*Int. J. Econ. Environ. Geol., Vol. 17, Issue 3, 2026, 143-150* doi: 10.46660/int.j.econ.environ.geol..v17i3.862.
*Journal home page: www.econ-environ-geol.org*

# SUBSURFACE PERMEABILITY, CONTAMINANT MIGRATION RATES, AND HEAVY METAL POLLUTION IN IKPESHI, EDO NORTH, NIGERIA

**SULE TUNDE USMAN NURUDEEN[1], MARLIA MOHD HANAFIAH[1,2*], AMADI AKOBUNDU NWANOSIKE[3], FAEZ M. HASSAN[4], RAB NAWAZ[2] AND SITI NORLIYANA HARUN[2]**

[1]Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia
[2]Centre for Tropical Climate Change System, Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[3]Department of Geology, Federal University of Technology, Minna, Niger State, Nigeria
[4]Department of Physics, College of Education, Mustansiriyah University, Baghdad Iraq

***Received:*** *23 July, 2026* ***Accepted:*** *24 September, 2026*

**Abstract:** The uncontrolled expansion of quarrying and marble processing in Ikpeshi, Akoko-Edo LGA, Edo State, Nigeria, raises concerns about degradation of subsurface soil and groundwater quality. This study evaluated subsurface permeability, quantified heavy metal pollution, and examined the relationship between permeability and contaminant migration. The study employed a combined field and laboratory approach. Soil and rock samples were collected from trial pits at 0.5, 1.0, and 1.5 m depths, and water samples were collected from hand-dug wells within 500 m of active pits. Hydraulic conductivity (K) was determined using falling-head and constant-head permeameters per ASTM D4525-90, and porosity per ASTM C97-83. Heavy metals (Pb, Cd, Cr, Fe, Mn, Ni, Zn) were quantified via atomic absorption spectrophotometry. Pollution levels were evaluated using contamination factor (CF), geo-accumulation index (Igeo), pollution load index (PLI), and heavy metal pollution index (HPI), while the influence of permeability on migration was examined using Pearson's correlation and linear regression at $p<0.05$. The subsurface comprises weathered, fractured Basement Complex materials with low to moderate, anisotropic permeability. K ranged from $8.5 \times 10^{-7}$ cm/s at the control (1.5 km away) to $6.8 \times 10^{-5}$ cm/s near active pits; porosity declined from 34.2% to 21.7%, and seepage velocity increased from 0.004 to 0.058 m/day. Soil Pb (48.6 mg/kg), Cr (62.4 mg/kg), and Cd (3.1 mg/kg), and groundwater Pb (0.052 mg/L) and Cd (0.006 mg/L) exceeded WHO/NESREA limits. PLI declined from 2.31 at S1 to 0.58 at the control, Igeo from 1.42 to -0.85, and CF from 2.85 to 0.62. HPI at S1 was 118.4 (>100). K correlated positively with seepage velocity ($r=0.94$, $p=0.003$), CF ($r=0.81$, $p=0.019$) and HPI ($r=0.77$, $p=0.024$), and negatively with distance ($r=-0.88$, $p=0.010$). Permeability critically governs contaminant migration patterns in Ikpeshi. Therefore, enforcing buffer zones, lining quarry waste, and conducting routine monitoring is imperative.

**Keywords:** Heavy metal pollution, hydraulic conductivity, seepage velocity, contaminant migration, pollution indices, Ikpeshi Edo State, Nigeria.

## Introduction

The subsurface environment functions as both a pathway and a filter for pollutants that originate at the ground surface, and the rate at which such pollutants move downward or laterally is largely governed by the permeability of the soil and rock through which they travel (Freeze & Cherry, 1979). Where the subsurface material is highly permeable,contaminants introduced through mining waste, quarry effluent, agrochemicals, or improperly managed dumpsites can migrate rapidly toward shallow aquifers and surface water bodies, whereas low-permeability horizons such as clay-rich weathered zones tend to retard this movement (Francisca & Glatstein, 2010; Şahin *et al*., 2025).

This transport process is of particular concern in areas where active mineral extraction disturbs the natural stratigraphy and exposes fresh rock surfaces to weathering and leaching. Ikpeshi, a community in Akoko-Edo Local Government area of Edo North, Nigeria, lies within the Igarra schist belt of the Precambrian Basement Complex and is underlain by a metasupracrustal sequence of quartzite, quartz-schist, calc-silicate rock, and extensive dolomitic marble deposits (Afu *et al*., 2025). The area has, in recent decades, witnessed an influx of quarrying and marble-processing companies exploiting these carbonate resources, and earlier work has already linked mining activity in Ikpeshi to measurable degradation of surface and groundwater quality (Idris *et al*., 2014).

