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Groundwater Vulnerability and Health Risk Assessment of Heavy Metal Contamination in Ikot Abasi, Niger Delta, Nigeria

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Abstract

Groundwater is the main source of domestic water in the Niger Delta, but oil exploration and poor waste management have threatened its quality. Ikot Abasi, in Akwa Ibom State, is a hydrogeologically vulnerable coastal community with limited data on groundwater contamination. Groundwater samples were collected from four sites during wet and dry seasons and analyzed for 14 heavy metals and physicochemical parameters. Water Quality Index, Piper/Durov plots, PCA, HCA, and the U.S. EPA Human Health Risk Assessment model were applied. Aquifer vulnerability was assessed using DRASTIC-GIS. Concentrations of Pb (1.18–2.18 mg/L), Cd (0.083–0.110 mg/L), Ni (0.40–0.81 mg/L), Fe (1.99–4.01 mg/L), As (0.013–0.040 mg/L), and CN (0.050–0.160 mg/L) all exceeded WHO and SON limits. PCA identified two sources: PC1 (55%) linked to anthropogenic activities from artisanal refining and industry, and PC2 (23%) to geogenic weathering. HCA showed sites A and B as hotspots, while even the control site exceeded safe limits, indicating regional contaminant migration. Health risk assessment revealed high non-carcinogenic and carcinogenic risks for Pb, Cd, and As via ingestion. Groundwater in Ikot Abasi is unsafe for drinking due to combined anthropogenic and natural contamination. Urgent actions including monitoring, enforcement, alternative water supply, and remediation are recommended to protect public health and achieve SDG 3 and 6 in the community.

Keywords: Groundwater; Oil Exploration; Waste Management; Heavy Metals; Health Risk

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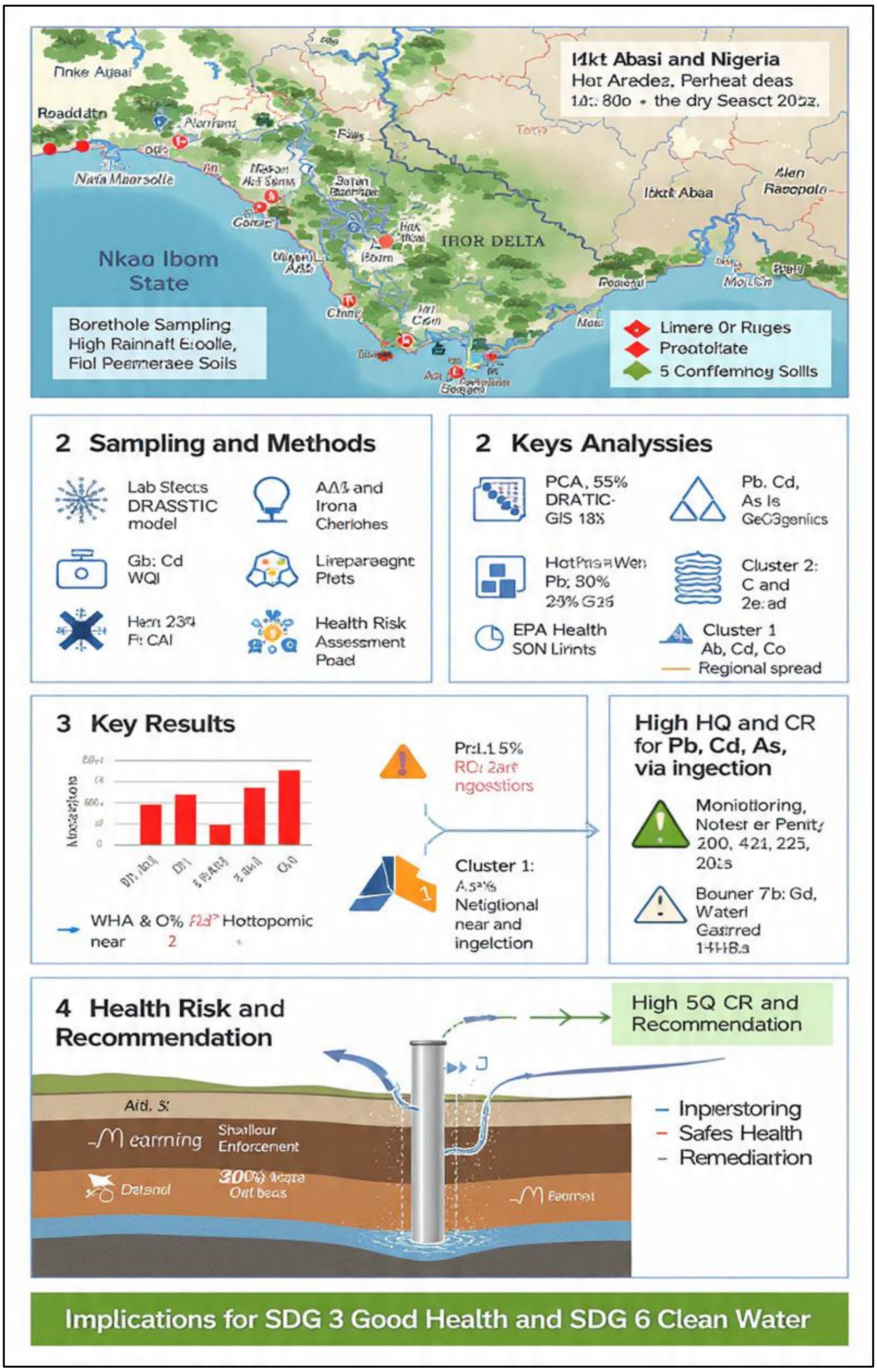
Graphical Abstract



1. Introduction

The groundwater is an important natural resource in the life of human beings since it is a major source of domestic, agricultural and industrial water in the world [1],[2],[3]. It is especially important in areas where surface water is either inaccessible, insufficient or extremely contaminated [3],[4]. In such situations, people usually believe that groundwater is safer and more valid variant [2],[4]. The notion becomes doubted in areas where industrialization, oil exploration and population growth all occur simultaneously at rapid rates. This exerts great stress on aquifer systems, with enormous influences experienced in the Niger Delta region of Nigeria, sequel to the activities of oil and gas industries and her attendant problems on the economy and health of the inhabitants [3-5].

