



doi:10.5281/zenodo.19280437

Multivariate Analysis of Groundwater Chemistry in Benin City: Atmospheric, Health and Environmental Perspectives

¹Asagha, E. N., ²Ngang, B. U., & ³Akporode, M.

Federal College of Education (Technical) Ekiadolor, PMB 1206 Benin City, Nigeria.

²Corresponding Author's Email: bngresearch4@gmail.com

ABSTRACT

This study investigates the multivariate characteristics of groundwater in Benin City, Nigeria, emphasizing atmospheric, health, and environmental implications. A total of 200 groundwater samples were analyzed for physicochemical parameters, major ions, and trace elements. Results revealed widespread acidity (pH range: 4.1–6.5), with lead (Pb) and aluminum (Al) concentrations exceeding WHO standards in New Benin and adjacent locations. Sulfate, nitrate, and chloride concentrations were within permissible limits, while variations in electrical conductivity (EC) and total dissolved solids (TDS) reflected geogenic and anthropogenic contributions. Multivariate techniques, including Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), identified key contamination sources, including atmospheric deposition, urban runoff, and lithogenic processes. The findings highlight critical implications for public health, atmospheric physics, analytical chemistry, hydrochemistry, and industrial applications, necessitating targeted policy measures and interdisciplinary research interventions. **Keywords:** Groundwater chemistry, atmospheric deposition, hydrochemistry, trace-metals contamination, health implications, environmental pollution.

1.0. INTRODUCTION

Groundwater is the primary source of potable water for millions in Benin City, Nigeria. Increasing urbanization, industrialization, and climate variability threaten its quality through processes such as acid deposition, trace metal contamination, and leaching. Acidified groundwater not only affects palatability but also exacerbates metal mobilization, increasing human exposure to toxic elements like lead and aluminum (Ngang, Agbazue, & Ihedioha, 2019).

Globally, studies have reported critical health risks associated with acidic pH and trace metal pollution in aquifers. Chronic exposure to lead has been linked to neurological dysfunction and anemia, while aluminum is implicated in neurodegenerative disorders such as Alzheimer's disease (USEPA, 2023; Santos, Dias, & Welch, 2022). In addition, urban expansion has amplified anthropogenic influences on aquifer systems, necessitating an integrated assessment of groundwater contamination sources and their implications (Adimalla & Qian, 2021).

This study integrates analytical chemistry, atmospheric physics, hydrochemistry, and health perspectives to provide a comprehensive assessment of groundwater quality in Benin City. Using multivariate statistical techniques, this research delineates contamination pathways while exploring implications for environmental sustainability, industrial applications, and public health.

2.0. METHODOLOGY

Study Area

Benin City is situated in Nigeria's tropical rainforest zone, characterized by sandy-loamy soils and heavy rainfall (~2000 mm/year). Its expanding population and industrial growth amplify stress on groundwater resources, necessitating systematic monitoring.

Sample Collection and Analysis

Two hundred groundwater samples were collected from boreholes and hand-dug wells across seven zones: Isihor, Ikpoba, Ringroad, New Benin, Ekosodin, Adolor, and Medical. Parameters analyzed included:

Physicochemical: pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, total hardness, alkalinity.

Major Ions: sulfate (SO_4^{2-}), nitrate (NO_3^-), chloride (Cl^-), phosphate (PO_4^{3-}).

Trace Elements: lead (Pb), aluminum (Al), arsenic (As).

Analytical procedures followed standardized methods (APHA, 2023), employing atomic absorption spectrometry (AAS) for trace metals and ion chromatography for major ions. Quality control measures included duplicate sampling, blank tests, and calibration using certified reference materials.

Statistical Analysis

Multivariate statistical tools applied include:

1. Principal Component Analysis (PCA) to reduce data dimensionality and identify dominant contamination sources using factor loadings.
2. Hierarchical Cluster Analysis (HCA) to classify contamination profiles based on Euclidean distances and Ward's linkage.

