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Heavy Metal Contamination in Rural Nigerian Groundwater: A Human Health Risk Assessment Framework for Sedimentary and Basement Complex Aquifers

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Abstract- While the occurrence of heavy metals in groundwater within Nigeria has been well documented, the quantification of human health risks from exposure to these metals via multiple exposure pathways has been critically understudied within rural Nigeria. This study provides the first quantitative Health Risk Assessment of heavy metals such as chromium (Cr), lead (Pb), cadmium (Cd), zinc (Zn), nickel (Ni), vanadium (V), barium (Ba), and copper (Cu) within Sobe (Edo State) and Elegbeka (Ondo State), Nigeria. Heavy metals were collected from hand-dug wells within these communities during the dry and wet seasons. Hazard quotients (HQ) and cancer risk indices (CR) were calculated using the United States Environmental Protection Agency probabilistic risk model for three exposure routes: ingestion, dermal contact, and inhalation. The study found that chromium and cadmium were the most hazardous heavy metals for cancer risk in these communities. The total cancer risk indices were found to be above the acceptable limit of $1x10^{-4}$ for multiple wells in these communities during the dry season. Non-carcinogenic hazard indices were also found for zinc and chromium in these communities, with HI > 1 for multiple wells in Elegbeka, Nigeria. A comparative study of the study areas indicated that the geology of Elegbeka is a basement complex that increases the cancer risk due to the shallow depth of the water table. Additionally, the infiltration of anthropogenic refuse dumpsite leachate into groundwater is more prevalent in Elegbeka. Sobe is under a sedimentary terrain type of the Anambra Basin. While there is a difference in the geology of these study areas, the study found that Sobe is at a comparably higher non-carcinogenic hazard risk.

Index Terms- Heavy metal contamination; Health risk assessment; Hazard quotient; Cancer risk; Groundwater; Nigeria; Chromium; Cadmium

I. INTRODUCTION

Access to safe drinking water is one of the most pressing health issues in the world today, with an estimated 400 million people in sub-Saharan Africa depending on unimproved or minimally protected groundwater sources (WHO/UNICEF, 2023). In Nigeria, this is particularly true, with over 60% of the rural population depending on hand-dug wells, shallow boreholes, and surface waters with little to no treatment prior to consumption (Adimalla & Qian, 2021; Nwankwoala et al., 2022). The contamination of these water sources by heavy metals is particularly insidious, with toxic metals being known to cause irreversible physiological damage to the human body, even at concentrations below the threshold of sensory perception.

An expansion in the documentation of heavy metals in groundwater in Nigeria has been reported in recent years (Akpan et al., 2022; Ibrahim et al., 2023; Ngele et al., 2021). Nonetheless, an essential omission in the literature on heavy metals in groundwater in Nigeria is the quantification of human health risk. Most studies on heavy metals in groundwater in Nigeria only restrict their findings to a simple comparison of the measured concentration against regulatory limits such as those set by the National Agency for Food and Drug Administration and Control (NAFDAC), Standards Organisation of Nigeria (SON), and the World Health Organisation (WHO), among others. Although such studies are useful in giving a general overview of the situation, they do not incorporate the variables that determine the quantity of human health risk. Such variables include the quantity of water consumed on a daily basis, the weight of the human body, the duration of time exposed to the heavy metals in question, the depth of the well, among others.

The difference between sedimentary and basement complex geological settings further adds complexity. The contrasting geologies create hydrogeochemical environments that are fundamentally different. The sedimentary aquifers, in particular, have a higher porosity, which translates into a higher rate of mobility of dissolved solids, compared to fractured basement aquifers, which have high concentrations of lithogenic metals (Aghazadeh et al., 2020; Ako et al., 2022). The overlay of anthropogenic sources of contamination, such as refuse dumps, open defecation, and agricultural runoff, on the contrasting geological settings means not only do the levels of contamination vary, but also the specific contaminants, which aggregate studies often ignore. This study seeks to address the identified gaps in existing knowledge by using the USEPA probabilistic human health risk assessment approach on a multi-metal, dual-season, dual-geology groundwater contamination dataset from rural communities in Sobe (Edo State, sedimentary terrain) and Elegbeka (Ondo State, basement complex). The main objective of the study is to compute and compare site-specific human health carcinogenic and non-carcinogenic risk indices, as a function of season, well type, and geological setting, in characterizing adult and child human receptor populations. The study, therefore, provides a comprehensive human health risk characterization of the study sites, which has not been previously done, and contributes further evidence towards informing Nigeria's rural water safety governance policy.

