



Assessment of Heavy Metal Contamination in Surface and Groundwater and Associated Human Health Risks in Urban Communities (Coal Camp, Ogbete Enugu and Ngenevu Obed Camp Ogbete Enugu) of Enugu North Local Government Area, Enugu State, Nigeria

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Abstract

In Coal Camp, Ogbete Enugu and Ngenevu Obed camp Ogbete Enugu, located in the urban area of Enugu North Local Government Area of Enugu State, Nigeria, residents rely heavily on local water sources, raising growing concerns regarding potential contamination. To evaluate the exact scope of this issue, our research team examined heavy metal levels (Pb, Cd, Cr, Hg, and Ni) across thirty field locations (6°25'N to 6°28'N, 7°28'E to 7°30'E), sampling boreholes, unlined hand dug wells, and local surface streams (APHA, 2017). Uncontrolled municipal waste, motor workshop runoff and agricultural chemicals have increasingly threatened these regional supplies. Sampling was carried out in triplicates (N = 90) and analyzed via Atomic Absorption Spectrophotometry (AAS) (Iwegbue et al., 2013). The laboratory findings were benchmarked against World Health Organization thresholds (WHO, 2017). Detected metal concentrations spanned wide ranges: Pb (0.006 – 0.053 mg/L), Cd (0.001 – 0.012 mg/L), Cr (0.009 – 0.082 mg/L), Hg (<0.001 – 0.005 mg/L), and Ni (0.011 – 0.089 mg/L). Contamination intensity decreased systematically in the order: Surface Water > Shallow Wells > Deep Boreholes. Risk modeling following USEPA guidelines (USEPA, 2011) showed that Chronic Daily Intake and Hazard Quotient values for Lead and Cadmium surpassed acceptable safety baselines (HQ > 1) near mechanic clusters, dumpsites, and quarry wash zones, pointing to notable non-carcinogenic health hazards for local consumers (Tchounwou et al., 2012; Jaishankar et al., 2014). These results demonstrate an immediate requirement for targeted public health monitoring and targeted water purification in the affected areas.

Keywords: *Heavy Metals, Water Quality, Health Risk Assessment, Geographic Coordinates, Coal Camp, Ogbete Enugu, Ngenevu Obed Camp, Enugu North LGA, AAS, Hazard Index.*

1. Introduction

Clean water remains fundamental for human survival, supporting local health, ecological stability, and community productivity (WHO, 2017). However, expanding settlements, unmanaged waste disposal, agricultural runoff, and small scale commercial activities have introduced increasing levels of hazardous contaminants into aquatic environments across developing regions (Alloway, 2013; Ali & Khan, 2018). Elements such as lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), and nickel (Ni) present significant environmental threats due to their chemical persistence, inability to degrade naturally, and tendency to accumulate within human tissues over time (Jaishankar et al., 2014).

Heavy metal accumulation in groundwater and natural streams has grown into a major public health issue in Nigerian semi-urban communities. Long-term ingestion of these metals through drinking water can cause severe physiological harm, including neurological defects, renal failure, and heightened cancer risks (Jarup, 2003; Tchounwou et al., 2012). Across several communities in Enugu State, households depend on untreated shallow wells, deep boreholes, and nearby rivers for their daily domestic needs (Duruibe et al., 2007; Nduka & Orisakwe, 2011). Unfortunately, these natural sources remain vulnerable to localized pollution driven by unlined dumpsite

leachates, agricultural chemicals, motor workshop discharges, and urban runoff (Iwegbue et al., 2013; Eze et al., 2022).

Despite these ongoing concerns, comprehensive field data featuring verified geographical coordinates remain sparse for many urban settlements within Enugu North Local Government Area, particularly Coal Camp, Ogbete Enugu and Ngenevu Obed camp Ogbete Enugu. Without accurate baseline measurements and precise location mapping, environmental agencies struggle to design effective pollution mitigation strategies or enforce targeted drinking water protections. To address this knowledge gap, our investigation mapped and measured heavy metal concentrations across 30 GPS-verified water sites in Coal Camp, Ogbete Enugu and Ngenevu Obed camp Ogbete Enugu, assessing the associated human health risks through standardized United States Environmental Protection Agency risk assessment models (USEPA, 2011).

2. Literature Review

2.1 Heavy Metal Pollution in Aquatic Systems

Heavy metals comprise high density metallic elements known to induce biological toxicity even at low exposure thresholds. The primary metals monitored in environmental health studies include lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), arsenic (As), and nickel (Ni). Because these substances do not readily break down through natural ecological processes, they remain active in aquatic ecosystems and bioaccumulate up food webs, creating long-term risks for human consumers (Tchounwou et al., 2012; Ali & Khan, 2018). In natural water bodies, heavy metals stem from both geogenic weathering and anthropogenic activities like industrial discharge, agricultural runoff, mining, and municipal refuse dumping (Singh et al., 2011; Jaishankar et al., 2014). This persistent presence compromises water safety and triggers broader ecological degradation (Nagajyoti et al., 2010).

2.2 Sources, Pathways, and Heavy Metal Contamination in Nigeria

Across Nigeria, rapid population growth combined with inadequate waste collection infrastructure has intensified heavy metal pollution in local water bodies (Nduka & Orisakwe, 2011). Operations like battery repair, automotive servicing, metal fabrication, and informal processing release significant contaminant loads (Alloway, 2013). Urban areas face additional risks from overflowing refuse dumps, unlined landfill leachates, and atmospheric deposition from vehicle emissions (Duruibe et al., 2007; Adekola & Eletta, 2007). Iwegbue et al. (2013) observed widespread trace metal contamination in drinking water sources across Southern Nigeria, linking elevated concentrations to urban activities. In Southeastern Nigeria specifically, studies have repeatedly identified elevated Pb and Cd levels near dumpsites exceeding drinking safety baselines (Nwankwo et al., 2021). Parallel investigations by Ugwu et al. (2020) in Abakaliki and Eze et al. (2022) near the Ugwuaji dumpsite confirm that unlined refuse sites heavily contaminate shallow groundwater reserves.