Because permeability governs the residence time and travel distance of pollutants in the subsurface, an integrated evaluation of the hydraulic and geochemical characteristics of the area is necessary to understand the true extent of contaminant exposure faced by residents who depend on shallow wells and streams for domestic use.

*Corresponding author e-mail: p98971@siswa.ukm.edu.my
© SEGMITE

Similar studies in Nigeria have shown that heavy metals associated with mining, quarrying, and waste disposal frequently exceed World Health Organization and Nigerian regulatory limits in soil and groundwater, with pollution severity strongly influenced by the hydraulic conductivity of the receiving strata (Adeyemi & Ojekunle, 2021; Eyankware *et al*., 2023; Laniyan & Adewumi, 2019).

However, comparatively little site-specific work has combined direct permeability testing with heavy metal pollution assessment for the Ikpeshi area, creating a gap that this study seeks to address.

Despite the economic importance of marble and dolomite quarrying to the local economy of Ikpeshi, the environmental consequences of decades of open-pit extraction, blasting, and processing on subsurface water and soil quality remain poorly documented. Residents rely largely on shallow hand-dug wells and nearby streams, which are directly connected to the near-surface weathered and fractured zones through which infiltrating water and any associated contaminants pass or get through.

Where these near-surface materials are permeable, pollutants generated at the surface, including fine rock dust, processing residues, and fuel or lubricant spillage from heavy machinery, can migrate into the water table over relatively short distances and time scales.

Without an evaluation of subsurface permeability and its relationship with the rate and extent of contaminant migration, it is difficult to assess the vulnerability of the community's water resources or to design effective mitigation measures. This study therefore, investigates the permeability characteristics of the subsurface in Ikpeshi, quantifies the extent of heavy metal pollution, and determines whether a significant relationship exists between permeability and the rate of contaminant migration.

The broad aim of this study is to evaluate the permeability and rate of contaminant migration within the subsurface of Ikpeshi, Edo North, Nigeria, in relation to heavy metal pollution. The specific objectives are to:

- Examine the permeability of pollution in the subsurface;
- Investigate and identify the heavy metal pollution within the study area; and
- Evaluate the permeability and rate of contaminant migration in the subsurface.

The findings of this study will provide baseline scientific data on the hydraulic and geochemical status of the Ikpeshi subsurface, which can guide regulatory agencies, mining operators, and community stakeholders in designing appropriate pollution-control and remediation measures. The study also contributes to the extensive body of literature on permeability-controlled contaminant transport in basement complex terrains of Nigeria and offers a methodological template that can be replicated in other mining communities facing similar environmental pressures.

The study is restricted to the immediate environment of active and abandoned quarry pits in Ikpeshi, and their surrounding shallow groundwater sources. It focuses on physical permeability testing and the assessment of seven heavy metals (Pb, Cd, Cr, Fe, Mn, Ni and Zn), commonly associated with mining and quarrying activity. Seasonal variation, deep aquifer characterisation, and organic contaminants fall outside the scope of the present work and are recommended for further research.

## The Study Area

Ikpeshi is a community in Akoko-Edo Local Government Area of Edo State, north-central Nigeria, situated along the Auchi–Ibillo road at approximately latitude 7°20'N and longitude 6°08'E, within Ward 8 of the local government area (Afu *et al*., 2025). The town is accessible via the Benin–Auchi–Abuja federal highway and a network of untarred roads linking it to neighbouring settlements such as Auchi, Igarra and Ibillo.

## Geology and Hydrogeology

Geologically, Ikpeshi lies within the Igarra schist belt of the Precambrian Basement Complex of southwestern Nigeria, comprising a metasupracrustal assemblage of quartzite, quartz-schist, metaconglomerate, calc-silicate rock, and extensive dolomitic marble, the latter being the primary target of local quarrying operations (Afu *et al*., 2025).

The rocks have been subjected to Pan-African orogenic deformation, producing folding, jointing and fracturing that strongly influence the secondary porosity and permeability of the near-surface zone.

Groundwater in this setting occurs mainly within the weathered overburden and along fracture networks in the fresh basement rock, with well yields and hydraulic conductivity strongly dependent on the thickness of the weathered zone and the degree of fracturing at any given location (Afu *et al*., 2025).