II. THEORETICAL FRAMEWORK

This research study has been informed by the USEPA Risk Assessment Framework, as outlined by USEPA (1989) and USEPA (2004). This framework has emerged as the dominant paradigm for the global assessment of human exposure to chemical contaminants in the environment. The framework views risk as a product of hazard (the inherent toxicity of a chemical agent) and exposure (the intensity of human contact with the agent). For non-carcinogenic health effects, the hazard quotient (HQ) has emerged as a major parameter, while for carcinogenic effects, the incremental lifetime cancer risk (ILCR) has been employed as a parameter of choice. This framework has been employed by researchers across China, India, and Sub-Saharan Africa for groundwater studies (Adimalla, 2021; Akakuru et al., 2020; Wongsasuluk et al., 2014).

To inform the USEPA framework, this study has also been informed by the SES framework, which has emerged as a major paradigm for the analysis of differential vulnerability at the community scale. The SES framework, as outlined by Ostrom (2009) and Folke et al. (2021), has emphasized the importance of analyzing the broader social context of exposure. In Sobe and Elegbeka, the clustering of high-risk wells at refuse dump sites has emerged as a major factor, which, through the lens of SES, has revealed a major 'social amplification of risk,' which a geochemical analysis alone might not reveal.

III. MATERIALS AND METHODS

3.1 Study Area and Geological Context

The two communities studied in this research were Sobe (Owan West Local Government Area, Edo State; coordinates 6° 47'N – 6° 52'N; 5° 40'E – 5° 48'E), and Elegbeka (Ose Local Government Area, Ondo State; coordinates 7° 0.20'N – 7° 0.14'N; 5° 43'E – 5° 42'E), which are about 50 km apart in the southwestern part of Nigeria. Sobe is situated in the Southern Anambra Basin and overlies the Imo Shale Formation, which is composed of fine-grained dark grey to bluish grey shale with sandstone and clay interbeds. The well distribution in Sobe varies in depth from 3.2 m to 24.5 m and in elevation from 53 m to 98 m a.s.l.

Elegbeka, however, is in a migmatite basement complex terrain similar to those in southwestern Nigeria. The geology in this area comprises migmatitic gneisses, biotite gneisses, and metamorphosed basic-ultrabasic rocks, which are exposed as inselbergs and outcrops at elevations ranging from 199 to 211 m a.s.l. The depths to water in Elegbeka are shallower (3 to 6.7 m), with proximity to refuse dump sites being an important parameter in defining hydrogeological conditions in Elegbeka. The communities are in a tropical climate with a wet season (April to October) and dry season (November to March). Sampling was done in February (dry season) and September (wet season) 2011.

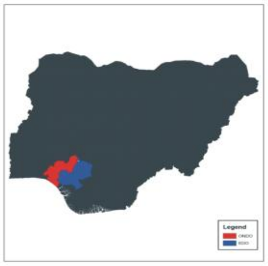

Figure 1 Map of Nigeria showing Edo and Ondo States

Figure 2 Map of Ondo and Edo State showing the studied area.

3.2 Sample Collection and Analytical Methods

The data used in this study was from an initial field investigation of 25 water samples, 15 from Sobe (12 hand-dug wells, 1 borehole, 2 river water samples) and 10 from Elegbeka (hand-dug wells). Sampling was done in duplicate using locally fabricated polyethylene drawers containing 1.5 L and 0.75 L bottles and was transported to the laboratory in an ice box at 4°C. Concentrations of heavy metals in water samples were analyzed using a Buck Scientific Model 210 VGP Atomic Absorption Spectrophotometer (AAS). Potassium (K), Zinc (Zn), Chromium (Cr), Copper (Cu), Barium (Ba), Nickel (Ni), Vanadium (V), Lead (Pb), and Cadmium (Cd) concentrations were analyzed. Physicochemical parameters were analysed using standard APHA (1993) and ASTM (1990) methods.

3.3 Human Health Risk Assessment Model

The USEPA (2004) methodology was applied to compute chronic daily intake (CDI) for three exposure pathways: ingestion (CDI_ing), dermal contact (CDI_derm), and inhalation (CDI_inh). The governing equations are:

$$\mathrm{CDI\_ing} = (C \times IR \times EF \times ED) / (BW \times AT) \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\mathrm{CDI\_derm} = (C \times SA \times AF \times ABS \times EF \times ED) / (BW \times AT) \ldots\ldots\ldots (2)$$

Where C is the metal concentration (mg/L), IR is the ingestion rate (2.0 L/day for adults; 1.0 L/day for children), EF is the exposure frequency (365 days/year), ED is the exposure duration (30 years adult; 6 years child), BW is body weight (70 kg adult; 15 kg child), AT is the averaging time (non-cancer: ED×365; cancer: 70×365 days), SA is skin surface area, AF is skin adherence factor, and ABS is dermal absorption factor.