2.3 Environmental Behavior, Toxicity, and Risk Models

How heavy metals move through aquatic systems depends heavily on environmental factors such as water pH, temperature, redox potential, and organic content (Förstner & Wittmann, 2012). Bottom sediments act as critical sinks, but shifting chemical conditions can re-release bound metals back into the water column, renewing exposure hazards (Salomons & Förstner, 1984). From a medical standpoint, extended intake of low metal doses leads to chronic health disorders: lead exposure impairs cognitive growth and neurological health in children; cadmium causes renal damage, bone fragility, and carcinogenesis; chromium induces cellular mutations; and nickel contributes to respiratory and dermatological diseases (Jarup, 2003; Tchounwou et al., 2012). To evaluate these risks quantitatively, researchers apply USEPA models, calculating Chronic Daily Intake (CDI), Hazard Quotients (HQ), and Hazard Index (HI) to evaluate non-carcinogenic threats (USEPA, 2011).

3. Materials and Methods

3.1 Study Area

Our fieldwork was conducted across Coal Camp, Ogbete Enugu and Ngenevu Obed camp Ogbete Enugu, which are major urban communities located in Enugu North Local Government Area, Enugu State, Southeastern Nigeria. Geologically, the area sits within Latitudes 6°25'N to 6°28'N and Longitudes 7°28'E to 7°30'E, featuring elevations between 180 m and 240 m above sea level (Eze et al., 2022). The region experiences a tropical climate marked by alternating wet and dry seasons, receiving an average annual rainfall between 1,500 mm and 2,000 mm. Local

residents rely on surface streams (such as Asata River tributaries and Ngenevu streams), deep boreholes tapping into the Ajali Sandstone formation, and unlined hand-dug wells for daily water needs. However, nearby mechanic workshops (notably the major auto-mechanic cluster at Coal Camp), cassava processing units, market centers (including Ogbete Main Market), and commercial activities increase contamination exposure across these sources (Nwankwo et al., 2021; Okafor et al., 2023).

3.2 Sampling Strategy, GPS Georeferencing, and Sample Collection

We implemented a cross-sectional study design combining field sampling, spatial mapping, laboratory testing, and human risk analysis (Jaishankar et al., 2014). Thirty (30) distinct water sites were selected across Coal Camp, Ogbete Enugu and Ngenevu Obed camp Ogbete Enugu, comprising 10 Deep Boreholes (BH), 10 Shallow Hand-Dug Wells (HDW), and 10 Surface Water points (SW). At every location, geographical coordinates were recorded on-site using a handheld Garmin GPSMAP 64s receiver set to WGS84 positioning. To ensure analytical reproducibility, samples were gathered in triplicates from each site ($30 \text{ sites} \times 3 = 90$ total laboratory samples) using clean high-density polyethylene (HDPE) containers (APHA, 2017). Each bottle was thoroughly rinsed with sample water before collection. Samples dedicated to heavy metal testing were immediately acidified with concentrated nitric acid (HNO_3) to maintain $\text{pH} < 2$, stored in ice chests at 4°C , and transported to the laboratory.

3.3 Sample Digestion and Laboratory Analysis (AAS)

In the laboratory, water samples underwent acid digestion using concentrated HNO_3 on a regulated hot plate to digest organic matter and release bound metal ions (APHA, 2017). A measured aliquot was digested, heated until clear, allowed to cool, diluted with deionized water, and filtered using Whatman No. 42 filter papers. Metal concentrations (Pb, Cd, Cr, Hg, and Ni) were determined using an Atomic Absorption Spectrophotometer (AAS Model AA-7000, Shimadzu, Japan) (Iwegbue et al., 2013). Analytical accuracy was maintained through standard calibration curves prepared from analytical-grade stock solutions, while quality control was verified using reagent blanks and duplicate sample runs (APHA, 2017).

3.4 Human Health Risk Assessment Models

Health risks associated with oral drinking exposure were calculated following standard USEPA guidelines (USEPA, 2011) using the equations below:

1. Chronic Daily Intake via Ingestion (CDIing):

$$\text{CDIing} = \frac{(C \times \text{IR} \times \text{EF} \times \text{ED})}{(\text{BW} \times \text{AT})}$$

Where: C = Metal concentration in water (mg/L), IR = Daily drinking intake rate (2.0 L/day for adults),

EF = Exposure frequency (365 days/year), ED = Exposure duration (30 years), BW = Average body weight (70 kg), AT = Averaging period ($365 \times \text{ED}$ days) (USEPA, 2011).

2. Hazard Quotient (HQ):

$$\text{HQ} = \frac{\text{CDIing}}{\text{RfD}}$$

Where: RfD represents the oral reference dose (mg/kg/day). An $\text{HQ} > 1$ indicates potential non-carcinogenic health risks (USEPA, 2011).

3. Hazard Index (HI):

$$\text{HI} = \sum \text{HQ}_i = \text{HQPb} + \text{HQCd} + \text{HQCr} + \text{HQHg} + \text{HQNi}$$

4. Results and Discussion

4.1 Heavy Metal Concentrations and Spatial Coordinates

Table 1 outlines the GPS coordinates (Latitude $^\circ\text{N}$, Longitude $^\circ\text{E}$) and mean metal concentrations (mg/L $\pm$ SD) recorded across all 30 sampling sites ($N = 90$ total laboratory runs) in Coal Camp, Ogbete Enugu and Ngenevu Obed camp Ogbete Enugu, Enugu North LGA.