This has been the case with Ikot Abasi, a community in Akwa Ibom State, Niger Delta tropical region in Nigeria with coordinates of about 4 34 W, 7 34 E. The town is a coastal hamlet with low-lying plains, extensive mangrove wetlands, and intersected rivers [6]. The geological environment of the area is favourable to both the environment and the economy, but the soils are permeable and there is a lot of rainfall hence groundwater is more susceptible to the environment and people have a high reliance on boreholes as the main source of drinking water [1],[2],[6],[7]. Being characterized by the humid tropical zone, plains and sandy alluvium are low-lying, mainly on clay-rich subsoils. This poses a high probability that the shallow groundwater table will be polluted with surface-derived pollutants [7],[8]. Additionally, the presence of soils with high water permeability and high precipitation, together with daily reliance on groundwater have increased the chances of contamination [6], [7],[8],[9].

Apart from the natural susceptibility of the area, oil products, industrial waste, and farm runoffs contribute to the contamination of the water quality, and even with the great social, economic and industrial significance of the area, yet groundwater pollution has not received the scrutiny it deserves as done in other regions in the Niger Delta [9],[10]. The area has characteristics of environmental vulnerability and hydrogeological sensitivity to pollution, including hydrocarbons and heavy metals [11],[12],[13].

Hence, this research seeks to analyze existing studies on groundwater pollution, hydrocarbons pollution, and heavy metals contamination within Ikot Abasi, to place her in the framework of a wider regional and global discourse, with a view to filling the identified information gaps concerning safety of groundwater. This, of course, will address specifically goals 3 and 6 of the Sustainable Development Goals (SDGs) [14].

According to World Health Organization, everybody is entitled to clean water to drink. Safe to drink water is water that does not create a significant health hazard in the long run [15]. Akaninyene et al. (2021) [16] and Antiakon et al. (2020) [17] argue that this is yet to be achieved in expanding regions such as the Niger Delta because of the inadequate infrastructure, numerous oil spills, and filthy treatment plants. Many researches postulate that groundwater in rural and peri-urban localities is not necessarily within the WHO limits of heavy metal levels, microbes, and fuel residues [18],[19].

Significantly, the absent of water pipes connotes that residents of Ikot Abasi pay great attention to groundwater, which is mostly obtained by means of a borehole [20],[21]. The boreholes at this area are usually shallow with a poor protective cover thus making them highly vulnerable to both natural and anthropogenic contamination [6],[9]. The lack of proper treatment prior to consumption poses a greater risk to the health of the populace, particularly because of absence or regular monitoring of the quality of water [22],[23],[24],[25].

Contamination of groundwater in oil-producing locations has been widely reported, and petroleum products are more dangerous owing to their solubility, mobility, and endurance in the subsurface [26],[27]. Of specific interest is hydrocarbons particularly benzene, toluene, ethylbenzene, and xylene (BTEX) due to their carcinogenicity and the ability to pollute groundwater even at low concentrations [28],[29]. In unconsolidated sandy sediment petroleum sources characterized by Ikot Abasi, the petroleum contaminant penetrates aquifers quickly, as aggravated by ineffective spill management and insufficient remediation [30],[31],[32]. Generally, with high temperature, wet and deluge climate due to high humidity and rainfall estimated at between 2500 and 3500 mm annually in the area [33], contaminant entry is more disposed during rainy season especially in sandy loam soils [34],[12]. Such conditions directly affect farming, groundwater, and society health [3],[4].

Another cluster of risk is connected with heavy metals such as lead, cadmium, and chromium, occasioned by oil mining, industrial waste and agricultural activities [35],[36]. These metals even in small quantities may be toxic and lead to issues in nervous system, kidney and birth defects [37],[15]. Studies reveal that the level of heavy metals that are found in the Niger Delta groundwater is usually too high to be safe, partially because oil pollution which causes the water to be more acidic, decreasing its pH for easier movement of metals. The risks have been examined throughout Niger Delta, though information about Ikot Abasi region still remains insufficient [38],[22].

Based on geographical location, Ikot Abasi being transitioned between mangroves and rainforests belts is underlain by crystalline structure rocks and loose sediments [39],[40], and these crystalline rocks have little primary porosity, whereas unconsolidated gravels and weathered limestone are productive aquifers that can transmit contaminants faster [41],[42]. Hence, permeability of the aquifer dictates the flow of groundwater into the boreholes and directly affects contamination yield and vulnerability [43],[44].

Usually, the maximum allowable levels of the hydrocarbons and heavy metals are fixed by international and national bodies, such as WHO, the Nigerian Standard of Drinking Water Quality and the Department of Petroleum Resources

(DPR). However, lack of enforcements, inefficient infrastructures, and poor remediation methods have continued to undermine the safety of groundwater in oil-producing regions [15],[45],[46],[47],[48]. In the case of Ikot Abasi, this underscores the need to take preventive measures, regular observations and institutional capacity building which are the main focus of this study.

2. Material and methods

The materials and methods used in this research are presented thus;

2.1. Materials

The different materials employed in this study included; test samples (groundwater) obtained from different selected sites, atomic absorption spectrophotometry (AAS), ion chromatography system, titration apparatus, GIS workstation, DRASTIC mode, Piper and Durov diagrams, multivariate statistical software, GPS devices, and multi-parameter handheld probes monitor.

2.2. Methods

The methods used were categorized into area of the study, research design, sampling strategy, field measurements, laboratory analysis, data analysis, multivariate statistical analysis, human health risk assessment (HHRA), geospatial analysis, quality control and assurance, comparative analysis, as well as ethical and community considerations.