3.0 RESULTS

Physicochemical Parameters

Groundwater pH ranged between 4.12 and 6.5, with New Benin exhibiting the most acidic conditions (pH: 4.12). Electrical conductivity (EC) values varied from 9 $\mu\text{S}/\text{cm}$ in Isihor to 232 $\mu\text{S}/\text{cm}$ in New Benin, while total dissolved solids (TDS) ranged from 4.5 to 116 mg/L. Both EC and TDS levels remained below WHO permissible limits, indicating moderate ionic strength.

Alkalinity was notably low (<6.18 mg/L), reflecting limited buffering capacity against acid inputs. Turbidity levels ranged from 0.19 NTU (Isihor) to 4.87 NTU (New Benin), largely influenced by urban storm water infiltration.

Major Ions and Trace Elements

Major ion concentrations (sulfate, nitrate, chloride, phosphate) were compliant with WHO standards. However, trace element analysis identified elevated lead (0.018 mg/L) and aluminum (0.044 mg/L) levels at New Benin, exceeding WHO thresholds for drinking water (Pb: 0.01 mg/L; Al: 0.2 mg/L). Arsenic remained below detection limits across all locations.

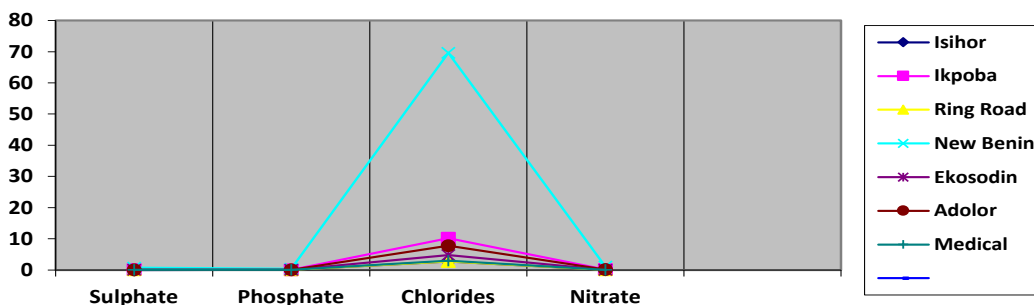


Fig. 3.2: Comparing major anions across groundwater samples in Benin City, Nigeria.

Multivariate Analysis

PCA- 84% of the total variance:

- PC1 reflected geogenic contributions (EC, TDS, major ions).
- PC2 highlighted anthropogenic inputs (Pb, Al), driven by atmospheric deposition and urban runoff.

HCA grouped samples into three clusters: low contamination (Isihor, Ringroad, Ekosodin), moderate contamination (Adolor, Medical), and high contamination (New Benin, Ikpoba).

4.0 DISCUSSION

Atmospheric Physics and Hydrochemistry

Acid rain and atmospheric deposition are critical drivers of groundwater acidification in tropical urban environments. Low alkalinity across most locations underscores the inability of aquifers to neutralize acidic inputs from SO₂ and NO_x emissions (Zhang, Li, & Wei, 2021). Geogenic contributions, such as silicate weathering, dominate ionic profiles, yet anthropogenic influences exacerbate contamination risks, as evidenced by elevated Pb and Al levels.