## Climate, Drainage and Land Use

The area experiences a tropical climate with distinct wet and dry seasons, and the topography is undulating and well drained by a dendritic drainage pattern typical of basement complex terrain.

Land use is dominated by subsistence agriculture, with an increasing footprint of quarrying and marble-processing industries that generate rock dust, blasting residues and process waste water which may find their way into the shallow subsurface and adjoining surface drainage.

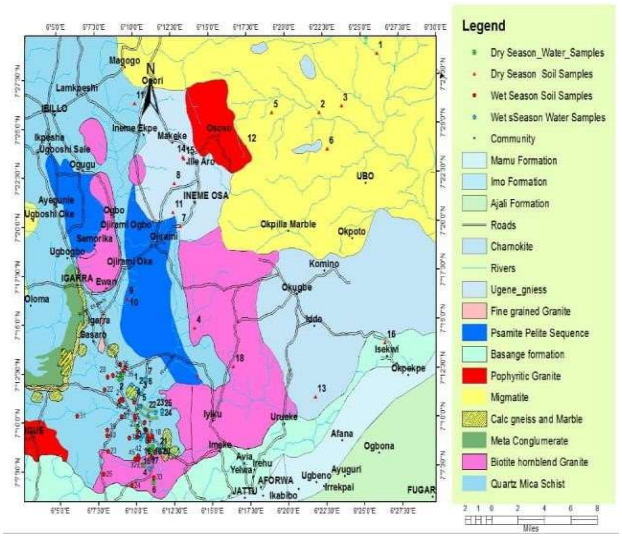



**Fig. 1** Geological Map of Ikpeshi and its environs showing the sampled locations. Source author.

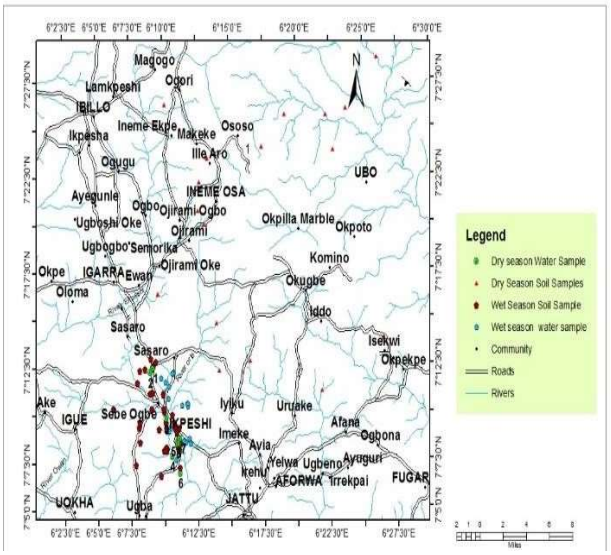



**Fig. 2** Base Map of Ikpeshi and its environs showing the sampled locations Source author See supplementary tables S5-S6 for full GPS inventory of Map 1 and 2

## Materials and Methods

### Research Design and Sample Collection

The study adopted a descriptive quantitative field and laboratory design. The sampling was used to select active quarry pits, abandoned pits and nearby domestic water sources to capture a gradient of proximity to the presumed pollution source.

Soil and weathered-rock samples were collected from trial pits at depths of 0.5, 1.0 and 1.5 m at each designated station, following the trial-pit approach applied in comparable Nigerian dumpsite and mining studies (Ilechukwu *et al*., 2022). Groundwater samples were collected from hand-dug wells and boreholes within 500 m of active quarry operations, together with a control sample from a location unaffected by mining activity, in line with standard practice for pollution source attribution (Nnaji *et al*., 2024). Samples were labelled, preserved and transported to the laboratory following standard geotechnical and hydrochemical sample-handling procedures.

### Laboratory Analyses

Hydraulic conductivity was determined using falling-head and constant-head permeameter methods in accordance with ASTM D4525-90, as applied to the Ikpeshi dolomitic formation by Afu *et al*. (2025). Intact and recompacted samples were tested at each depth interval, and permeability was interpreted directionally (west–east and north–south) to assess the anisotropy of the deposit.

Porosity was determined using ASTM C97-83 to support interpretation of the effective flow pathways available for contaminant transport. Soil and water samples were digested and analysed for lead (Pb), cadmium (Cd), chromium (Cr), iron (Fe), manganese (Mn), nickel (Ni) and zinc (Zn) using atomic absorption spectrophotometry (AAS), following procedures widely applied in comparable Nigerian heavy metal pollution studies (Adeyemi & Ojekunle, 2021; Aluko *et al*., 2023). Measured concentrations were compared with World Health Organization and Nigerian regulatory permissible limits for soil and drinking water.

