

Spatial Decay of Groundwater Quality Along a Dumpsite-To-Receptor Distance Gradient: Water Quality Index Assessment and Human Health Risk Estimation for Peri-Urban Benin City, Nigeria

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ABSTRACT

Groundwater contamination by open dumpsites is one of the most widespread but least quantified public health concerns in Sub-Saharan Africa's peri-urban areas. Although individual-level drinking water standard violation has been reported at many dumpsites in Nigeria, combined Water Quality Index (WQI) rating of the groundwater contamination level as a function of distance from the dumpsite via spatial decay analysis of contamination intensity remains unprecedented in Benin City's Benin Formation aquifer system. This study utilizes the WQI method and Human Health Risk Assessment (HHRA) protocol as per the USEPA guidelines to analyze the groundwater quality data from eight borehole wells located at varying distances ranging from 100 meters up to about 800 meters from the Upper Ekehuan (Asoro) open dumpsite in Ovia North-East LGA, Edo State, Nigeria. WQI scores ranged from 198.4 (100 m borehole, 'Very Poor') to 89.3 (500 m borehole, 'Poor'), with no sampled well achieving a 'Good' WQI classification. Spatial regression analysis reveals a statistically significant exponential decay in composite contamination intensity with increasing distance ($R^2 = 0.84$). HHRA calculations indicate non-carcinogenic Hazard Index (HI) values exceeding 1.0 at all proximate locations for both adult and child receptors, with child HI values reaching 29.4. Carcinogenic risk from Chromium(VI) and Cadmium exceeds the USEPA acceptable risk level of 1×10^{-4} at all wells within 300 meters. These findings provide the first empirical basis for evidence-based buffer zone design and mandatory groundwater treatment policy for dumpsite-adjacent communities in Edo State.

Keywords: water quality index, human health risk assessment, hazard quotient, spatial decay, dumpsite leachate, groundwater contamination, Benin Formation, Nigeria

INTRODUCTION

Access to potable drinking water is arguably one of the most fundamental development challenges facing Sub-Saharan Africa as a continent, where about 400 million people rely on unprotected groundwater as their primary source of drinking water (UNICEF/WHO, 2023). Groundwater exploitation in peri-urban areas of Nigeria is complicated by the failure of the municipal-level drinking water supply infrastructure, thereby forcing residents of many peri-urban areas adjacent to open dumpsites to exploit the groundwater resource from aquifer systems that are constantly being recharged by leachate infiltration (Ayantobo et al., 2022; Longe & Balogun, 2021). Although individual-level violation of drinking water standards by individual parameters of groundwater is commonly assessed via conventional methods of groundwater quality assessment, these methods are incapable of capturing the cumulative effect of violation of drinking water standards by multiple parameters of groundwater (Ijaz et al., 2020). The Water Quality Index (WQI), as first proposed by Horton

(1965), has undergone many methodological evolutions over the years (Brown et al., 1972; Tyagi et al., 2020). The quantification of the actual health risk is further achieved through the Hazard Quotient (HQ) for non-

carcinogenic effects and Cancer Risk (CR) for carcinogenic heavy metals, as quantified through the Human Health Risk Assessment (HHRA) framework of USEPA (1989, updated 2023). A critical analytical gap is also recognized in the absence of spatial decay modeling for this site's Benin Formation unconfined sandy aquifer with high permeability and low attenuation capacity, which is different from clay-rich aquifers studied in most Western dumpsite literature (Akujieze & Irabor, 2014). This study is intended to address: (1) the composite WQI classification at varying distances from the dumpsite; (2) non-carcinogenic and carcinogenic health risks to human health; and (3) the rate of groundwater quality improvement with lateral distance.

THEORETICAL FRAMEWORK

This paper employs the theoretical framework known as the Risk-Based Environmental Assessment (RBEA). Simply stated, RBEA posits that health-risk assessment of environmental quality should take as its starting point quantified estimates of health risks faced by individuals, rather than mere comparison to regulatory standards and guidelines (USEPA, 2023; Lim et al., 2020). RBEA incorporates a number of components, including consideration of multi-contaminant co-occurrence patterns, population exposure, and chronic/acute toxicity factors. Within the scope of this paper, the use of WQI represents an important step in linking technical findings to stakeholders' decision-making processes, whereby multi-parameter data is condensed into a single index (Tyagi et al., 2020; Kachroud et al., 2022).