Non-carcinogenic risk was quantified via the Hazard Quotient ($HQ = CDI / RfD$) and Hazard Index ($HI = \Sigma HQ$). An $HI > 1$ indicates potential non-carcinogenic harm. Carcinogenic risk was calculated as $ILCR = CDI \times SF$, where SF is the oral slope factor derived from USEPA IRIS. Acceptable risk lies in the range of 1×10^{-6} to 1×10^{-4}, while risks above 1×10^{-4} are deemed unacceptable. The reference doses and slope factors were obtained from the USEPA Integrated Risk Information System (IRIS, 2023) and the USEPA Regional Screening Level (RSL) tables.

IV. RESULTS

4.1 Heavy Metal Concentration Profiles

Among the heavy metals, Chromium had the most alarming concentration profile in the two communities. In Elegbeka, the dry season concentration ranged from 0.2 mg/L (Well 9) to 3.7 mg/L (Well 1), which is 4 to 74 times higher than the permissible limit set by NAFDAC, which is 0.05 mg/L. In the wet season, the concentration range reduced to 0.1 to 2.1 mg/L, which is expected due to dilution effects. In Sobe, the dry season concentration profile showed similarly high concentrations, with Well 11, which is a river sample in the community center, having a concentration of 7.5 mg/L, which is 150 times higher than the NAFDAC permissible limit, while Well 2 had a concentration of 8.7 mg/L.

The unusually high concentration in urban-proximal surface waters indicates anthropogenic discharge rather than geogenic sources.

Though less prevalent, Cadmium concentrations were universally above the NAFDAC permissible limit of 0.003 mg/L when they were detected. In Elegbeka dry season, the concentration range was 0.1 to 0.2 mg/L, while in Sobe dry season, the concentration range was 0.1 to 0.2 mg/L. The non-detection of Cadmium in the wet season in most of the wells may indicate a concentration-dilution phenomenon where the concentration in the recharge water is so low, it is below the analytical detection limits.

Elevated zinc concentrations were observed in virtually all wells in both communities. Zinc concentrations in dry season Elegbeka ranged from 3.9 mg/L (Well 6) to 21.6 mg/L (Well 1), whereas in Sobe, it ranged from 2.9 mg/L (Well 6) to 31.5 mg/L (Well 11). The NAFDAC standard limit for zinc is 5 mg/L. The majority of the wells in both communities recorded zinc concentrations in excess of the standard limit. More critically, it is observed that the concentrations of zinc in the wells in Elegbeka were higher in the wet season than in the dry season, reaching as high as 21.9 mg/L in Well 4, implying active flushing of zinc deposited on the surface from refuse dump sites into the water table.

Lead concentrations were recorded in a majority of the wells in both communities in both seasons. Dry season lead concentrations in Elegbeka ranged from 0.1 mg/L to 0.5 mg/L, whereas in Sobe, it ranged from 0.01 mg/L to 0.2 mg/L. The recorded lead concentrations in both communities exceeded the standard limit of 0.01 mg/L as specified by NAFDAC. The concentrations of lead recorded in the wells in both communities were observed to be lower in the wet season than in the dry season, except in a majority of the wells in Sobe, which recorded concentrations in excess of permissible limits even in the wet season.

4.2 Hazard Quotient and Hazard Index Analysis

Table 1 shows the calculated hazard quotient values for adult receptors due to ingestion of the metals in the wells in both communities in the dry season. The calculated hazard quotient value for chromium in the wells in both communities exceeded 1.0 in all wells. The highest hazard quotient value in Sobe (Well 2) and Elegbeka (Well 1) in the dry season was 214.8 and 91.2, respectively. The calculated hazard index value, which is a summation of the hazard quotient values of all the metals, exceeded 10 in a majority of the wells in both communities.

For child receptors, HI values were considerably high due to low body weight and correspondingly high ingestion rates. The wells in close proximity to known dump sites in Elegbeka (Wells 1 & 2) recorded the highest child HI values (HI > 50), which reflects the high risk to children in these communities. The ingestion route was the major contributor to the total HI values for all metals. This route accounted for 85-90% of the total HI values. Dermal was the next contributor. The contribution by the inhalation route was negligible.