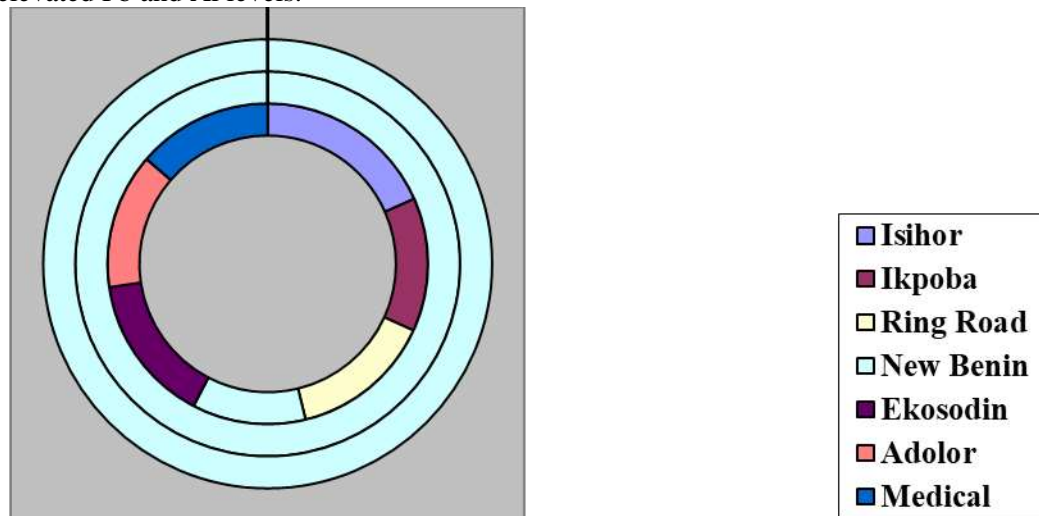


Fig. 4.1: Analysis of acid-driven mobilization effect: pH versus trace metals

Health Implications

Lead and aluminum contamination pose significant public health concerns. Chronic lead exposure can cause cognitive deficits, while aluminum is neuro-toxic and linked to Alzheimer's disease. Acidic groundwater increases the bioavailability of these metals, emphasizing the need for advanced household filtration systems (USEPA, 2023; Santos, Dias, & Welch, 2022).

Environmental and Industrial Impacts

The corrosion effects of acidic pH and trace metals threaten industrial machinery, particularly in agro-processing and beverage sectors relying on groundwater. Contaminated water also depletes soil fertility, indirectly affecting agricultural productivity and biodiversity.

Research and Policy Recommendations

1. Seasonal monitoring of groundwater quality to capture temporal variations.
2. Rainwater sampling to quantify atmospheric deposition impacts.
3. Strengthened enforcement of industrial and vehicular emission standards.
4. Artificial recharge zones to mitigate contamination pathways.
5. Public health awareness campaigns to promote household water treatment solutions.

5.0 CONCLUSION

This study highlights the alarming deterioration of groundwater quality in Benin City due to a combination of geogenic, atmospheric, and anthropogenic factors. Acidic pH and elevated trace metal levels pose serious risks to public health, environmental sustainability, and industrial processes. Multivariate analysis offers critical insights into contamination pathways, underscoring the need for interdisciplinary approaches to mitigate risks and ensure sustainable water resource management.

REFERENCES

- Adimalla, N., & Qian, H. (2021). Groundwater quality under climate change scenarios: Impacts and mitigation strategies. *Environmental Research*, 194, 110667. <https://doi.org/10.1016/j.envres.2021.110667>
- APHA. (2023). Standard methods for the examination of water and wastewater. American Public Health Association.
- Kumar, S., Sharma, P., & Patel, D. (2021). Statistical modeling of trace metal contamination in tropical aquifers. *Journal of Environmental Sciences*, 110, 220–229. <https://doi.org/10.1016/j.jes.2021.04.005>
- Ngang, B. U., Agbazue, V. E., & Ihedioha, J. N. (2019). Hydrochemistry and water quality index of groundwater resources in Enugu North District, Nigeria. *Environmental Monitoring and Assessment*, 191, 150. <https://doi.org/10.1007/s10661-019-7271-0>
- Oluwasola, F., Afolabi, A., & Ibeh, K. (2022). Trace metals in Nigerian groundwater systems: Sources and health risks. *Hydrology Research*, 53, 220–236. <https://doi.org/10.2166/nh.2022.106>
- Santos, L. C., Dias, J., & Welch, D. P. (2022). Acid rain and aquifer dynamics in urbanized tropical zones. *Geochemistry Journal*, 57, 456–467. <https://doi.org/10.1016/j.gca.2022.02.022>
- Ukah, B. U., Egbuna, N., & Udeh, J. (2021). Hydrogeochemical assessment of groundwater quality in urban regions. *International Journal of Environmental Monitoring*, 34, 112–122. <https://doi.org/10.1016/j.envres.2021.110667>
- USEPA. (2023). National primary drinking water standards. Washington, D.C.: United States Environmental Protection Agency.
- Zhang, J., Li, P., & Wei, H. (2021). Atmospheric influences on urban groundwater quality. *Water Resources Research*, 58, e2021WR031012. <https://doi.org/10.1029/2021WR031012>