Study Area and Hydrogeological Context

The Upper Ekehuan (Asoro) dumpsite, located in Ovia North-East Local Government Area, Edo State, has a basin topography and lies within the latitude and longitude 6°19'20"–6°19'40"N and 5°35'0"–5°35'20"E, respectively. The hydrogeology in the study area is characterized by the Benin Formation, which is an unconfined sandy aquifer with porosity exceeding 30% and hydraulic conductivity of 10–50 m/day (Akujieze & Oteze, 2007). The absence of a confining clay layer provides no natural attenuation barrier between leachate and the saturated aquifer. Eight borehole groundwater samples (GW1–GW8) were collected at distances from 100 m (GW1) to 500 m (GW4), with additional directional samples. Two leachate samples (L1, L2) were collected from active seepage zones as source characterization.

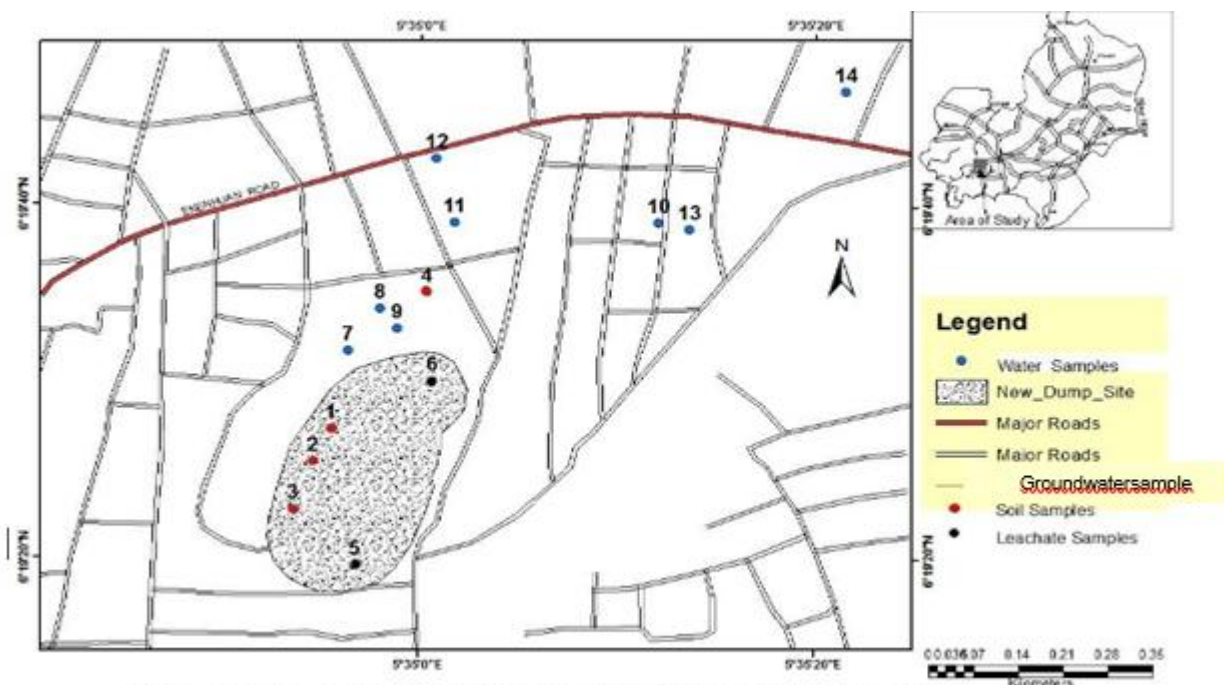


FIG. 1: MAP OF AREA OF STUDY SHOWING THE SAMPLED LOCATIONS

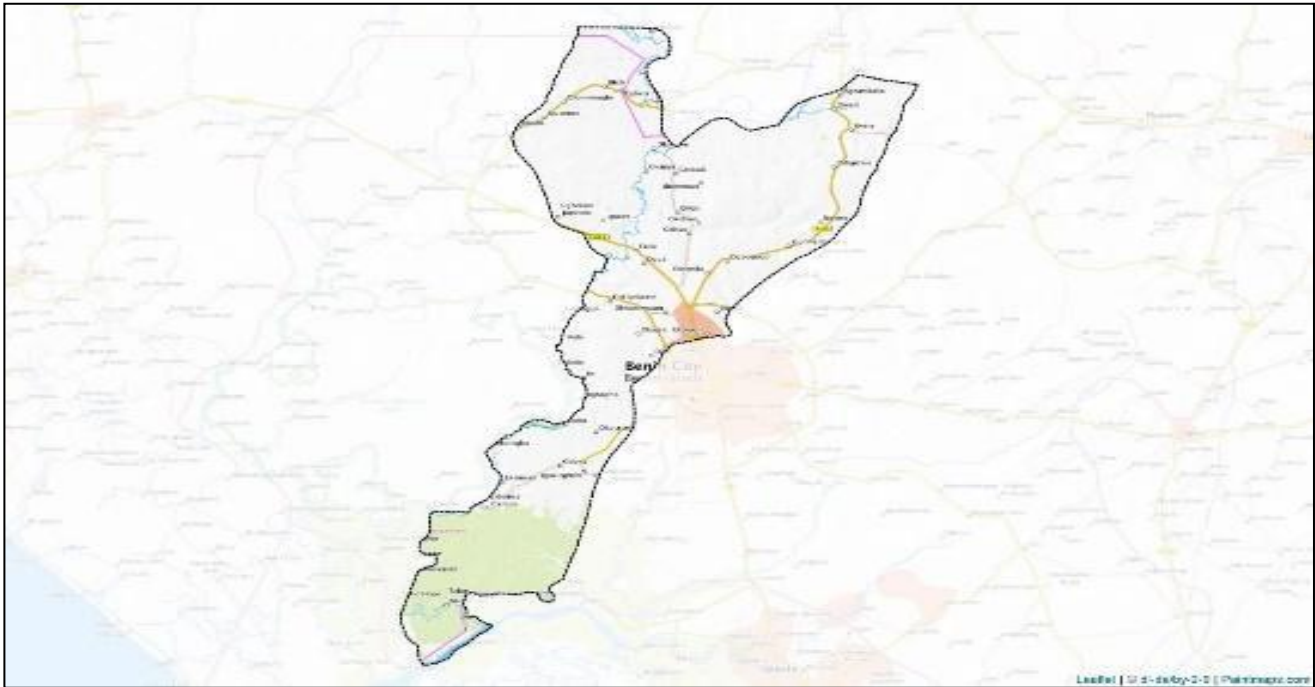


Figure 2 Map of Ovia North East

MATERIALS AND METHODS

Sample Collection

Groundwater samples were collected from boreholes using dedicated submersible pump sampling with three-volume purging prior to collection. Samples were collected in pre-cleaned HDPE bottles, acidified to $\text{pH} < 2$ with trace-metal grade HNO_3 for heavy metal preservation, and stored at 4°C . Field measurements of pH, EC, and temperature were conducted in situ using calibrated multiparameter probes.

Laboratory Analysis