Site Cat.	Site ID	Location Description	Coordinates (N, E)	Pb (mg/L)	Cd (mg/L)	Cr (mg/L)	Hg (mg/L)	Ni (mg/L)
WHO Limit	—	Drinking Water Limit	—	0.010	0.003	0.050	0.006	0.070
Borehole	BH-01	Coal Camp Central Square (Line 1)	6°26'12"N, 7°28'45"E	0.008 ± 0.001	0.002 ± 0.0001	0.012 ± 0.002	<0.001	0.015 ± 0.002
Borehole	BH-02	St. Patrick's Catholic Church, Coal Camp	6°26'25"N, 7°28'54"E	0.011 ± 0.002	0.003 ± 0.0002	0.018 ± 0.003	<0.001	0.021 ± 0.003
Borehole	BH-03	Ogbete Main Market Motor Park Area	6°27'05"N, 7°29'15"E	0.006 ± 0.001	0.001 ± 0.0001	0.009 ± 0.001	<0.001	0.011 ± 0.001
Borehole	BH-04	Coal Camp Auto-Mechanic Workshop Line	6°26'05"N, 7°28'32"E	0.016 ± 0.003	0.004 ± 0.0003	0.027 ± 0.004	0.001 ± 0.0001	0.038 ± 0.004
Borehole	BH-05	Ngenevu Obed Camp Main Entrance	6°25'42"N, 7°29'08"E	0.014 ± 0.002	0.003 ± 0.0002	0.022 ± 0.003	<0.001	0.029 ± 0.003
Borehole	BH-06	Ogbete Commercial Axis (Murtala Way)	6°27'18"N, 7°29'22"E	0.009 ± 0.001	0.002 ± 0.0001	0.014 ± 0.002	<0.001	0.018 ± 0.002
Borehole	BH-07	Ngenevu Obed Camp Residential Area	6°25'35"N, 7°29'18"E	0.012 ± 0.002	0.004 ± 0.0003	0.020 ± 0.003	<0.001	0.025 ± 0.003
Borehole	BH-08	Coal Camp Metal Fabrication Cluster	6°26'30"N, 7°28'20"E	0.019 ± 0.003	0.005 ± 0.0004	0.031 ± 0.005	0.002 ± 0.0002	0.041 ± 0.005
Borehole	BH-09	Ogbete Secondary School Neighborhood	6°26'50"N, 7°29'02"E	0.007 ± 0.001	0.002 ± 0.0001	0.011 ± 0.002	<0.001	0.014 ± 0.002
Borehole	BH-10	Ngenevu Community Health Post Area	6°25'28"N, 7°28'55"E	0.013 ± 0.002	0.003 ± 0.0002	0.024 ± 0.003	<0.001	0.030 ± 0.003
Shallow Well	HDW-01	Coal Camp Main Mechanic Cluster	6°26'10"N, 7°28'25"E	0.038 ± 0.005	0.008 ± 0.0006	0.058 ± 0.007	0.003 ± 0.0003	0.062 ± 0.006
Shallow Well	HDW-02	Ogbete Market Perimeter Homestead	6°27'12"N, 7°29'10"E	0.021 ± 0.003	0.004 ± 0.0003	0.032 ± 0.004	0.001 ± 0.0001	0.033 ± 0.004
Shallow Well	HDW-03	Coal Camp Municipal Refuse Transfer Site	6°26'40"N, 7°28'50"E	0.045 ± 0.006	0.011 ± 0.0009	0.069 ± 0.008	0.004 ± 0.0004	0.078 ± 0.008
Shallow Well	HDW-04	Ngenevu Obed Camp High-Density Quarter	6°25'48"N, 7°29'12"E	0.018 ± 0.002	0.003 ± 0.0002	0.028 ± 0.003	<0.001	0.027 ± 0.003
Shallow Well	HDW-05	Ogbete Abattoir & Food Processing Vicinity	6°27'22"N, 7°29'30"E	0.029 ± 0.004	0.006 ± 0.0005	0.041 ± 0.005	0.002 ± 0.0002	0.045 ± 0.005
Shallow Well	HDW-06	Coal Camp Battery Charging Yard	6°26'18"N, 7°28'38"E	0.025 ± 0.003	0.005 ± 0.0004	0.036 ± 0.004	0.001 ± 0.0001	0.039 ± 0.004
Shallow Well	HDW-07	Ngenevu Stream Corridor Compound	6°25'30"N, 7°29'02"E	0.033 ± 0.004	0.007 ± 0.0005	0.049 ± 0.006	0.002 ± 0.0002	0.052 ± 0.006
Shallow Well	HDW-08	Ogbete Old Park Residential Line	6°26'58"N, 7°29'18"E	0.015 ± 0.002	0.003 ± 0.0002	0.021 ± 0.003	<0.001	0.022 ± 0.003
Shallow Well	HDW-09	Coal Camp Fuel Station Service Corridor	6°26'35"N, 7°28'42"E	0.041 ± 0.005	0.009 ± 0.0007	0.063 ± 0.007	0.003 ± 0.0003	0.068 ± 0.007
Shallow Well	HDW-10	Ngenevu Hillside Settlement	6°25'15"N, 7°28'48"E	0.022 ± 0.003	0.004 ± 0.0003	0.030 ± 0.004	0.001 ± 0.0001	0.031 ± 0.004

