromium anomaly at W9 as secondary but genuine concerns warranting continued observation.

DISCUSSION

The convergence of contamination and health-risk indices in this study describes a water system under severe, multi-element anthropogenic contamination, with mercury, cadmium, arsenic, selenium, and lead, in roughly that order of severity, driving both the geochemical enrichment signal and the human health risk burden. The elevated mercury contamination factors recorded here, reaching into the hundreds and low thousands at several sites, are considerably more consistent with historical or ongoing ASGM amalgamation activity than with tin-columbite ore weathering alone, since cassiterite processing does not itself introduce mercury into the system (Hentschel et al., 2002; Bose-O'Reilly et al., 2010). This finding is significant for the wider Jos Plateau tin belt, where gold and tin mineralisation have often historically overlapped, and suggests that mercury contamination legacies may be more widespread across derelict tin workings in this region than has previously been documented.

The spatial pattern observed here, in which the upper-numbered cluster of ponds (W11-W20) consistently records the most severe contamination across nearly every element and every index, is consistent with a source-proximity model in which primary sulphide leaching zones drive a downgradient contamination plume that dilutes progressively toward the lower-numbered cluster (Gray, 1997; Nordstrom, 2011). Reductive

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dissolution of iron oxyhydroxides along a shared groundwater flow path offers a plausible mechanism for the co-mobilisation of arsenic, lead, and cadmium observed at these sites (Smedley and Kinniburgh, 2002).

Table 6 places the Hazard Index values recorded in this study alongside comparable groundwater and mine-water risk assessments from the regional literature.

Study	Setting	Adult HI range	Child HI range
This study	Barkin-Ladi mine ponds, Nigeria	1.20-18.02	2.81-42.05
Wongsasuluk et al. (2014)	Agricultural groundwater, Thailand	up to 4.2	not reported
Emenike et al. (2018)	Groundwater, southwest Nigeria	1.8-9.4	not reported
Mohammed et al. (2021)	Mining catchment groundwater, northern Nigeria	up to 6.1	not reported

The maxima recorded in the present study substantially exceed all three comparators using directly analogous exposure assumptions and reference doses, and cannot reasonably be attributed to methodological artefact. This places the Barkin-Ladi mine pond water system among the more severely contaminated legacy mining water resources reported in the recent sub-Saharan African literature. The chromium anomaly detected at W9 merits specific mention. Because total chromium analysis cannot distinguish the comparatively benign trivalent form, Cr(III), from the considerably more toxic and carcinogenic hexavalent form, Cr(VI) (Kotas and Stasicka, 2000; IARC, 2012), the health significance of this single, spatially isolated detection remains uncertain pending dedicated speciation analysis, a priority recommendation arising directly from this study.

From a management perspective, these findings indicate that mine pond water in this landscape functions as a long-term, slow-release reservoir of potentially harmful elements, sustained by the ongoing, thermodynamically favourable oxidation of residual sulphide minerals (Skousen et al., 2017). Without active remediation, this contamination will likely persist for decades. Passive treatment approaches, such as constructed wetlands or anoxic limestone drains, or more intensive interventions including capping, alkaline dosing, or iron co-precipitation, represent established options that should be evaluated for this setting (Skousen et al., 2017; Simate and Ndlovu, 2014). From a management perspective, these findings indicate that mine pond water in this landscape functions as a long-term, slow-release reservoir of potentially harmful elements, sustained by the ongoing, thermodynamically favourable oxidation of residual sulphide minerals (Skousen et al., 2017). Without active remediation, this contamination will likely persist for decades. Passive treatment approaches, such as constructed wetlands or anoxic limestone drains, or more intensive interventions including capping, alkaline dosing, or iron co-precipitation, represent established options that should be evaluated for this setting (Skousen et al., 2017; Simate and Ndlovu, 2014).

Beyond technical remediation, the findings also carry immediate risk-communication implications. Because many of the sampled ponds are already in active informal use for drinking, bathing, swimming, and irrigation, the most urgent, lowest-cost intervention available to local health and environmental authorities is direct community engagement: identifying the specific ponds corresponding to the most severe contamination clusters (particularly W12, W13, and W16-W19) and communicating clearly, in accessible language, that these specific waters should not be used for drinking, cooking, or irrigating food crops pending remediation. This kind of targeted risk communication does not require capital investment and could meaningfully reduce exposure in the short term, while longer-term treatment options are evaluated and funded. Any such communication strategy should explicitly prioritise households with young children, given the substantially higher hazard index values calculated for this age group throughout the dataset.

This study has several limitations worth noting. First, sampling was restricted to the dry season, and while this is the period of expected peak trace-element concentration due to reduced dilution, wet-season sampling would be needed to characterise seasonal variability in contaminant flux. Second, total chromium and total mercury were measured without speciation, meaning the proportion of the more toxic hexavalent chromium and methylmercury fractions could not be determined; this is a priority for future work, particularly given the

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W9 chromium detection. Third, the health risk assessment considered only the ingestion pathway; dermal contact during bathing and swimming, both documented uses of these ponds, would add an additional, unquantified exposure route, meaning the Hazard Index values reported here should be regarded as conservative, minimum estimates of the true cumulative risk.

From a regulatory and community-health perspective, the findings reported here have direct, practical implications. Under the NESREA regulatory framework applicable to Nigerian surface waters, arsenic, lead, cadmium, and mercury should be treated as the four priority contaminants of concern for this site, and immediate risk-communication with the communities that use these ponds for drinking, bathing, and irrigation is warranted regardless of the pace of any subsequent remedial works. Interim measures could include clearly signposting the most severely affected ponds (W12-W20), providing alternative protected water sources where feasible, and discouraging the use of mine pond water for infant formula preparation and other high-exposure domestic uses in the short term while longer-term treatment options are evaluated.

CONCLUSION

Mine pond water across the derelict tin and columbite workings of Barkin-Ladi is severely and pervasively contaminated with potentially harmful elements, principally arsenic, lead, cadmium, and mercury, at concentrations that translate into a non-carcinogenic health hazard exceeding internationally recognised safety thresholds at every one of the twenty locations sampled, for both adult and child receptors. Children face a disproportionately greater burden, with a cumulative Hazard Index exceeding ten at the majority of sites. These waters are not suitable for direct human consumption, cooking, bathing, or irrigation without substantial treatment, and the mercury signature identified here warrants closer scrutiny of the historical overlap between artisanal gold and tin mining across the wider Jos Plateau. Arsenic, lead, cadmium, and mercury should be designated as the four priority contaminants of concern for any remedial action plan targeting this site, with dedicated chromium speciation at W9 recommended as an immediate follow-up investigation.

Declarations

Author contributions: Ezeani, I. P. conceived the study, conducted field sampling, performed laboratory analysis and data interpretation, and drafted the manuscript. Igwe, O. and Onwuka, O. S. supervised the research design and reviewed the manuscript. All authors read and approved the final manuscript.

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Conflict of interest: The authors declare no conflict of interest.

Data availability: The datasets generated and analysed during this study are available from the corresponding author upon reasonable request.

Ethical approval: Fieldwork involved no human or animal experimentation beyond informal community consultation prior to sampling; no formal ethical clearance was therefore required, though verbal consent was obtained from land and water users prior to sample collection.

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