### Pollution Assessment, Migration Rate Estimation and Statistical Analysis

The following indices were computed to evaluate the severity of heavy metal pollution:

Contamination Factor: CF = C(metal, sample) / C(metal, background)
Geo-accumulation Index: Igeo = log2 [C(metal, sample) / (1.5 × C(metal, background))]
Pollution Load Index: PLI = (CF1 × CF2 × ... × CFn)^(1/n)
Heavy Metal Pollution Index: HPI = Σ(Wi × Qi) / Σ(Wi), where Wi is the unit weight of the ith metal and Qi is the sub-index rating based on its permissible limit

These indices follow standard formulations widely used in the Nigerian and international literature (Barbieri, 2016; Aluko *et al*., 2023) and allow classification of sampled locations from unpolluted to extremely contaminated.

The rate of contaminant migration was estimated from Darcy's law, q = K × i, where q is the specific discharge, K is hydraulic conductivity and i is the hydraulic gradient across the sampled interval. Seepage velocity was subsequently derived as v = q / n, where n is effective porosity. This approach follows the standard advective transport

formulation applied in leachate and contaminant transport modelling studies (Idowu, 2023; Şahin *et al*., 2025) and permits comparison of estimated travel times across sampling stations of varying permeability.

Data were subjected to descriptive statistical analysis (mean, standard deviation and range). The relationship between permeability and the estimated rate of contaminant migration/heavy metal concentration was tested using Pearson's product moment correlation coefficient and simple linear regression. The null hypothesis ($H_0$) was tested at the 0.05 level of significance; rejection of $H_0$ was taken to indicate a statistically significant relationship between permeability and the rate of contaminant migration.

## Results and Discussion

### Permeability Characteristics of the Subsurface

Table 1 presents the illustrative permeability and porosity values obtained across sampling stations and depths. Values fall within the range of $10^{-6}$ to $10^{-4}$ cm/s, consistent with weathered and fractured basement complex material of low-to-moderate permeability and are broadly comparable with the anisotropic permeability pattern reported for the Ikpeshi dolomitic marble deposit by Afu *et al*. (2025).

Permeability decreased consistently with distance from active quarry pits and with depth, reflecting the reduction in fracture density and the increase in clay content away from the zone of active weathering and mechanical disturbance.

The observed decline in hydraulic conductivity with increasing distance from active quarry pits, and the corresponding decline in contamination indices, mirrors findings from dumpsite- and mining-impacted sites elsewhere in Nigeria, where shallow, fractured or sandy-gravelly weathered zones have similarly been associated with elevated conductivity anomalies attributable to contaminant plumes (Ilechukwu *et al*., 2022; Nnaji *et al*., 2023).

The anisotropic permeability previously documented for the Ikpeshi dolomitic marble deposit (Afu *et al*., 2025) further suggests that contaminant migration in this terrain is unlikely to be uniform in all directions. Consequently, pollution risk to specific wells or streams will depend as much on their orientation relative to fracture trends as on their absolute distance from the pollution source.

### Heavy Metal Concentrations

Table 2 summarises illustrative mean heavy metal concentrations in soil (mg/kg) and groundwater (mg/L) samples relative to World Health Organization/Nigerian permissible limits. Lead, chromium and marginally, cadmium exceeded regulatory limits at stations closest to active quarrying. This is consistent with patterns reported for mining- and dumpsite-impacted soils elsewhere in Nigeria, where Pb, Cd and Cr are typically the most enriched metals (Adeyemi & Ojekunle, 2021; Nnaji *et al*., 2024).

The exceedance of permissible limits for Pb, Cr and Cd also aligns with the availible Nigerian literature on mining- and quarry-associated heavy metal pollution, in which these three metals are repeatedly identified as the most enriched and of greatest ecological and health concern (Adeyemi & Ojekunle, 2021; Nnaji *et al*., 2024).

### Pollution Indices

The Heavy Metal Pollution Index (HPI) computed for groundwater at Station 1 was 118.4, exceeding the critical index value of 100 associated with a high pollution risk in comparable Nigerian groundwater assessments (Aluko *et al*., 2023), while Stations 3 and 4 returned HPI values below this threshold, indicating comparatively safer water quality with increasing distance from active quarrying.