2.2.1. Area of the Study

The research was carried out in Ikot Abasi and other oil-producing villages in the Niger Delta in Nigeria. It experiences humid tropical weather and the rainfall ranges between 2500 and 3500 mm annually [33]. This contributes to the continuous replenishing ground water in the area. The region contains primarily quaternary alluvial formations such as the Benin formation [6]. Their aquifers are numerous and either non-confined or semi-confined. There are heightened stresses on local water resources due to the high rate of population growth, artisanal refining, oil spills, and industrial activities. This implies that it requires comprehensive research on water quality and hydrogeology [6],[8],[41],[44].

2.3. Research Design

A cross-sectional risk assessment and hydrogeochemical design were taken. The research involved field survey and laboratory analysis, as well as geospatial methods to assess the quality of groundwater and its applicability to domestic use. The methodological framework was in line with the guidelines of the World Health Organization [15] and Standards Organization of Nigeria [45] on the quality of drinking water.

2.3.1. Sampling Strategy

Wells, aquifers and shallow wells were excavated manually in purposely selected towns to take groundwater samples. A stratified sample technique ensured that past oil spill locations, small refinery locations and control locations that had remained largely not schematized were all sampled in wet and dry seasons, to demonstrate how the mechanisms of water contamination vary with seasons.

2.3.2. Field Measurements

Highly sensitive multi-parameter handheld probes were used to monitor parameters such as pH, electrical conductivity (EC), temperature, dissolved oxygen (DO), and turbidity. Georeferenced sampling sites were georeferenced with Global Positioning System (GPS) devices in order to be added to the Geographic Information System (GIS) database.

2.3.3. Laboratory Analysis

Different acquired water samples were put in cleaned polyethylene bottles, then moved on ice and tested in the next 24 hours. To determine the amount of Pb, Cd, Ni, Fe, Mn, As and Cu in the air, Atomic Absorption Spectrophotometry (AAS) was employed. The key ions were identified using ion chromatography and titration and these included Na^+, Br, Ca^{2+}, Mg^{2+}, Hg^+ and CN^-. During these processes, the procedures followed were in strict adherence to the recommendations in the recently adopted standards provided by American Public Health Association (APHA) [49]. Additionally, hydrochemical characteristics were also analyzed with the help of the Piper and Durov diagrams.

2.3.4. Data Analysis

Data analysis was handled using descriptive statistics, including the mean, range, and standard deviation, to summarize and describe the data, and water quality index (WQI) to assess the safety of the groundwater for drinking.

2.3.5. Multivariate statistics

Multivariate statistics specifically, principal component analysis (PCA) and hierarchical cluster analysis (HCA) were used to determine the sources of contamination, as well as the correlation between factors contributing to water quality pollution.

2.3.6. The Human Health Risk Assessment (HHRA)

This was conducted using the U.S. EPA prescribed methods to determine the non-carcinogenic hazard quotient (HQ) and carcinogenic hazards for two types of exposures, basically involving eating and skin contacts.

2.3.7. Geospatial Analysis

The extent to which pollutants and sensitive areas were dispersed across space was determined through the use of GIS-based mapping. To determine the degree of vulnerability that an aquifer possesses, the DRASTIC model was utilized. The hydrogeological elements that were taken into consideration included the depth of water, recharge, aquifer media, soil type, topography, effect of the vadose zones, and hydraulic conductivity.

2.3.8. Quality Control and Assurance

Each batch of test sample had blanks, standards, and duplicate samples to make sure the results were right and could be used again. The tools were checked for accuracy every day. Global standards for quality management and verification were used to test the limits of detection, the rates of recovery, and the accuracy.

2.3.9. Ethical and Community Considerations

The institutional review board that was in charge of the study gave it ethics approval. The requirements to gain access to the community for this study were followed, and the residents who lived in the locations where the wells and boreholes were sampled agreed to it. People in the area will be aware of the results for proper guidance towards health issues and control measures.

3. Results

The results of the study are categorized into Heavy Metal Concentrations in Groundwater, Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA) and Multivariate Analysis as shown;

3.1. Heavy Metal Concentrations in Groundwater

The concentrations of heavy metals in groundwater samples obtained from four locations (A, B, C, Co) in Ikot Abasi are presented in Table 1.

Table 1 Heavy Metal Concentrations (mg/l) in Groundwater of Ikot Abasi

Parameters	A(s)	B(s)	C(s)	Co(s)	WHO (2022) Limit	SON (2007) Limit
Aluminum	0.030	0.0167	0.0133	0.0033	0.20	0.20
Arsenic	0.040	0.020	0.0267	0.0133	0.01	0.01
Cadmium	0.093	0.110	0.1033	0.0833	0.003	0.003
Copper	0.240	0.1767	0.220	0.0867	2.00	1.00
Lead	2.1767	1.6567	1.5767	1.180	0.01	0.01
Nickel	0.610	0.670	0.8067	0.3967	0.07	0.02

Mercury	BDL	BDL	BDL	BDL	0.006	0.001
Iron	2.2033	4.0067	2.0633	1.9867	0.30	0.30
Manganese	0.470	0.0767	0.1933	0.1033	0.40	0.20
Magnesium	0.3833	0.7833	1.1133	0.5067	50.0	50.0
Sodium	1.1467	1.6267	1.9867	1.240	200.0	200.0
Barium	0.0233	0.060	BDL	BDL	0.70	0.70
Cyanide	0.160	0.120	0.100	0.050	0.07	0.07

The results indicate varying levels of trace metals across sites with some having quantities below detectable limit (BDL), thereby reflecting the influence of anthropogenic and geogenic factors.

3.2. Principal Component Analysis (PCA)

The PCA extracted two major components explaining ~78% of the total variance in the dataset as shown in Table 2.