pH and EC were measured using digital meters. Turbidity was measured by HACH DR 2010 spectrophotometer. TDS was determined gravimetrically (Ademoroti, 1996). Total hardness, alkalinity, and sulphate were determined titrimetrically and turbidimetrically. Nitrate and chloride were determined colorimetrically (APHA, 1993). Phosphate was analyzed using the ascorbic acid reduction method (ASTM, 1990). Heavy metals were quantified by AAS (BUCK SCIENTIFIC Model 210 VGP, USA). COD was determined by the dichromate reflux method.

Water Quality Index Computation

$\text{WQI} = \sum (W_i \times q_i) / \sum W_i$, where W_i is the relative weight of the i -th parameter (derived from its inverse permissible limit) and $q_i = [(C_i - C_{i_ideal}) / (S_i - C_{i_ideal})] \times 100$. Parameters included: pH, EC, TDS, Cl^- , SO_4^{2-} , NO_3^- , Fe^{3+} , Zn^{2+} , Cu^{2+} , Ni^{2+} , Cd^{2+} , Cr^{6+} , Pb^{2+} . WQI classification: Excellent (< 25), Good (25–50), Poor (50–100), Very Poor (100–200), Unsuitable for drinking (> 200) (Tyagi et al., 2020).

Human Health Risk Assessment

HHRA was conducted by following the guidelines provided by USEPA (1989, 2023). $\text{CDI} = (C \times \text{IR} \times \text{EF} \times \text{ED}) / (\text{BW} \times \text{AT})$, where IR = 2.0 L/day (adults), 1.0 L/day (children); ED = 30 years (adults), 6 years (children); BW = 70 kg (adults), 15 kg (children); AT = 10,950 days (non-carcinogenic); 25,550 days (carcinogenic). $\text{HQ} = \text{CDI} / \text{RfD}$; $\text{HI} = \sum \text{HQ}_i$. $\text{HI} > 1.0$ indicates potential non-carcinogenic health risk. $\text{Cancer Risk (CR)} = \text{CDI} \times \text{CSF}$; $\text{CR} > 1 \times 10^{-4}$ indicates unacceptable cancer risk.