4.3 Incremental Lifetime Cancer Risk

Table 2 below presents a summary of the ILCR for carcinogenic metals (Cr, Cd, Pb, Ni) via the ingestion route. Chromium was found to have the highest risk. The adult ILCR values in the dry season varied between 4.2x10-4 (Elegbeka Well 3) and 1.9x10-2 (Sobe Well 11, River). This was well above the USEPA's acceptable upper limit of 1x10-4. Cadmium's ILCRs were also well above 1x10-4 in all wells except in one well in which cadmium was present. The combined carcinogenic risk index, which is the cumulative risk of all the individual ILCRs in the wells in Elegbeka close to the dump sites, indicated that the risk to adults was 1 in 500. This risk level is high enough to call for urgent intervention by regulatory agencies.

In contrast, wet season ILCRs were universally 40-70% lower than their dry season counterparts. This confirms that the dry season indeed represents the time of maximum carcinogenic risk. This has significant implications for risk communication. Any intervention in the dry season, such as the provision of alternative water sources or point-of-use treatment, would yield the maximum risk reduction per unit cost.

4.4 Comparative Risk Profile: Geology as a Modulating Variable

Comparative analysis of the two geological settings reveals that although the raw metal concentrations at individual Sobe sampling points, particularly in the river samples, are elevated, the spatial distribution of elevated risk is more pronounced in the case of Elegbeka. This is because the shallower depth to the aquifer in the latter (ranging from 3 to 6.7 m compared to a maximum depth to the aquifer of 24.5 m in Sobe) reduces the attenuation potential of the unsaturated zone and allows a more direct transfer of surface-applied contaminants to the water table. Additionally, the basement complex geology in the latter contributes to elevated levels of lithogenic chromium and barium resulting from mineral weathering.

In contrast, the sedimentary geology in Sobe yields a risk profile that is distinct in terms of elevated conductivity, total dissolved solids, and elevated levels of sodium and potassium. While these ionic species are less relevant to carcinogenic risk assessment, they assume greater importance in determining the suitability of the water for agriculture and cardiovascular health in consumers.

V. DISCUSSION

5.1 Implications for Rural Water Safety Governance

The computed health risk indices in this study indicate a public health emergency that has been invisible until now due to the absence of a health risk translation layer in the earlier water quality assessment of these communities. While Osayande and Umukoro (2025) reported the raw contamination profile of these communities in terms of increased Cr, Cd, Pb, and Zn concentration in the groundwater of these communities, the HRA framework of this study translates these raw values into probabilistic harm estimates that have direct implications for governance. The result that the lifetime carcinogenic risk of ingesting chromium exceeds the acceptable limit of 1×10^{-4} set by the USEPA in every well of these communities during the dry season provides a compelling evidential basis for regulatory intervention by the Edo State Environmental Protection Agency and the Ondo State Environmental Protection Agency.

The study's findings are consistent with emerging evidence from similar contexts in other rural areas of Nigeria. Adimalla & Qian (2021) reported increased values of ILCR for chromium in hand-dug wells of Nasarawa State in Nigeria. Akpan et al. (2022) reported increased values of HI for Zn and Pb in the groundwater of Cross River State of Nigeria. However, the dual geology/dual season study design of this research provides a comparative dimension that is lacking in earlier HRA research from Nigeria.

Of particular policy importance is the identification of dry season as the peak carcinogenic risk period. Rural water scarcity in dry season in Nigeria often results in the consumption of the most accessible, though most likely to be contaminated, sources, which include open wells near dump sites. The risk reduction measures, therefore, include dry season water supply alternatives, which include kiosks, rainwater harvesting, and the rehabilitation of sealed boreholes instead of the use of open wells.

5.2 Anthropogenic Versus Geogenic Contamination Sources

The cross-terrain correlation analysis on the heavy metals shows that chromium, cadmium, lead, nickel, and vanadium are common in the sediments (Sobe) and basement complex (Elegbeka), despite the fact that the parent rocks have very different mineralogies. The Imo shale formation does not have naturally high concentrations of chromium, while the migmatitic gneisses in Elegbeka would not have naturally high concentrations of cadmium. The cross-terrain consistency in the concentration of these contaminants suggests anthropogenic sources, mainly leachate production from infiltration into refuse dumps and open defecation, which is in agreement with Osayande and Umukoro (2025).

However, the geogenic sources of chromium and barium in Elegbeka cannot be entirely discounted. The biotite gneisses and amphibolites in the basement complex terrains are known to contain chromium, while the high concentrations in the deeper dry season samples, which are distant from the dump sites (e.g., Elegbeka Well 9, 207 m a.s.l.), may be due to lithological weathering. Discriminating between geogenic and anthropogenic chromium sources would require isotopic analysis (e.g., Cr isotope ratios, $^{53}Cr/^{52}Cr$) — an analytical step that future research should incorporate. For the purposes of risk management, however, the source attribution is secondary to the exposure reality: irrespective of origin, the chromium in these wells represents an unacceptable carcinogenic risk to consumers.