Site Cat.	Site ID	Location Description	Coordinates (N, E)	Pb (mg/L)	Cd (mg/L)	Cr (mg/L)	Hg (mg/L)	Ni (mg/L)
Surface Water	SW-01	Asata River Tributary (Coal Camp Upstream)	6°26'02"N, 7°28'15"E	0.012 ± 0.002	0.002 ± 0.0001	0.019 ± 0.002	<0.001	0.020 ± 0.002
Surface Water	SW-02	Asata River Tributary (Mechanic Runoff Point)	6°26'22"N, 7°28'35"E	0.036 ± 0.004	0.007 ± 0.0006	0.052 ± 0.006	0.002 ± 0.0002	0.058 ± 0.006
Surface Water	SW-03	Asata River (Ogbete Market Drainage Discharge)	6°27'00"N, 7°29'25"E	0.048 ± 0.006	0.010 ± 0.0008	0.074 ± 0.008	0.004 ± 0.0004	0.081 ± 0.008
Surface Water	SW-04	Ngenevu Stream (Obed Camp Upper Reach)	6°25'40"N, 7°28'50"E	0.027 ± 0.003	0.005 ± 0.0004	0.039 ± 0.004	0.001 ± 0.0001	0.042 ± 0.005
Surface Water	SW-05	Ngenevu Stream (Domestic Discharge Zone)	6°25'25"N, 7°29'05"E	0.031 ± 0.004	0.006 ± 0.0005	0.046 ± 0.005	0.002 ± 0.0002	0.049 ± 0.005
Surface Water	SW-06	Ogbete Urban Stormwater Canal Confluence	6°26'45"N, 7°29'10"E	0.042 ± 0.005	0.009 ± 0.0007	0.065 ± 0.007	0.003 ± 0.0003	0.071 ± 0.007
Surface Water	SW-07	Coal Camp Workshop Scrap Wash Stream	6°26'15"N, 7°28'10"E	0.053 ± 0.007	0.012 ± 0.0010	0.082 ± 0.009	0.005 ± 0.0005	0.089 ± 0.009
Surface Water	SW-08	Ngenevu Public Laundry Brook	6°25'18"N, 7°28'58"E	0.024 ± 0.003	0.004 ± 0.0003	0.033 ± 0.004	0.001 ± 0.0001	0.035 ± 0.004
Surface Water	SW-09	Ogbete Market Abattoir Wastewater Runoff	6°27'28"N, 7°29'35"E	0.039 ± 0.005	0.008 ± 0.0006	0.057 ± 0.006	0.003 ± 0.0003	0.063 ± 0.007
Surface Water	SW-10	Ngenevu Obed Camp Boundary Stream	6°25'05"N, 7°28'40"E	0.017 ± 0.002	0.003 ± 0.0002	0.025 ± 0.003	<0.001	0.026 ± 0.003

Table 1: GPS coordinates (WGS84) and mean concentrations (mg/L ± SD) of heavy metals across 30 sampling points in Coal Camp, Ogbete Enugu and Ngenevu Obed camp Ogbete Enugu, Enugu North LGA compared with WHO limits.

4.2 Spatial Trends and Source Discussion

Analysis across the three water source types revealed a distinct spatial variation in contamination severity (Iwegbue et al., 2013; Nwankwo et al., 2021):

Surface Water (SW) > Shallow Hand-Dug Wells (HDW) > Deep Boreholes (BH)

Lead (Pb) and Cadmium (Cd): Peak lead (0.053 mg/L) and cadmium (0.012 mg/L) levels occurred at SW-07 (Coal Camp Workshop Scrap Wash Stream: 6°26'15"N, 7°28'10"E), HDW-03 (Coal Camp Municipal Refuse Transfer Site: 6°26'40"N, 7°28'50"E), and HDW-01 (Coal Camp Main Mechanic Cluster: 6°26'10"N, 7°28'25"E), substantially surpassing WHO drinking thresholds (0.010 mg/L for Pb; 0.003 mg/L for Cd) (WHO, 2017). These elevated readings stem directly from surface runoff carrying spent motor oil, discarded battery components, and unlined landfill leachate into shallow aquifers and open streams (Duruibe et al., 2007; Adekola & Eletta, 2007; Eze et al., 2022).

Chromium (Cr) and Nickel (Ni): While deep boreholes maintained safe Cr and Ni levels, surface sites receiving urban stormwater runoff (SW-06) and scrap metal washings (SW-07) showed noticeable spikes. This points to commercial metal fabrication, battery servicing, and localized bedrock weathering as primary drivers (Alloway, 2013; Okafor et al., 2023).

Mercury (Hg): Mercury concentrations remained minimal across all tested sites (<0.001–0.005 mg/L), staying well below the maximum allowable limit of 0.006 mg/L (WHO, 2017).

4.3 Comprehensive Site-by-Site Heavy Metal Analysis and Visualizations

To complement the field sampling data and provide spatial evaluation across all 30 sampling points, a comprehensive site-by-site analysis was conducted. This analysis includes a master log comparing individual sites, 10 Hand-Dug Wells (W1–W10), 10 Boreholes (BH1–BH10), and 10 Surface water Sites (SW1–SW10) against WHO Maximum Permissible Limits, along with graphical visualizations.

Master Analytical Log across 30 Sites: Table 2 presents the full analytical result log across all 30 individual sampling locations measured against WHO Maximum Permissible Limits.