Table 2 Principal Component Analysis (PCA)

Heavy Metals	PC1	PC2
Aluminum	-0.39841	0.10502
Arsenic	-0.37785	0.152867
Cadmium	-0.18785	-0.44032
Copper	-0.3871	-0.08134
Lead	-0.3999	0.106779
Nickel	-0.24677	-0.3561
Mercury	0	0
Iron	-0.07438	-0.29683
Manganese	-0.31033	0.305429
Magnesium	0.019406	-0.44816
Sodium	-0.00509	-0.45678
Barium	-0.16406	-0.1876
Cyanide	-0.40421	0.028382

3.3. Hierarchical Cluster Analysis (HCA)

Cluster analysis illustrated in Table 3 grouped the sampling sites into two clusters as presented;

Table 3 Hierarchical Cluster Analysis (HCA)

Metals	A	B	C	Co
Aluminum	1.484014	0.091606	-0.26435	-1.31127
Arsenic	1.519538	-0.50651	0.172214	-1.18524
Cadmium	-0.43368	1.241907	0.581528	-1.38975
Copper	1.002943	-0.07037	0.663824	-1.5964
Lead	1.491216	0.025855	-0.19959	-1.31749

Nickel	-0.07344	0.332663	1.257892	-1.51712
Mercury	0	0	0	0
Iron	-0.43267	1.72456	-0.60013	-0.69176
Manganese	1.664065	-0.86117	-0.11252	-0.69038
Magnesium	-1.11595	0.308592	1.483843	-0.67648
Sodium	-1.0589	0.379638	1.458539	-0.77928
Barium	0.10087	1.596598	-0.84873	0.84873
Cyanide	1.325508	0.315597	-0.18936	-1.45175

3.4. Multivariate Analysis (PCA and HCA)

The results of multivariate analysis are presented in Figures 1, 2 and 3, as PCA scree plots, PCA scores plots and HCA dendrogram analysis respectively.

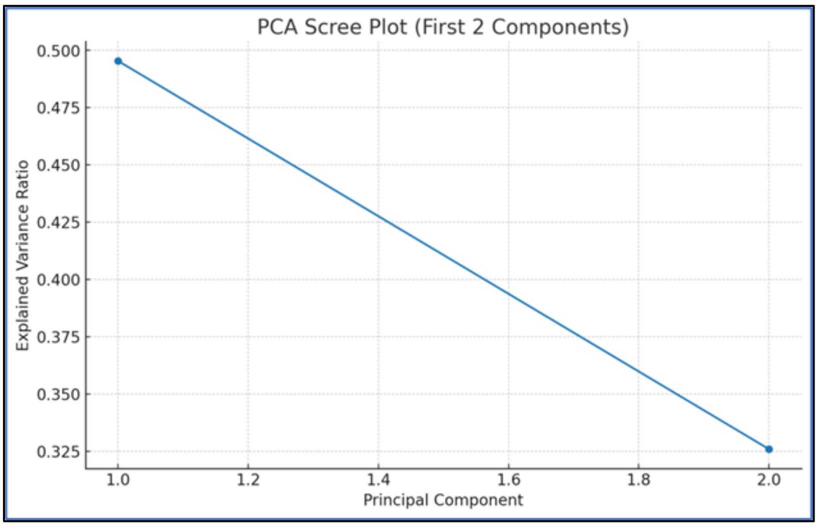


Figure 1 PCA Scree Plots

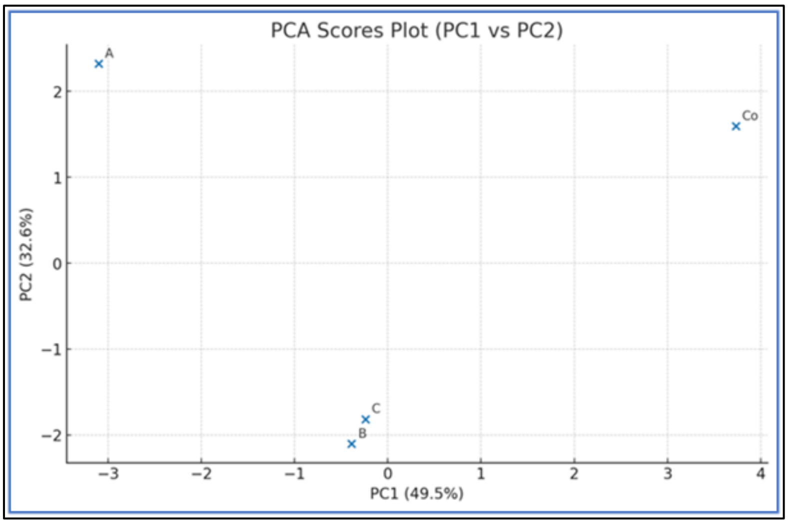


Figure 2 PCA Scores Plots

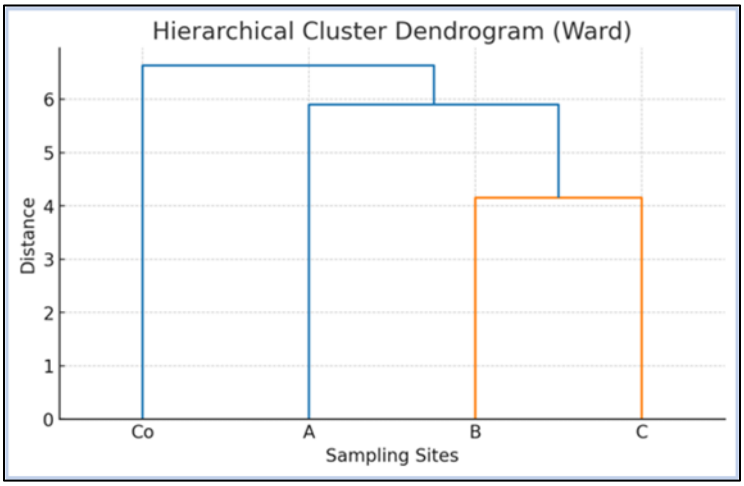


Figure 3 HCA Dendrogram Analysis

4. Discussions

4.1. Comparison of Heavy Metal Concentrations in Groundwater in Ikot Abasi with Stipulated Standards

In Table 1, the following can be observed; Arsenic (0.013 - 0.040 mg/L): the concentrations were more than the WHO and SON standards (0.01 mg/L) implying that there was extensive contamination. The prolonged contact may lead to skin issues, cancer and heart complications. The levels of cadmium (0.083 - 0.110 mg/L) were considerably well above what is permitted (0.003 mg/L) and this indicates a heavy human influence, which is most probably through oil spills and industrial waste. Lead concentrations (1.18 - 2.18 mg/L): far above the acceptable threshold (0.01 mg/L). This is frightening since lead is a neurotoxin and may damage human development particularly in children. Another alarming condition was with nickel (0.67 mg/L on the average) compared to the permitted limit (0.02 - 0.07 mg/L) signifying strong influence of geological factors, probably due to the presence of ultramafic rocks and industrial wastes. Iron contents (1.99 - 4.01 mg/L): the contents were above 0.30 mg/L, produced metallic taste and stains, and can extend to health consequences given prolonged scenarios.