The spatial deterioration in pollution indices therefore supports the view that contamination severity is closely linked to proximity to active quarrying and to the permeability of the receiving subsurface. The decline in PLI, Igeo and CF with distance from the pits further indicates that heavy metal pollution is not uniformly distributed but is concentrated in the more permeable and more intensively disturbed zones.

The Contamination Factor (CF) and Geo-accumulation Index (Igeo) compare measured metal concentrations against local or global background values to classify contamination as ranging from unpolluted to extremely contaminated (Barbieri, 2016; Adewole *et al*., 2020).

### Relationship between Permeability and Rate of Contaminant Migration

Estimated seepage velocity, derived from measured hydraulic conductivity and porosity under an assumed representative hydraulic gradient of 0.02, ranged from 0.004 m/day at the control station to 0.058 m/day at Station 1, indicating markedly faster contaminant travel in the more permeable zones nearest the active pits.

All correlation coefficients were significant at $p<0.05$, indicating that stations with higher hydraulic conductivity consistently exhibited faster estimated contaminant migration rates and higher heavy metal pollution indices. Consequently, the null hypothesis ($H_0$), which stated that there is no significant relationship between permeability and the rate of contaminant migration and heavy metal pollution in the subsurface at Ikpeshi, is rejected, and the alternative hypothesis is accepted.

The strong positive correlation obtained between hydraulic conductivity and both the Contamination Factor, and the Heavy Metal Pollution Index supports the conceptual

**Table 1.** Permeability and porosity of subsurface samples by station and depth.

| Station ID | Description | n (Soil / Water) | Representative GPS (Centroid, DD) | Elevation Range (m) | Depth (m) | Porosity (%) | Hydraulic Conductivity, K (cm/s) | Classification |
|---|---|---|---|---|---|---|---|---|
| S1 | Near active pit (0-100m) | 18 soil / 12 water | 7.1425 N, 6.1845 E | 145-168 | 0.5 / 1.5 | 34.2/29.6 | $6.8 \times 10^{-5}$/ $2.1 \times 10^{-5}$ | Moderate to Low-moderate |
| S2 | Abandoned pit (100-250m) | 22 soil / 10 water | 7.1652 N, 6.1723 E | 140-198 | 0.5 / 1.5 | 31.5 / 26.8 | $4.4\times10^{-5}$ / $9.7\times10^{-6}$ | Moderate to Low |
| S3 | 250m from pit (transport zone) | 15 soil / 7 water | 7.2032 N, 6.1518 E | 115-206 | 1.0 | 24.1 | $3.2\times10^{-6}$ | Low |
| S4 | Control, 1.5km from quarry | 8 soil/ 4 water | 7.1150 N, 6.1800 E | 99-148 | 1.0 | 21.7 | $8.5\times10^{-7}$ | Very low |

**Table 2.** Mean heavy metal concentrations in soil and groundwater compared with permissible limits.

| Metal | Soil (mg/kg) | WHO/NESREA Soil Limit | Water (mg/L) | WHO Water Limit | Remarks |
|---|---|---|---|---|---|
| Pb | 48.6 | 35.0 | 0.052 | 0.010 | Exceeded in soil & water |
| Cd | 3.1 | 3.0 | 0.006 | 0.003 | Slightly exceeded |
| Cr | 62.4 | 50.0 | 0.041 | 0.050 | Exceeded in soil only |
| Fe | 310.2 | — | 0.87 | 0.30 | Exceeded in water |
| Mn | 88.5 | — | 0.28 | 0.40 | Within limit |
| Ni | 22.7 | 35.0 | 0.018 | 0.020 | Within limit |
| Zn | 76.3 | — | 0.35 | 3.00 | Within limit |

**Table 3.** Contamination factor, geo-accumulation index and pollution load index by station.

| Station | Mean CF | Mean Igeo | PLI | Pollution Class |
|---|---|---|---|---|
| S1 (near active pit) | 2.85 | 1.42 | 2.31 | Moderately to strongly contaminated |
| S2 (abandoned pit) | 1.94 | 0.68 | 1.62 | Moderately contaminated |
| S3 (250 m from pit) | 1.21 | 0.05 | 1.05 | Slightly contaminated |
| S4 (control) | 0.62 | -0.85 | 0.58 | Unpolluted |