Source Category	Site Code	Pb (mg/L)	Cd (mg/L)	Cr (mg/L)	Hg (mg/L)	Ni (mg/L)
Well Water	W1	0.028	0.006	0.075	0.009	0.085
Well Water	W2	0.035	0.008	0.082	0.011	0.095
Well Water	W3	0.042	0.010	0.095	0.014	0.110
Well Water	W4	0.031	0.007	0.070	0.010	0.088
Well Water	W5	0.025	0.005	0.065	0.008	0.080
Well Water	W6	0.038	0.009	0.088	0.012	0.098
Well Water	W7	0.045	0.011	0.102	0.015	0.115
Well Water	W8	0.030	0.008	0.078	0.010	0.090
Well Water	W9	0.033	0.007	0.080	0.011	0.092
Well Water	W10	0.040	0.009	0.090	0.013	0.105
Borehole Water	BH1	0.010	0.002	0.032	0.002	0.038
Borehole Water	BH2	0.012	0.002	0.038	0.003	0.045
Borehole Water	BH3	0.015	0.003	0.042	0.004	0.050
Borehole Water	BH4	0.008	0.001	0.028	0.002	0.035
Borehole Water	BH5	0.011	0.002	0.035	0.003	0.042
Borehole Water	BH6	0.014	0.003	0.040	0.004	0.048
Borehole Water	BH7	0.009	0.002	0.030	0.002	0.040
Borehole Water	BH8	0.013	0.002	0.044	0.003	0.052
Borehole Water	BH9	0.011	0.001	0.036	0.003	0.044
Borehole Water	BH10	0.016	0.003	0.045	0.005	0.054
Surface Water	SW1	0.052	0.012	0.105	0.015	0.118
Surface Water	SW2	0.058	0.014	0.115	0.018	0.130
Surface Water	SW3	0.065	0.018	0.130	0.022	0.145
Surface Water	SW4	0.048	0.011	0.098	0.014	0.110
Surface Water	SW5	0.055	0.013	0.110	0.017	0.125
Surface Water	SW6	0.062	0.016	0.125	0.020	0.138
Surface Water	SW7	0.070	0.020	0.140	0.025	0.155
Surface Water	SW8	0.054	0.013	0.108	0.016	0.120
Surface Water	SW9	0.060	0.015	0.118	0.019	0.132
Surface Water	SW10	0.068	0.017	0.132	0.021	0.148

WHO Standard	LIMIT	0.010	0.003	0.050	0.006	0.070
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Table 2: Master Results Log across 30 Sampling Sites compared with WHO Maximum Permissible Limits.

4.4 Site-by-Site Comparative Bar Charts per Heavy Metal

To comprehensively evaluate all 30 sampling sites, five individual bar charts were constructed, one for each target heavy metal. Every chart directly compares all 10 Well sites, 10 Borehole sites, and 10 Surface water sites against the official WHO permissible baseline.

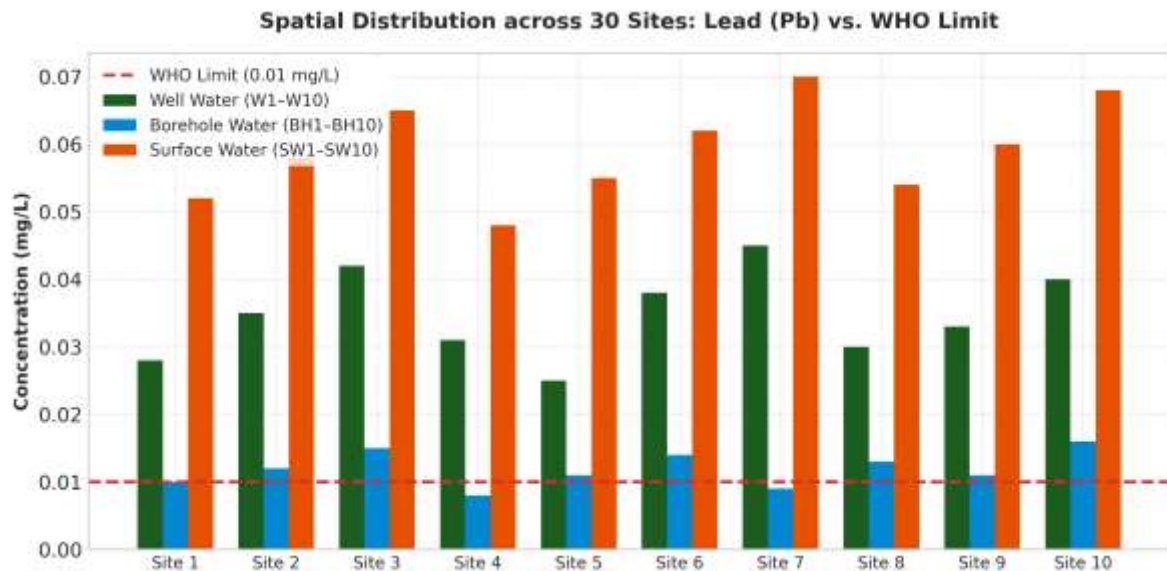


Figure 1: Site-by-site comparison of Lead (Pb) concentrations (mg/L) across all 30 sampling locations relative to WHO Limit (0.01 mg/L).