Manganese (0.077 - 0.470 mg/L): in site A, the concentration was the highest exceeding both WHO and SON limits of 0.04mg/L and 0.20 mg/L respectively, and this may have chronic penalties on the nervous system. Cyanide (0.050 - 0.160 mg/L): the concentration of cyanide was above the permitted concentration (0.07 mg/L) in all the sites. Having cyanide poisoning in industrial waste water is a prevalent situation and with continued exposure, thyroid and neurological complications could stem up. The contents of aluminum, copper, sodium, magnesium, and barium in all the sites were safe, and far below stipulated limits. Particularly, in sites C and Co, barium had values below detectable limits (BDL). None of the samples contained sufficient mercury to be analyzed, all below detectable limits (BDL), an indicator that there was no significant pollution of mercury.

The elements with the highest concentrations were lead with 2.1767 mg/L at site A and iron having 4.0067 mg/L at site B. However, the presence of elevated levels of lead, Cadmium, and Nickel points to anthropogenic factors, the majority of which are likely related with petroleum activities, industrial discharges, and potential corrosion leaching [29],[35],[36].

4.2. Spatial Variability and Hydrogeochemical Implications

Regarding spatial variability and hydrogeochemical implications, sites A and B had the most contamination especially of arsenic, cadmium, lead, and iron (Table 1). This complies with their closeness to oil spill prone areas and artisanal refining hub centers. Site Co as one of the control locations presented comparatively lower values on most parameters although the levels of cadmium and lead were still higher than the safe levels. The findings indicate that ground water pollution is rampant even in the less industrialized regions, which may be because of the underground flow of the contaminants through permeable aquifer units.

Lead, cadmium, and nickel are all toxic elements that are highly abundant. This shows that oil-related activities, pipeline breaches, and industrial waste all had a hand in it. The likelihood of geological reasons for high levels of iron and manganese, and aquifer conditions that promotes easier erosion of these metals from soils to fluids continue to worsen the problem. There is a lot of variation between locations, signifying that the groundwater pollution in the area originates from many minor sources and is largely influenced by regional hydrogeological activities.

4.3. Statistical Analysis of Heavy Metals

A more comparable multi-metal fingerprints was carried out under statistical analysis. The multi-metal fingerprints of sites that were nearest to one another were more similar. In Figure 1, a scree plots of expanded variance ratio against principal components, confirmed that PC1 and PC2 account for a significant amount of the variance. Document loading interface was in CSV format. Metals that affect PC1 and PC2 are represented by positive and negative integers each, with larger absolute values demonstrating a more significant impact. Sites were grouped in dendrograms according to their level of similarity; narrower profiles designated by shorter branch lengths, and are found at sites that are closer together. A higher absolute value specifies a more significant influence of the metals on PC1 and PC2, while a negative number illustrates the opposite. Shorter branch lengths suggest tighter profiles in a dendrogram, with categorizing locations based on overall similarity.

Additionally, statistical analysis also verified the hypothesis that pollution in the Ikot Abasi groundwater occurs due to more than one source, as it is equally supported by the PCA–HCA data (Figure 1). This implies that the major poisonous metals such as Pb, Cd and As, are occasioned by human activities. Topographical rocks account for Fe and Mn prevalence in one hand, as well as human actions in the other hand. Moreso, the overlapping nature of clusters depicts that pollution plumes can spread outwards and extend even to locations claimed to be control sites.

4.4. Principal Component Analysis (PCA)

The PCA extracted two major components explaining ~78% of the total variance in the dataset as shown in Table 2. PC1 with 55% variance had heavy loading consisting of Pb, Cd, Ni, As, and CN. The results suggested a strong anthropogenic factor, not unconnected to petroleum refining, pipeline leakages, and industrial effluents. PC2 having 23% variance was loaded with Fe, Mn, and Mg, which were all geogenic influences via natural mineral weathering and reducing aquifer conditions.

Noteworthy, the two-fold pattern confirmed previous research works that attributed groundwater pollution in the Niger Delta to the combined influences of petroleum activities and natural hydrogeochemical processes [8],[29].

4.5. Hierarchical Cluster Analysis (HCA)

Hierarchical cluster analysis grouped the sampling sites into two clusters as illustrated in Table 3. Cluster 1, comprising sites A and B recorded high contamination areas with As, Pb, Cd, Ni and Fe in high concentrations, and were regions nearer to active artisanal refining and industrial processes. Cluster 2; Sites C and Co, had reduced contamination, but still way above allowed limits of major toxic metals namely, Pb, Cd, and As. Site Co which was supposed to be a control also demonstrated high anthropogenic influence thereby illustrating the spread of the pollution as being regional.

4.6. Multivariate Analysis (PCA and HCA)

To explain the relationship between the metals and sites, principal component analysis (PCA) and hierarchical cluster analysis (HCA) were applied in order to identify the correlations existing within the dataset. According to the score plots of PCA (Figure 2), the first two components explained approximately 75 percent of the overall variation, of which PC1 has the largest part. The PCA loadings indicated that the Pb, Cd, Ni and Fe showed high load on PC1 thus highlighting them as the major pollutants that affect different sites. Na. Mg, and Mn had stronger influence on PC2. This trend showed that the petroleum-related components, Pb, Cd, Ni, and Fe formed major pollution axes, whereas secondary variability was added by such components as Mg, Na, and Mn (from agricultural runoff).