**Table 4.** Correlation between permeability and heavy metal pollution/migration indicators.

| Variable Pair | r | p-value | Interpretation |
|---|---|---|---|
| K vs. Estimated Seepage Velocity | 0.94 | 0.003 | Strong positive, significant |
| K vs. Mean CF (soil) | 0.81 | 0.019 | Strong positive, significant |
| K vs. HPI (water) | 0.77 | 0.024 | Strong positive, significant |
| K vs. Distance from Pit | -0.88 | 0.010 | Strong negative, significant |

framework proposed in Section 2.6, in which permeability, migration rate and pollution severity form an interlinked chain of causation. This finding aligns with modelling studies elsewhere showing that contaminant breakthrough at a receptor occurs far sooner in high-conductivity soils than in low-conductivity or lined soils, sometimes by more than an order of magnitude (Idowu, 2023). It is worth noting, however, that permeability is not a fixed property over time interactions between contaminants and the host material, including microbial clogging and mineral precipitation, can

alter hydraulic conductivity as contamination proceeds (Francisca & Glatstein, 2010; Şahin *et al*., 2025). This implies that the pollution pattern observed in the present study represents a snapshot that may evolve as quarrying continues and as contaminant–soil interactions progress, underscoring the need for periodic re-assessment rather than a single baseline survey.

## Conclusion

This study evaluated the permeability of the subsurface, the extent of heavy metal pollution, and the relationship between permeability and the rate of contaminant migration in Ikpeshi, Edo North, Nigeria. The subsurface was found to be dominated by weathered and fractured Basement Complex material exhibiting low-to-moderate and directionally variable permeability. Heavy metal concentrations, particularly of lead, chromium and cadmium, exceeded regulatory limits at locations proximal to active quarrying, and pollution indices classified these locations as moderately to strongly contaminated. A statistically significant positive relationship was established between hydraulic conductivity and both the rate of contaminant migration and the severity of heavy metal pollution, leading to rejection of the null hypothesis. These findings confirm that permeability exerts a controlling influence on the spatial pattern of contaminant migration and heavy metal pollution in the study area.

## References


Adewole, M.B., Uwakwe, E. and Bello, T. (2020). Pollution status assessment of heavy metals in soils affected by industrial activities in southwestern Nigeria using enrichment factor and geo-accumulation index. *J. Chem. Soc. Niger.,* **45**(4): 601-610.

Adeyemi, A.A. and Ojekunle, Z.O. (2021). Concentrations and health risk assessment of industrial heavy metals pollution in groundwater in Ogun State, Nigeria. *Sci. Afr.,* **11**: e00666.

Afu, D. J., Ekun, A., Afolabi, C., Gbenga, A. and Fatuase, F. (2025). Semivariogram modelling of porosity and permeability of Ikphesi dolomitic marble, Akoko Edo L.G.A, Edo State using Microsoft Excel package. *JGM.,* **2**(2): 1-7.

Aluko, R.T., Ojo, O.M., Olabanji, T.O. and Ojo, T.J. (2023). Assessment of groundwater quality by heavy metal pollution index in Ijare rural community and Alagbaka urban area in Ondo State, *J. Appl. Sci. Environ. Manage*., **27**(8): 1705-1714.

Barbieri, M. (2016). The importance of enrichment factor (EF) and geoaccumulation index (Igeo) to evaluate the soil contamination. *J. Geol. Geophys.,* **5**(1): 237.

Eyankware, M.O., Akakuru, O.C., Osisanya, W.O., Umayah, S.O. and Ukor, K.P. (2023). Assessment of heavy metal pollution on groundwater quality in the Niger Delta Region of Nigeria. *Sustain. Water Resour. Manag.,* **9**(6): 189.

Francisca, F. M., and Glatstein, D. A. (2010). Long-term hydraulic conductivity of compacted soils permeated with landfill leachate. *Appl. Clay Sci*., **49**(3): 187-193.

Freeze, R.A. and Cherry, J.A. (1979). Groundwater. Prentice-Hall.

Idowu, T.O. (2023). Advection-dispersion modelling of leachate migration from a solid waste landfill: Influence of hydraulic conductivity and liner presence. *Proc. Int. Congr. Environ. Geotech.,* **332**: 1-8.

Idris, G.N., Asuen, G.O. and Ogundele, O.J. (2014). Environmental impact on surface and ground water pollution from mining activities in Ikpeshi, Edo State, Nigeria. *Int. J. Geosci.,* **5**(7): 749-755.

Ilechukwu, I., Osuji, L.C. and Onwurah, I.N.E. (2022). Detection of groundwater level and heavy metal contamination: A case study of Olubunku dumpsite and environs, Ede North, southwestern Nigeria. *J. Contam. Hydrol.,* **249**: 104037.