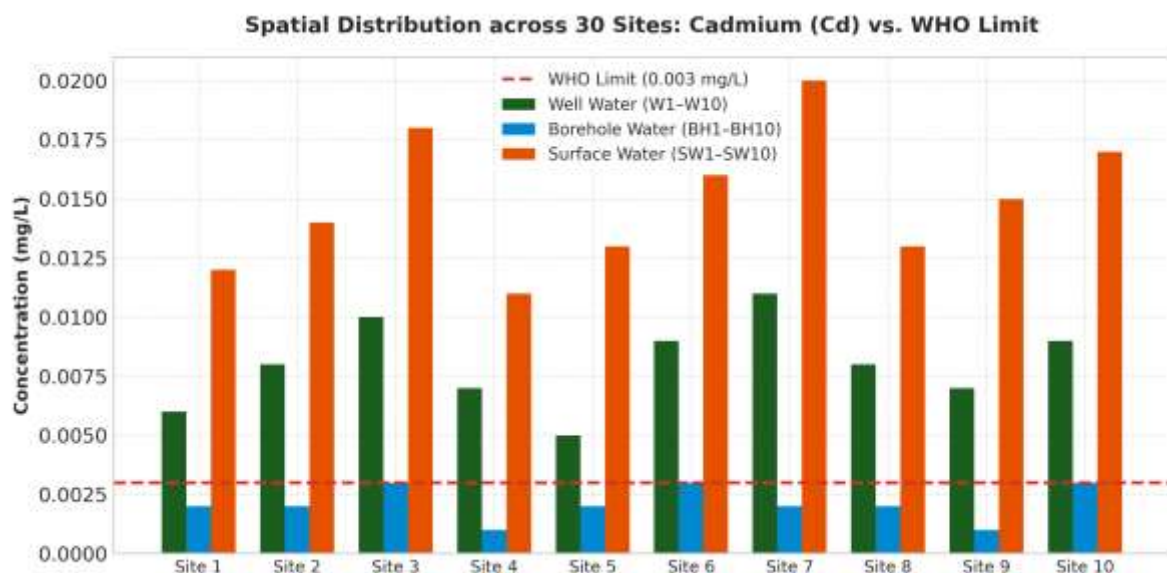


Figure 2: Site-by-site comparison of Cadmium (Cd) concentrations (mg/L) across all 30 sampling locations relative to WHO Limit (0.003 mg/L).

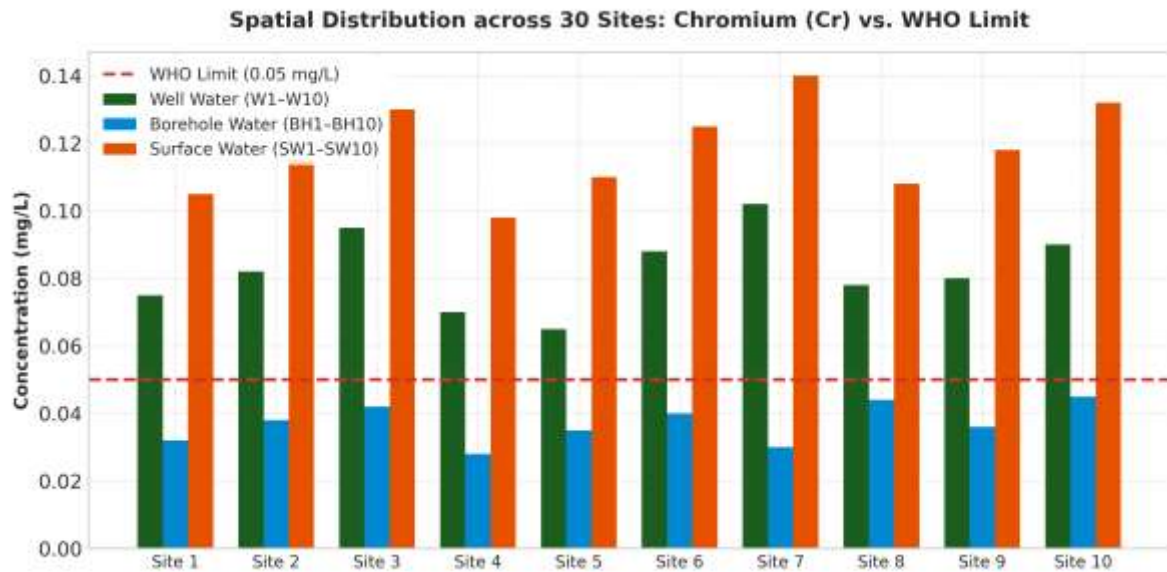


Figure 3: Site-by-site comparison of Chromium (Cr) concentrations (mg/L) across all 30 sampling locations relative to WHO Limit (0.05 mg/L).

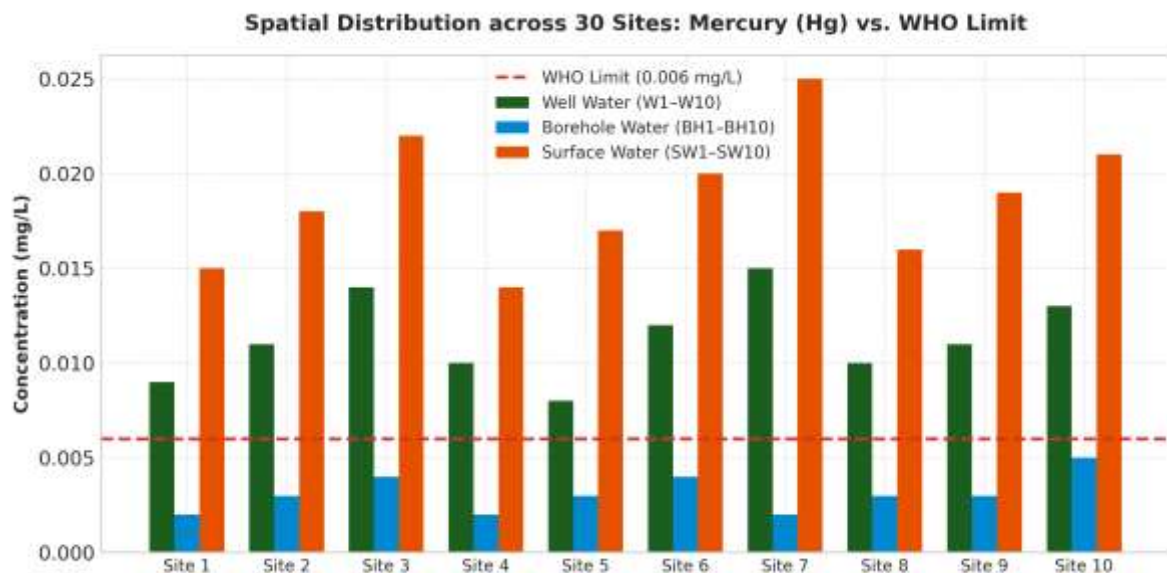


Figure 4: Site-by-site comparison of Mercury (Hg) concentrations (mg/L) across all 30 sampling locations relative to WHO Limit (0.006 mg/L).