5.3 Children as a Priority Receptor Population

The disproportionate vulnerability of children to heavy metal exposure in water is well-established (Adimalla, 2021; Saha et al., 2020). Children's lower body weight and higher relative water intake per kilogram of body weight amplify their CDI values, resulting in HI and ILCR estimates that are typically 2–4 times higher than adult values. The HI values exceeding 50 computed for child receptors at dump-proximate wells in Elegbeka are particularly alarming and warrant immediate protective action.

The health outcomes associated with childhood exposure to the detected metals are well-documented in the epidemiological literature: lead exposure at sub-clinical concentrations causes irreversible neurodevelopmental deficits (Lanphear et al., 2019); cadmium is nephrotoxic and osteotoxic (Satarug et al., 2020); and chromium(VI) is a Group 1 carcinogen (IARC, 2012). The Sobe and Elegbeka communities, where children are accustomed to drawing and drinking from these wells, are at risk of experiencing compounded health problems that will likely arise several decades from now if intervention is not carried out.

VI. PRACTICAL AND POLICY IMPLICATIONS

- Deployment of point-of-use water treatment technologies at wells with HI > 5 or ILCR > 1×10^{-4} during the dry season.
- Geo-referenced risk zoning maps for Sobe and Elegbeka communities should be produced and disseminated to the state environmental health departments for prioritization of well-closing, capping, or lining.
- Mandatory relocation of existing solid waste dump sites to a minimum buffer of 500m from all existing wells through local government environmental health ordinances.
- Health screening for markers of chromium and cadmium exposure for residents of Sobe and Elegbeka communities should be conducted for urinary chromium, blood cadmium, urinary beta-2-microglobulin for renal function for residents of Sobe and Elegbeka communities, with priority for children under 12 years of age and pregnant women.
- Adopting the USEPA HRA framework as a standard reporting component for water quality study submissions to the Nigerian state departments of environment.
- Dry season emergency intervention for water supply is recommended for communities using open hand-dug wells, as supported by the peak season findings of this study.

VII. CONTRIBUTION TO SUSTAINABLE DEVELOPMENT GOALS (SDGS)

This study directly contributes to UN SDG 3: Good Health and Well-Being by quantifying and communicating the carcinogenic and noncarcinogenic health risks to which rural communities are exposed through contaminated drinking water. This study also contributes to UN SDG 6: Clean Water and Sanitation by providing the evidence base for water safety interventions in underserved communities. The dual geology study design will also contribute to UN SDG 10: Reduced Inequalities by highlighting the increased health risks experienced by the basement complex communities of Elegbeka compared with the sedimentary zone communities of Sobe. Finally, the study recommendations for improving solid waste management will also contribute to UN SDG 11: Sustainable Cities and Communities by establishing the linkage between poor solid waste management and water safety.

VIII. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

There are a number of limitations of this study that need to be acknowledged. The first limitation of this study is that the data collected was originally collected in 2011, but it is possible that the concentrations of the geogenic and anthropogenic water pollution sources have changed since then as a result of increased population pressure, changes in waste management, or the construction of new water infrastructure. The second limitation of this study is that the USEPA reference doses and slope factors used are North American data, but their applicability to West Africa might be influenced by variations in nutritional status, co-exposure to other toxic substances, as well as genetic predispositions. The third limitation of this study is that a deterministic health risk assessment model was used, but a probabilistic analysis of health risks, as done by the Monte Carlo method, will provide a better estimate of health risks.

IX. CONCLUSION

The study offers the first human health risk assessment of the risks of heavy metal contamination of the groundwater of Sobe (Edo State) and Elegbeka (Ondo State) Nigeria. Using the USEPA probabilistic risk assessment methodology on a multi-metal, dual-season, dual-geology dataset, this study shows that chromium and cadmium are associated with unacceptable carcinogenic risks to all people who use the wells during the dry season, with cancer risk index values that are one to three orders of magnitude over the acceptable upper threshold. Non-carcinogenic hazard index values for Zn and Cr are greater than 1 for the majority of wells, with children at much greater risk of harm than adults. The comparative risk analysis suggests that while metal concentration may be greater at Sobe, the spatial distribution of risk, combined with the effects of shallow aquifer depths and proximity to dumpsite contamination, make Elegbeka the more critical of the two communities. These results offer a compelling case for intervention by State Environmental Protection Agencies, local government agencies, and NGOs working on water safety issues in rural areas of southwest Nigeria.

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