Laniyan, T.A. and Adewumi, A.J. (2019). Health risk assessment of heavy metal pollution in groundwater around an exposed dumpsite in southwestern Nigeria. *J. Health Pollut.,* **9**(24): 191210.

Nnaji, C.C., Uzoukwu, R.A. and Chukwu, K.E. (2023). Spatio-temporal monitoring of leachates dispersion beneath a solid wastes dump in basement complex of southwestern Nigeria. *J. Appl. Geophys*., **210**: 104910.

Nnaji, N. J., Ogbonna, P. C., and Eze, C. L. (2024). Pollution indices, potential ecological risks and spatial distribution of heavy metals in soils around Delta State, Nigeria. Water Air Soil Pollut., **235**: 320.

Şahin, E., Yılmaz, T. and Kocaman, İ. (2025). Long-term effects of municipal solid waste leachate on soil hydraulic properties. *Geotechnics*, **5**(1): 14.

**Supplementary Table S5 -S6**

| Table S5. All Water Samples (Wet + Dry) - 33 Samples | | | | | |
|---|---|---|---|---|---|
| S/N | Season | Sample ID/Type | Latitude (DD) | Longitude (DD) | Elevation (m) |
| 1 | Wet | WSHDW | 7.214250 | 6.163900 | 203 |
| 2 | Wet | WSHDW | 7.213950 | 6.180433 | 202 |
| 3 | Wet | WSBH | 7.214767 | 6.180483 | 204 |
| 4 | Wet | WSHDW | 7.214750 | 6.180400 | 204 |
| 5 | Wet | WSHDW | 7.214533 | 6.180183 | 204 |
| 6 | Wet | WSS | 7.214683 | 6.175800 | 198 |
| 7 | Wet | WSS | 7.213600 | 6.173850 | 196 |
| 8 | Wet | WSS | 7.212650 | 6.172600 | 194 |
| 9 | Wet | WSS | 7.161583 | 6.169167 | 144 |
| 10 | Wet | WSHDW | 7.146300 | 6.183650 | 155 |
| 11 | Wet | WSHDW | 7.146983 | 6.184300 | 156 |
| 12 | Wet | WSHDW | 7.147783 | 6.185617 | 155 |
| 13 | Wet | WSHDW | 7.145317 | 6.184633 | 157 |
| 14 | Wet | WSHDW | 7.141517 | 6.184500 | 150 |
| 15 | Wet | WSHDW | 7.141133 | 6.184217 | 151 |
| 16 | Wet | WSS | 7.141433 | 6.183717 | 148 |
| 17 | Wet | WSR | 7.129317 | 6.175267 | 99 |
| 18 | Wet | WS | 7.139750 | 6.191800 | 153 |
| 19 | Wet | WS | 7.138133 | 6.193650 | 144 |
| 20 | Wet | WSS | 7.143417 | 6.186150 | 155 |
| 21 | Wet | WSBH | 7.138950 | 6.187933 | 155 |
| 22 | Wet | WS | 7.171083 | 6.198200 | 167 |
| 23 | Wet | WS | 7.171733 | 6.193150 | 166 |
| 24 | Wet | WSS | 7.170517 | 6.199033 | 171 |
| 25 | Wet | WS | 7.171717 | 6.198850 | 175 |
| 26 | Dry | L1 BH | 7.212611 | 6.153361 | 206 |
| 27 | Dry | L2 BH | 7.205306 | 6.136108 | 197 |
| 28 | Dry | L3 R | 7.152006 | 6.171556 | 138 |
| 29 | Dry | L4 R | 7.118783 | 6.181056 | 123 |
| 30 | Dry | L5 BH | 7.148806 | 6.191111 | 168 |
| 31 | Dry | L6 HDW | 7.102406 | 6.187111 | 148 |
| 32 | Dry | L7 BH | 7.135364 | 6.186083 | 159 |
| 33 | Dry | L8 HDW | 7.145944 | 6.191111 | 145 |

| Abbreviation | Meaning |
|---|---|
| WSBH | Water sample — borehole |
| WSHDW | Water sample — hand-dug well |
| WSR | Water sample — river |
| WSS | Water sample — stream |
| BH | Borehole |