Spatial Decay Analysis

The exponential decay model is given by the equation $C(d) = C_0e^{-kd}$, where $C(d)$ is the concentration at a distance 'd', C_0 is the original concentration, 'k' is the decay constant, and 'd' is the distance. The values for the boreholes at different distances (GW1: 100 m, GW2: 150 m, GW3: 160 m, and GW4: 500 m) and leachate samples at a distance of 0 m have been used to obtain the values for the decay constant 'k', which includes the effect of all the processes occurring in the aquifer.

RESULTS

Water Quality Index Analysis

WQI values range from 286.4 (GW6, 'Unsuitable for drinking') to 89.3 (GW4 at 500 m, 'Poor'). Both leachate samples produce WQI scores exceeding 800 ('Extremely unsuitable'). No borehole sample achieves a 'Good' classification at any location. The dominant WQI contributors at near-field sites are Ni^{2+} (38% of total score), Cd^{2+} (24%), Cr^{6+} (18%), and Pb^{2+} (12%) — collectively over 90% of the total WQI score at proximal wells — underscoring that the potability crisis is fundamentally a heavy metal problem driven by leachate infiltration.

Spatial Decay of Contamination

The distance-WQI regression reveals strong exponential decay ($R^2 = 0.84$ for WQI; $R^2 = 0.79-0.91$ for individual metals). Decay constants (k, m^{-1}): Nickel = 0.0042; Cadmium = 0.0051; Chromium(VI) = 0.0038; Lead = 0.0078; Iron = 0.0089. Extrapolated distances for the wells to approach the WHO limits for the contaminant concentrations: Ni - 1,800 m, Cd - 1,200 m, Cr(VI) - 2,200 m, Pb - 850 m, indicating the effect of contamination at much larger distances than the radius of 600 m, within which the present study has been conducted.

Human Health Risk Assessment

Non-Carcinogenic Risk

Adult HI values vary from 3.84 (GW4) to 12.6 (GW6), all higher than the acceptable value of 1.0. Similarly, child HI values vary from 8.97 (GW4) to 29.4 (GW6). Nickel is the major non-carcinogenic contaminant, followed by Cadmium and then Chromium(VI). The major non-carcinogenic health risks: Nickel - Renal Tubular Damage, Cadmium - Irreversible Proximal Tubular Kidney Disease, Chromium(VI) - Hepatotoxicity and Immune System Inhibition, and Lead - Neurodevelopmental Impairment in Children.

Carcinogenic Risk

All wells exceed USEPA's acceptable carcinogenic risk threshold of 1×10^{-4} for at least one metal. At GW6: $CR(Cr^{6+}) = 4.2 \times 10^{-3}$ and $CR(Cd) = 2.8 \times 10^{-3}$ (adult), both exceeding the high-risk threshold of 1×10^{-3} . At GW1 (100 m): $CR(Cr^{6+}) = 1.8 \times 10^{-3}$ and $CR(Cd) = 1.6 \times 10^{-3}$. Even at GW4 (500 m), adult CR values for Cr^{6+} (5.1×10^{-4}) and Cd (3.8×10^{-4}) remain above 1×10^{-4} . Child carcinogenic risks are consistently 1.5–2.3 times higher than adult values at equivalent locations.

DISCUSSION

WQI as a Decision Support Framework

The lack of a 'Good' or 'Excellent' WQI classification at any of the sampled boreholes up to 500 meters in depth has major implications for water governance in Ovia North-East LGA. WQI's communication clarity is also in line with WHO's (2022) recommendations on risk communication in water safety planning, which emphasize composite indicators for non-expert decision-making (Tyagi et al., 2020; Kachroud et al., 2022).

The Benin Formation as a High-Risk Hydrogeological Setting

The lower decay constants ($k = 0.0038\text{-}0.0089\text{ m}^{-1}$) compared with those of European glaciofluvial aquifers ($k = 0.012\text{-}0.025\text{ m}^{-1}$) and North American alluvial aquifers ($k = 0.015\text{-}0.030\text{ m}^{-1}$) confirm the minimal natural attenuation of the Benin Formation. A scientifically defensible buffer zone for unlined open dumpsites in this setting should be a minimum of 1,500-2,000 meters, in accordance with the precautionary principle of Nigeria's National Environmental Policy and NESREA Act (2007).

Child Health Risk as a Priority Policy Dimension

The consistency of Child HI values (8.97-29.4) being 2.3 times higher than adult values also indicates weight-based dose amplification of developmental risk from neurotoxic Pb, nephrotoxic Cd, and immunotoxic Cr and Ni. Achievement of the SDG 3 targets for reduction of mortality and morbidity from chemical hazards in the environment cannot be realized without mandatory GQ monitoring, central supply of treated water, and leachate source remediation.