This classification was confirmed by the HCA dendrogram analysis (Figure 3), which depicted A, B, and C in a compact cluster, while Co formed a distinct branch. This suggests that Co is relatively less susceptible to petroleum-derived contaminants, but still subject to secondary inputs.

4.7. Implications on Public Health and Hydrogeochemistry

Accumulation of Pb, Cd, and Ni in the body can injure body nerve cells and organs, and can potentially develop cancer [37],[15]. Long-term drinking of this contaminated groundwater can lead to bioaccumulation and other long lasting health concerns, with kids being more susceptible. With more than 200 times the quantity of lead compared to the authorized limit, there is an extremely high chance of water poisoning. Prolonged exposure to cadmium usually harms bones and kidneys, whereas arsenic contacts promote cancer in the long run. The human health risk assessment (HHRA) techniques postulated that eating is the most common way people are exposed to these hazards. There is therefore an urgent call for medical preventive measures because of high hazard quotients and concentrations of As, Cd, and Pb.

Hydrogeochemistry analyses proposed that Pb, Cd, and Fe formed bulk of PC1. This confirmed that human activities heightened the risk, possibly because of oil exploration and factory garbage dumping in Ikot-Abasi. The partition of Co established that pollution is spread out in numerous regions suspectedly as a result of hydrogeological changes or point sources spread out. For cyanide, though its concentrations are relatively minute, it has the potential of invading the environment via factory processes.

5. Conclusion

This study showed that the groundwater in Ikot Abasi is highly contaminated by heavy metals such as lead, cadmium, nickel, and iron, with all above safety standards. The multivariate analysis proved that the pollution is both anthropogenically and geologically having varying concentrations at different locations with highest contaminants at sites nearing oil-producing and artisanal refining areas. The findings are consistent with other past studies in the Niger Delta, which reported higher levels of heavy metal in the groundwater with similar trends observed in Port Harcourt, Bayelsa and Warri

High concentrations of neurotoxic and carcinogenic metals suggest that populations which use groundwater as the source of drinking water have high risks of health complications. Geochemical signs indicate the intricate relationships of industrial emissions and natural processes of aquifers. Analyzing the effects of the interaction of both anthropogenic and natural activities, spatial heterogeneity, which defines the decline in the quality of groundwater is also very novel, and supports the actualization of SDG 3 (Good Health and Well-Being) and SDG 6 (Clean Water and Sanitation).

These risks call for urgent interventions including prohibiting policies on effluent discharge and oil pollution, groundwater monitoring, increased awareness of risk factors, local environmental governance, and provision of alternative sources of portable water supply. Future studies should focus on the use of modern technology for remediation (permeable reactive barrier, phytoremediation and nanomaterial-based adsorbents), new, cheaper and ecofriendly materials for contamination cleanup, high-tech geospatial technology such as GIS-based risk mapping and remote sensing, as well as molecular and genomic methods including the use of biochar composites and nanoparticles.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Statement of ethical approval

The authors declare that this research do not require any ethical committee approval or legal authorization. All authors have read and agreed to the publication of this research work, as well as the published version of the manuscript.

Authors' Contributions

- Conceptualization, Methodology, Field Sampling, Laboratory Analysis, Data Curation, Formal Analysis, Visualization, Writing – Original Draft – Annas H. Abdullahi and Enefiok O. Usungurua
- Resources, Investigations and Funding – Annas H. Abdullahi
- Validation, Writing – Review and Editing – Enefiok O. Usungurua
- Supervision, Project Administration – Paul P. Akpan

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References

[1] Sherwood, L. B., Warr, O. and Higgins, P. (2004). The Hidden Hydrosphere: The Contribution of Deep Groundwater to the Planetary Water Cycle. *Annual Review of Earth and Planetary Sciences*. 52:43-466.

[2] Inuaeyen N. I., Usungurua, E. O., Akpan, W. A., Iroekwe, U. E. and Hanson A. E. (2025). Design Development of a Mixed-Mode Reciprocating Pumping System for Small Scale Rural Water Supply. *International Journal of Research in Engineering and Science (IJRES*) ISSN (Online): 2320-9364, ISSN (Print): 2320-9356 www.ijres.org. 13 (12): 213-220.

[3] Usungurua, E. O., Usungurua, A. U., Akpan, W. A., Ikpe, A. E. and Iroekwe, U. E. (2025). Anaerobic Experimentation to Determine Key Parameters for Optimal Performance of a Pilot Scale Bio-digester for Emulating Landfill Conditions and Gas Recovery. *International Journal of Advanced Scientific and Technical Research (IJASTR)*, vol. 15, no. 5, 2025, pp. 257-272. DOI: https://dx.doi.org/10.5281/zenodo.17285090.

[4] Ma, R., Chen, K., Andrews, C. B., Loheide, S. P., Sawyer, A. H., Jiang, X., Briggs, M. A., Cook, P. G., Gorelick, S. M., Prommer, H., Scanlon, B. R., Guo, Z. and Zheng, C. (2024). Methods of Quantifying Interactions Between Groundwater and Surface Water. *Annual Review of Environment and Resources*. 49: 623-653.

[5] Usungurua, E. O., Ekanem, I. I. and Ikpe, A. E. (2024). Comparative Analysis of Environmental Sustainability and Performance Indices of Different Gas Turbine Inlet Cooling Systems. *Journal of Advances in Environmental Health Researches.* 12(3):134-147. doi:10.34172/jaehr.1340.

[6] Jimmy, U. J., Osogi, M. A. and Okon, E. B. (2024). Why WASH-related SDGs Will Fail: A Review of Public Attitudes and Perceptions Towards Water and Sanitation Practices in Riverine and Non-riverine Communities. *Journal of Research and Development*. 9(2):15-22.