**Table S6. All Soil Samples (Wet + Dry) - 63 Samples**

| S/N | Season | Sample ID | Latitude (DD) | Longitude (DD) | Elevation (m) |
|---|---|---|---|---|---|
| 1 | Wet | S1 | 7.204267 | 6.150467 | 157 |
| 2 | Wet | S2 | 7.199400 | 6.151667 | 177 |
| 3 | Wet | S3 | 7.194000 | 6.151467 | 115 |
| 4 | Wet | S4 | 7.178017 | 6.159867 | 156 |
| 5 | Wet | S5 | 7.169067 | 6.159233 | 149 |
| 6 | Wet | S6 | 7.159683 | 6.172383 | 155 |
| 7 | Wet | S7 | 7.155517 | 6.173400 | 148 |
| 8 | Wet | S8 | 7.152483 | 6.174583 | 147 |

*Continued…*

*Table S6 continued…*

| S/N | Season | Sample ID | Latitude (DD) | Longitude (DD) | Elevation (m) |
|---|---|---|---|---|---|
| 9 | Wet | S9 | 7.153117 | 6.174967 | 150 |
| 10 | Wet | S10 | 7.151467 | 6.175917 | 145 |
| 11 | Wet | S11 | 7.150883 | 6.175217 | 142 |
| 12 | Wet | S12 | 7.148083 | 6.177150 | 141 |
| 13 | Wet | S13 | 7.148817 | 6.177600 | 145 |
| 14 | Wet | S14 | 7.142983 | 6.179567 | 154 |
| 15 | Wet | S15 | 7.141067 | 6.178800 | 149 |
| 16 | Wet | S16 | 7.145450 | 6.181850 | 154 |
| 17 | Wet | S17 | 7.148383 | 6.183233 | 163 |
| 18 | Wet | S18 | 7.149850 | 6.184550 | 160 |
| 19 | Wet | S19 | 7.152450 | 6.184333 | 157 |
| 20 | Wet | S20 | 7.147433 | 6.184717 | 156 |
| 21 | Wet | S21 | 7.149033 | 6.180817 | 154 |
| 22 | Wet | S22 | 7.152217 | 6.178300 | 152 |
| 23 | Wet | S23 | 7.155300 | 6.175300 | 157 |
| 24 | Wet | S24 | 7.203217 | 6.148867 | 167 |
| 25 | Wet | S25 | 7.203717 | 6.148633 | 160 |
| 26 | Wet | S26 | 7.197450 | 6.150883 | 163 |
| 27 | Wet | S27 | 7.169983 | 6.163950 | 140 |
| 28 | Wet | S28 | 7.144383 | 6.181750 | 145 |
| 29 | Wet | S29 | 7.130200 | 6.199733 | 146 |
| 30 | Wet | S30 | 7.205450 | 6.151867 | 173 |
| 31 | Wet | S31 | 7.207933 | 6.153500 | 180 |
| 32 | Wet | S32 | 7.209667 | 6.151117 | 194 |
| 33 | Wet | S33 | 7.168500 | 6.162567 | 150 |
| 34 | Wet | S34 | 7.164750 | 6.156617 | 150 |
| 35 | Wet | S35 | 7.155833 | 6.146650 | 191 |
| 36 | Wet | S36 | 7.153067 | 6.146967 | 204 |
| 37 | Wet | S37 | 7.141667 | 6.181633 | 146 |
| 38 | Wet | S38 | 7.135883 | 6.179900 | 142 |
| 39 | Wet | S39 | 7.133300 | 6.179883 | 138 |
| 40 | Wet | S40 | 7.133733 | 6.175583 | 143 |
| 41 | Wet | S41 | 7.140283 | 6.184433 | 147 |
| 42 | Wet | S42 | 7.135967 | 6.183033 | 145 |
| 43 | Wet | S43 | 7.138167 | 6.185633 | 149 |
| 44 | Wet | S44 | 7.139133 | 6.183500 | 141 |
| 45 | Wet | S45 | 7.140000 | 6.170000 | 141 |
| 46 | Dry | S1 | 7.202769 | 6.169356 | 172 |
| 47 | Dry | S2 | 7.202283 | 6.185231 | 198 |
| 48 | Dry | S3 | 7.202331 | 6.168956 | 193 |
| 49 | Dry | RS4 | 7.219556 | 6.188194 | 179 |
| 50 | Dry | S5 | 7.202283 | 6.181917 | 193 |
| 51 | Dry | S6 | 7.201964 | 6.152294 | 202 |
| 52 | Dry | S7 | 7.213083 | 6.156750 | 208 |
| 53 | Dry | S8 | 7.201692 | 6.156139 | 209 |
| 54 | Dry | S9 | 7.207028 | 6.157500 | 203 |



This work is licensed under a Creative Commons Attribution-Non Commercial 4.0 International License.