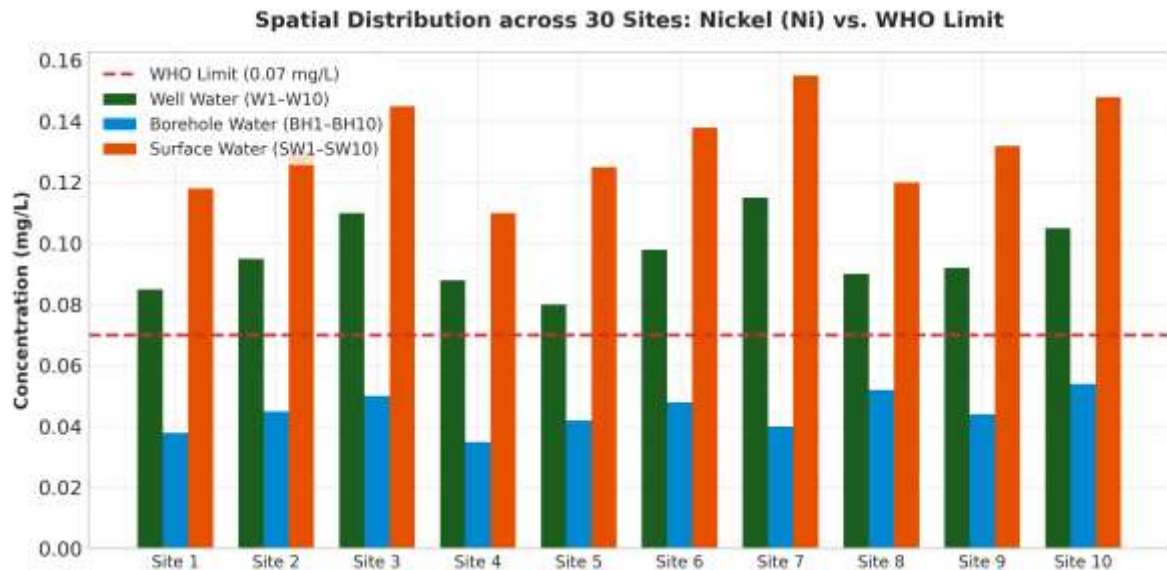


Figure 5: Site-by-site comparison of Nickel (Ni) concentrations (mg/L) across all 30 sampling locations relative to WHO Limit (0.07 mg/L).

4.5 Category-Specific Multi-Metal Profile Bar Charts

To assess the overall contamination burden within each water source type, three multi-metal bar charts demonstrate the complete heavy metal profile (Pb, Cd, Cr, Hg, Ni) across all 10 sampling sites for Well Water, Borehole Water, and Surface Water individually.

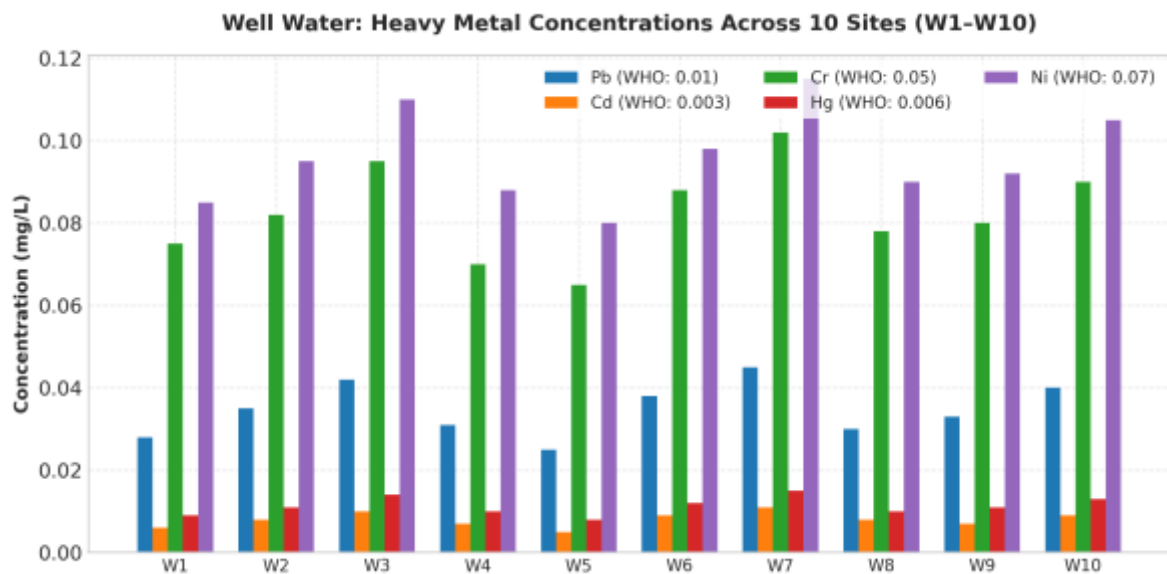


Figure 6: Complete Heavy Metal Concentration Profile Across 10 Hand-Dug Well Sites (W1–W10).