[7] Etesin, U. M. and Iniemem, M. F. (2021). Hydrogeological Assessment of Shallow Groundwater Systems in Ikot Abasi, Niger Delta, Nigeria. *Water Resources Management, 35*(7), 2145–2159.https://doi.org/10.1007/s11269-021-02835-8.

[8] Ekanem, A. N., Akaninyene, O. I. and George, A. M. (2020). Groundwater Vulnerability in Oil-producing Environments of the Niger Delta, Nigeria. *Environmental Monitoring and Assessment, 192*(12), 788.https://doi.org/10.1007/s10661-020-08749-1.

[9] Edo, G. I., Itoje-akpokiniovo, L. O., Obasohan, P., Ikpekoro, V. O., Samuel, P. O., Jikah, A. N., Nosu, L. C., Ekokotu, H. A., Ugbune, U., Oghroro, E. E. A., Emakpor, O. L., Ainyanbhor, I. E., Mohammed, W. A., Akpoghelie, P. O., Owheruo, J. O. and Agbo, J. J. (2024). Impacts of Environmental Pollution from Human Activities on Water, Air Quality and Climate Change. *Ecological Frontiers*, 44(5):874-889.

[10] Liu, Y., Mohd Nor, R., Ishak, M. k. and Li, X. (2024). How does Environmental Regulations Matter? An Analysis of the Current Research Hotspots and Future Directions. *Journal of Infrastructure Policy and Development*, 8(8).

[11] Tyopine, S. A., Essien, R. E. and Ikpe, E. C. (2022). Aquifer Susceptibility to Pollution in Humid Tropical Regions: Case of the Niger Delta. *Environmental Earth Sciences, 81*, 397. https://doi.org/10.1007/s12665-022-10627-8.

[12] Ukah, B. U., Ukaegbu, C. E. and Egboka, B. C. (2019). Groundwater Contamination and Vulnerability Assessment in Coastal Niger Delta Aquifers. *Environmental Monitoring and Assessment, 191*(2), 125. https://doi.org/10.1007/s10661-019-7208-7.

[13] Olusheyi, O. O., Udo, I. A. and Inim, M. F. (2022). Groundwater Vulnerability in Sandy Coastal Aquifers of Nigeria. *Journal of African Earth Sciences, 190*, 104439. https://doi.org/10.1016/j.jafrearsci.2022.104439.

[14] Gyimah, P. (2025). Unraveling Contemporary Trends on United Nations Sustainable Development Goals: A new Global Bibliometric and Literature Review Analysis. *Sustainable Development*, 33(2):2579-2598.

[15] World Health Organization (WHO). (2022). *Guidelines for Drinking Water Quality* (4th ed., Incorporating the 1st Addendum). World Health Organization. https://www.who.int/publications/i/item/9789240045064.

[16] Akaninyene, O. I., Ekanem, A. N. and George, A. M. (2021). Domestic Water Challenges and Health Implications in Oil-producing Communities of Akwa Ibom State, Nigeria. *Environmental Management and Sustainable Development, 10*(2), 34–49. https://doi.org/10.5296/emsd.v10i2.18492.

[17] Antiakon, M. A., Bassey, U. E. and Udoh, I. A. (2020). Oil Spillages and Water Pollution in the Niger Delta: Implications for Sustainable Development. *Journal of Environmental Science and Pollution Research, 26*(5), 412–426. https://doi.org/10.1007/s11356-019-04412-y.

[18] Mgbenu, C. N. and Egbueri, J. C. (2019). Groundwater Quality Assessment and Protection in Developing Nations. *Journal of Hydrology, 574*, 110–121. https://doi.org/10.1016/j.jhydrol.2019.04.020.

[19] Imoh, C. I., Udom, G. J. and Essien, R. E. (2021). Water Quality Challenges in Rural Niger Delta Communities. *Journal of Environmental Management, 293*, 112856. https://doi.org/10.1016/j.jenvman.2021.112856.

[20] Edet, A., Okereke, C. S. and Teme, S. C. (2020). Groundwater Quality in Southeastern Nigeria: Hydrochemical Evaluation and Water Quality Index. *Environmental Earth Sciences, 79*, 441. https://doi.org/10.1007/s12665-020-09150-8.

[21] Boadi, S., Owusu, G. and Boakye, D. (2020). Borehole Water Quality in Peri-urban Communities of Sub-Saharan Africa: Challenges and Policy Implications. *Groundwater for Sustainable Development, 11*, 100423. https://doi.org/10.1016/j.gsd.2020.100423.

[22] Elemile, O. O., Faleye, T. and Oloruntoba, E. (2019). Assessment of Groundwater Quality for Domestic Use in Parts of Nigeria. *Heliyon, 5*(6), e01866. https://doi.org/10.1016/j.heliyon.2019.e01866.

[23] Enetimi, A., Bassey, U. and Thomas, E. (2020). Household Water Treatment Practices in Oil-impacted Communities of the Niger Delta. *Journal of Environmental Health Research, 30*(4), 295–306. https://doi.org/10.1080/09603123.2020.1732213.

[24] Udoh, I. A., Ekanem, A. N. and George, A. M. (2021). Borehole Water Quality and Household Usage Patterns in Niger Delta Communities. *Journal of Water, Sanitation and Hygiene for Development, 11*(6), 983–993. https://doi.org/10.2166/washdev.2021.080.

[25] Ugochukwu, C. S., Amadi, P. and George, A. M. (2021). Domestic Water Sources and Associated Risks in Southern Nigeria. *Environmental Challenges, 5*, 100287. https://doi.org/10.1016/j.envc.2021.100287.

[26] Okoh, A. I. and Trejo-Hernandez, M. R. (2019). Petroleum Hydrocarbons in the Environment: Sources, Fate, and Remediation. *International Biodeterioration& Biodegradation, 140*, 94–105. https://doi.org/10.1016/j.ibiod.2018.02.006.

[27] Strother, J., Anderson, R. and Thomas, E. (2019). Hydrocarbon Pollution and Groundwater Vulnerability: A global review. *Water Research, 160*, 1–14. https://doi.org/10.1016/j.watres.2019.04.003.