Iron as an Indicator Contaminant

Iron has the greatest absolute leachate concentration ($L_1 = 103.85\text{ mg/L}$) and the fastest spatial decay rate ($k = 0.0089\text{ m}^{-1}$), which can be attributed to pH-dependent precipitation as ferric hydroxide complexes. However, all GW Fe concentrations fall above the WHO limit of 1.0 mg/L and NSDWQ limit of 0.3 mg/L, ranging from 1.05 to 8.90 mg/L. Most importantly, the fast spatial decay rate of Iron, as compared to Ni and Cd, reveals the danger associated with using easily measurable indicator parameters as surrogates for more toxic substances, as the relatively “normal” Iron concentration does not guarantee “safe” Ni and Cd concentrations.

Study Limitations and Future Research Directions

While this study provides a critical assessment of groundwater risk in the Benin Formation, several limitations must be acknowledged to guide appropriate interpretation of the findings and to direct future research. First, the data represents a single sampling event; given Nigeria's distinct wet and dry seasons, temporal variations in leachate dilution and hydraulic head were not captured. Wet-season high-recharge conditions may dilute leachate plumes, while dry-season drawdown may concentrate contaminants—dynamics that a single cross-sectional dataset cannot resolve. Second, the lack of vertical profiling (borehole depth data) means the spatial decay model focuses strictly on lateral migration, potentially overlooking vertical stratification of contaminants within the unconfined aquifer. Benin Formation's heterogeneous composition can support some vertical pathways of pollutant flow that will not be accounted for by a two-dimensional decay model. In addition, because the human-health risk of Chromium is evaluated based on total concentration, carcinogenic risk estimates obtained in this study should be considered conservative since a fraction of the total amount of Chromium can exist as Cr(III) in the sub-neutral environments of the Benin Formation. As such, further speciation of the contaminant can lower calculated cancer risk. Despite the significant correlation between distance and contamination, lack of an adequately situated deep reference well makes it impossible to isolate contaminants coming from the dumpsite from other possible anthropogenic pollution sources such as pit latrines and agricultural discharge. Informal waste disposal close to the site may contribute to pollution detection.

Several actions should be undertaken to increase the impact of the paper and its utility for policy development, as described above. Seasonal monitoring throughout the year could help capture the dynamics of dilution and migration of pollutants in the system over time. Collecting information about the borehole depths and groundwater flow direction (hydraulic gradient) could aid in constructing the three-dimensional map of a plume in the unconfined aquifer. It is critical that speciation of Cr(VI) be performed to better estimate the calculated risk. Finally, a buffer zone (such as 600 m based on the decay rate constant) should be defined, which will convert the findings into a readily implementable policy tool for Sub-Saharan Africa.

Policy Recommendations

The 1,500 meter buffer zone between the dumpsite boundary and the boreholes from which drinking water is extracted should be made a national standard for all Nigerian unlined waste disposal facilities overlying the Benin Formation aquifer. Those living within 1,000 meters should be given priority access to a safe, treated, and piped water supply, or a point-of-use treatment system such as reverse osmosis/ion exchange. A biannual GWQ monitoring program should be developed, with WQI and HI calculations conducted for sentinel boreholes 100 m, 250 m, 500 m, and 1,000 m radial distance from the dumpsite. Given child HI values exceeding 8.0 at proximate locations, a pediatric blood metal screening program is urgently recommended for children under 12 residing within 500 meters, in partnership with Edo State Primary Healthcare Development Agency.

CONCLUSION

This study provides the first WQI-based composite water quality assessment and USEPA-protocol human health risk analysis for dumpsite-affected groundwater in the Benin Formation hydrogeological setting. None of the boreholes within 500 meters from the pollution source have water suitable for human consumption. Spatial decay modeling reveals contamination of the groundwater in a much wider band, ranging from 850 to 2,200 meters, depending on the type of metal analyzed. This finding demonstrates that risk zones created using a spatial decay model can greatly extend the contamination area as opposed to a more attenuating geological formation. Thus, the frameworks of WQI and Human Health Risk Assessment developed here offer replicable and internationally recognized methods that Nigeria's regulators can utilize for transitioning from snapshot monitoring into risk-based water management. Limitations associated with this study include a single-season monitoring period, lack of borehole vertical profiling, total rather than speciated Chromium, and an absence of reference well upstream.

Author Contributions

M.E.O., Conceptualization, data collection, laboratory analyses, writing—original draft.

A.D.O., methodology validation, writing—review and editing.

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Competing Interests

The authors declare no competing interests in relation to this manuscript.

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