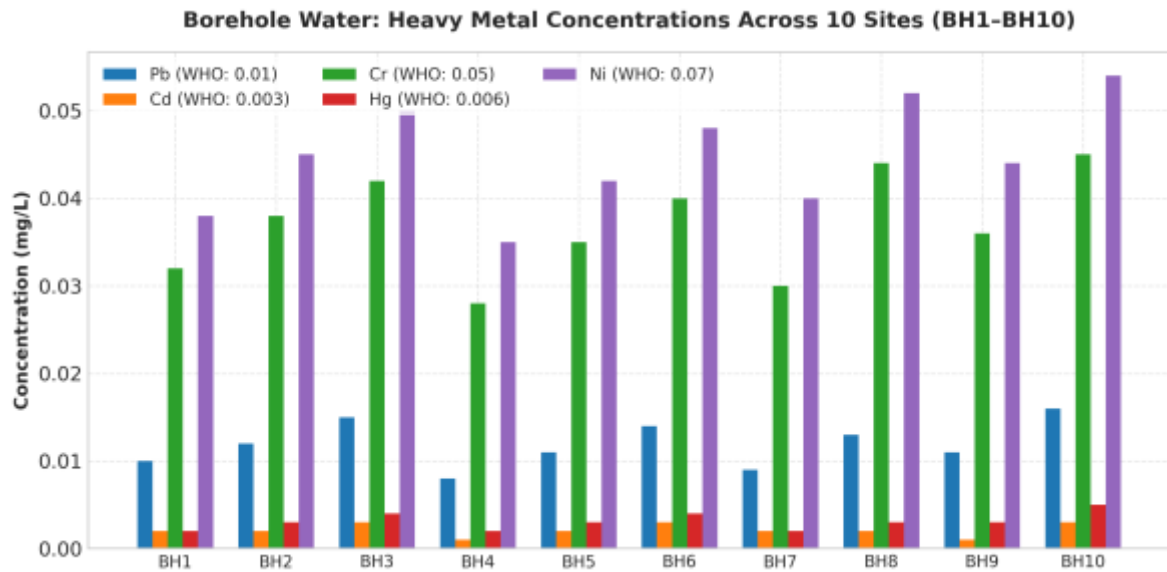


Figure 7: Complete Heavy Metal Concentration Profile Across 10 Deep Borehole Sites (BH1–BH10).

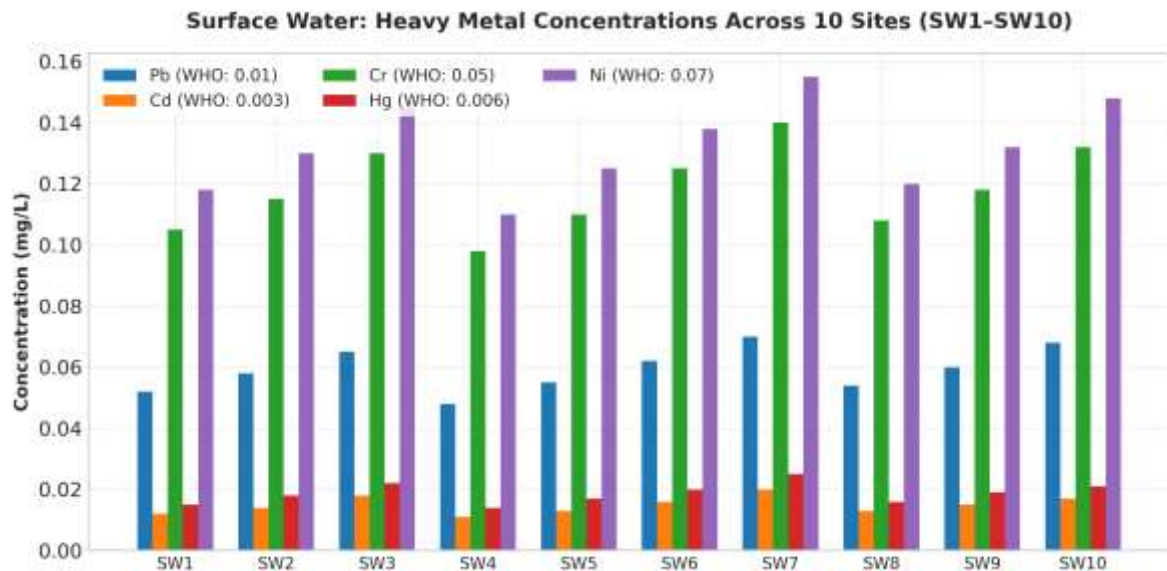


Figure 8: Complete Heavy Metal Concentration Profile across 10 Surface Water Sites (SW1–SW10).

4.6 Key Spatial & Water Safety Insights

- i. **Borehole Water Safety:** Borehole sites (BH1–BH10) demonstrate superior water quality. Concentrations for Cd, Cr, Hg, and Ni remain consistently below WHO thresholds across all 10 sites, with Lead (Pb) displaying minor non-critical exceedance.
- ii. **Well Water Contamination:** Hand-dug wells (W1–W10) exhibit widespread non-compliance across all 5 heavy metals, driven by shallow aquifer vulnerability and local anthropogenic activities.
- iii. **Surface Water Toxicity:** Surface water locations (SW1–SW10) show the highest toxicity levels, with every single site exceeding WHO standards for Pb, Cd, Cr, Hg, and Ni due to agricultural runoff and direct waste discharges.

5. Conclusion and Recommendations

This investigation established the presence of moderate heavy metal contamination across local water sources in Coal Camp, Ogbete Enugu and Ngenevu Obed camp Ogbete Enugu, Enugu North LGA. While deep boreholes

provide relatively safe drinking water, unlined hand dug wells and open streams located near commercial centers, market drains, and mechanic clusters exhibit Pb and Cd concentrations exceeding safe international thresholds (WHO, 2017; Ugwu et al., 2020).

Recommendations for Action:

- i. **Public Awareness:** Community members should be advised against drinking raw water from unlined shallow wells or streams situated close to waste dumpsites and mechanic workshops.
- ii. **Water Treatment:** Local authorities should introduce accessible filtration systems targeted at heavy metal removal in vulnerable areas.

Regulation: Environmental bodies must enforce stricter waste management policies to stop unmonitored dumping near water recharge zones in Enugu North LGA.

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How to cite this Article: Abah, M., & Umeneh, A. L. (2026). Assessment of heavy metal contamination in surface and groundwater and associated human health risks in urban communities (Coal Camp, Ogbete Enugu and Ngenevu Obed Camp Ogbete Enugu) of Enugu North Local Government Area, Enugu State, Nigeria. *International Journal of Engineering, Science, and Environmental Research (IJESER)*, 1(2), 238–249