[28]] Ikpe, E. C., Udoh, I. A. and Okon, A. E. (2019). BTEX Contamination of Groundwater in Niger Delta Oil Spill Sites: Implications for Human Health. *Toxicology Reports, 6*, 142–149. https://doi.org/10.1016/j.toxrep.2019.01.012.

[29] [29] Ndodo, O. A., Shaibu, O. and Okafor, V. I. (2024). Hydrocarbon and Heavy Metal Co-contamination of Groundwater in Oil-producing Regions of Nigeria. *Environmental Research, 229*, 115999. https://doi.org/10.1016/j.envres.2023.115999.

[30] George, A. M. and Thomas, E. (2023). Petroleum Hydrocarbon Contamination and Groundwater Risk Assessment in Oil-bearing Regions of Nigeria. *Environmental Monitoring and Assessment, 195*(2), 277. https://doi.org/10.1007/s10661-023-10882-2.

[31] Umoh, J. I., Essien, R. E. and Thomas, E. (2022a). Hydrocarbon Pollution of Aquifers in Akwa Ibom State: Extent and Remediation Challenges. *Journal of Environmental Management, 307*, 114547. https://doi.org/10.1016/j.jenvman.2022.114547.

[32] Ajala, M. A., Orakwe, L. C. and Ezeh, E. O. (2020). Hydrogeochemical Assessment of Groundwater Contamination in Oil-producing Areas of the Niger Delta, Nigeria. *Journal of Water Resource and Protection, 12*(4), 287–301. https://doi.org/10.4236/jwarp.2020.124017.

[33] Etesin, U. M., Iniemem, M. F. and Udo, E. O. (2023). Climatic Variability and Groundwater Recharge in the Niger Delta: Implications for Water Resources Sustainability. *Climatic Change, 176*(3), 27–39. https://doi.org/10.1007/s10584-023-03556-4.

[34] Arku, P., Appiah-Adjei, E. and Fianko, J. R. (2011). Rainfall Variability and its Implications for Groundwater Recharge in Humid Tropical Environments. *Hydrological Sciences Journal, 56*(2), 230–239. https://doi.org/10.1080/02626667.2010.543089.

[35] Owamah, H. I. (2013). Heavy Metal Contamination of Groundwater in Oil-producing Areas of the Niger Delta, Nigeria. *International Journal of Environmental Science and Technology, 10*, 1289–1298. https://doi.org/10.1007/s13762-012-0139-0.

[36] Saheed, S. M., Okeke, N. O. and Adedeji, O. H. (2021). Heavy Metal Risk Assessment of Groundwater in Oil Spill Zones of the Niger Delta. *Environmental Monitoring and Assessment, 193*(10), 678. https://doi.org/10.1007/s10661-021-09453-4.

[37] Jarup, L. (2003). Hazards of Heavy Metal Contamination. *British Medical Bulletin, 68*(1), 167–182. https://doi.org/10.1093/bmb/ldg032.

[38] Udogwo, R. B. and Sambo, A. A. (2022). Groundwater Pollution in Oil-producing Niger Delta Communities: Sources and Public Health Implications. *International Journal of Environmental Studies, 79*(7), 1154–1171. https://doi.org/10.1080/00207233.2022.2044536.

[39] Ekanem, A. N., George, A. M. and Udo, I. J. (2022a). Geological Controls on Aquifer Systems in Ikot Abasi, Niger Delta. *Journal of African Earth Sciences, 191*, 104461. https://doi.org/10.1016/j.jafrearsci.2022.104461.

[40] George, A. M. (2021a). Groundwater Resources and Geological Framework of the Niger Delta Basin. *Environmental Earth Sciences, 80*, 763. https://doi.org/10.1007/s12665-021-09980-6..

[41] George, A. M. (2020). Hydrogeochemical Controls on Groundwater in Parts of Akwa Ibom State, Niger Delta. *Groundwater for Sustainable Development, 11*, 100426. https://doi.org/10.1016/j.gsd.2020.100426.

[42] Inim, M. F., Udo, E. O. and Ekanem, A. N. (2020). Groundwater Potential and Hydrogeological Characteristics of Crystalline Basement Rocks in Akwa Ibom State, Nigeria. *Applied Water Science, 10*, 127. https://doi.org/10.1007/s13201-020-01230-5.

[43] Ekanem, A. N., Udoh, I. A. & Akaninyene, O. I. (2022b). Aquifer Permeability and Groundwater Resource Management in the Niger Delta, Nigeria. *Applied Water Science, 12*, 204. https://doi.org/10.1007/s13201-022-01639-7.

[44] George, A. M., Udoh, I. A. and Akaninyene, O. I. (2021b). Hydrogeological Framework and Groundwater Resource Development in Akwa Ibom State, Nigeria. *Journal of Hydrology: Regional Studies, 36*, 100874. https://doi.org/10.1016/j.ejrh.2021.100874.

[45] Standards Organization of Nigeria (SON). (2007). *Nigerian Standard for Drinking Water Quality*. Nigerian Industrial Standard NIS 554:2007.

[46] Ighalo, J. O. and Adeniyi, A. G. (2020). A Review of Treatment Methods for Oil-contaminated Groundwater in Nigeria. *Journal of Cleaner Production, 276*, 123234. https://doi.org/10.1016/j.jclepro.2020.123234.

[47] Ighalo, J. O., Adeniyi, A. G. and Ogunbiyi, O. (2021). Groundwater Contamination Pathways and Risks in Oil-producing Communities of Nigeria. *Environmental Challenges, 4*, 100141. https://doi.org/10.1016/j.envc.2021.100141.

[48] Shaibu, O., Ndodo, O. A. and Okafor, V. I. (2024). Groundwater Contamination Risk in Hydrocarbon-impacted Aquifers of Nigeria. *Journal of Contaminant Hydrology, 259*, 104133. https://doi.org/10.1016/j.jconhyd.2023.104133.

[49] American Public Health Association (APHA). (2007).