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From Oil to Health: Groundwater Quality and Its Potential Health Effects in Mgbede Oil Fields of South-South Nigeria

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Abstract

Rationale: The quality of groundwater in the Mgbede Oil Fields of South-South Nigeria has raised significant concerns due to the risk of contamination from industrial activities, especially gas flaring. Evaluating the effects of these operations on groundwater quality is essential for safeguarding the health and well-being of local communities, as well as protecting the environment. **Objective:** This study aimed to evaluate the quality of groundwater in the Mgbede Oil Fields, specifically examining whether the water meets international drinking water standards and identifying any contaminants present due to gas flaring. **Method:** Purposeful selection of water sampling points was employed to ensure the objectives of the study were met. Groundwater samples were collected from various locations within the Mgbede Oil Fields and analyzed for key quality parameters, including pH, manganese, and turbidity, among others. **Results:** The analysis revealed that while most groundwater samples were within acceptable international drinking water limits, there were notable exceptions. pH levels ranged from 5.17 to 6.16, manganese concentrations from 0.001 to 0.136 mg/L, and turbidity levels from 0.00 to 825 mg/L. All sampled locations exhibited traces of manganese and high acidity, indicating particulate pollution likely resulting from gas flaring activities. **Conclusions:** The study concluded that the groundwater quality in the Mgbede Oil Fields is negatively impacted by continuous gas flaring. Contaminants such as manganese and increased acidity levels exceed acceptable international standards, posing potential risks to environmental health. **Recommendations:** To mitigate these risks, it is recommended that immediate measures should be taken to reduce gas flaring and its associated particulate emissions. Regular monitoring of groundwater quality should be implemented to track improvements and ensure compliance with international standards. Additionally, introducing filtration systems or alternative water sources could help protect the health of local communities. **Significance Statement:** This study underscores the significant impact of industrial activities, specifically gas flaring, on groundwater quality in the Mgbede Oil Fields. The findings highlight the urgent need for regulatory measures and continuous monitoring to safeguard environmental health and ensure the availability of safe drinking water.

Keywords

Groundwater Quality, Mgbede Oil Fields, Gas Flaring, Water Contamination, Environmental Health, Industrial Pollution, Toxic Metals, Drinking Water Safety, Manganese, pH, Turbidity, Niger Delta, Nigeria

1. Introduction

The quality of groundwater in oil-producing regions is a critical environmental and public health concern, particularly in areas like the Niger Delta of Nigeria, where extensive industrial activities, including gas flaring, are prevalent. Groundwater serves as a primary source of drinking water for many communities, and its contamination poses significant risks to human health and the environment [1]-[15]. Access to safe and clean drinking water is a fundamental human right, explicitly recognized by the UN General Assembly in 2010. Sustainable Development Goal (SDG) 6.1 aims for universal and equitable access to safe and affordable drinking water by 2030 [11]-[16]. The World Health Organization (WHO) underscores the importance of safe, readily available water for public health, economic growth, and poverty reduction. Contaminated water is linked to the transmission of diseases such as cholera, dysentery, hepatitis A, and typhoid, contributing to over 3.4 million deaths annually, with young children being the most affected. This issue is exacerbated in developing regions like Africa and Asia, where access to clean water is limited [17]-[26]. Existing research has highlighted the severe impact of industrial activities on water quality in the Niger Delta. Studies by Raimi and Sabinus [27], Olalekan and Ezugwu [28], Premoboere and Raimi [29], Olalekan *et al.* [30], Raimi [31], Raimi *et al.* [32], Ezekwe *et al.* [33], Ezekwe and Oji [34], Olalekan *et al.* [35], Raimi *et al.* [36], Ordinioha and Brisibe [37], Ordinioha and Sawyerr [38], Olalekan *et al.* [39], Raimi and Sawyerr [40], Ezekwe *et al.* [41], Richard *et al.* [42], Raimi *et al.* [43], Olalekan *et al.* [44], Deinkuro *et al.* [45], Deinkuro *et al.* [46], Awogbami *et al.* [47], Omoyajowo *et al.* [48], Segun and Olalekan [49], Stephen *et al.* [50], Awogbami *et al.* [51], Segun and Raimi [52] and Raimi *et al.* [3] have documented the presence of toxic metals and other contaminants in water sources in oil and gas field areas. The degradation of water quality due to oil spills, gas flaring, and industrial waste has been extensively reported, with significant health implications for local communities. For example, studies have shown that groundwater in urban and industrial areas of the Niger Delta is often polluted by waste products from industrial activities, posing serious health risks [53]-[57]. Despite the extensive documentation of water contamination, there remains a gap in understanding the specific impacts of continuous gas flaring on groundwater quality in the Niger Delta. While surface water contamination has been widely studied, less attention has been given to the quality of groundwater, which is often perceived as safer. There is a need for comprehensive studies that assess the extent of groundwater contamination, identify the sources of pollutants, and evaluate the potential health risks. Addressing this gap is crucial for developing effective strategies to protect groundwater resources and ensure the health and safety of communities in oil-producing regions. This study aims to fill this gap by investigating the quality of groundwater in the Mgbede Oil Fields of South-South Nigeria, focusing on the impacts of gas flaring and other industrial activities. This study will provide valuable insights into the levels and sources of groundwater contamination in the Mgbede Oil Fields, highlighting the environmental and health risks associated with industrial activities. By identifying specific pollutants and their concentrations, the study will inform regulatory measures and remediation strategies to improve groundwater quality and protect public health.

2. Materials and Methods

2.1. Study Area

The Nigerian Agip Oil Co. Ltd. (NAOC), part of the Italian Eni Group, began its operations in Nigeria in 1962. A significant milestone was the discovery of the Ebocha and Mgbede oil fields in 1965, which led to the commencement of production activities in 1970 and 1972, respectively. These fields are integral to the larger Oil Mining Lease (OML 61) [58], located onshore, south of OML 60, covering an extensive area of 1499 km^2 (370,410 acres). The exploration journey in OML 61 initiated with the discovery of the Ebocha oil and gas condensate field in 1965. Within the Mgbede Oil Fields, approximately seven communities are affected by these operations: Ebocha, Mgbede, Aggah, Umudike, Okwuzi, Abaezi, and Etekwuru. The activities in these fields have significant implications for these communities (as illustrated in **Figure 1**). This study presents a structured overview of the key points while clarifying the relationships between NAOC, its operational history, and the affected communities.

2.2. Sample Collection and Preparation

This study involved the purposeful selection of six hand-dug wells across key communities in the Mgbede Oil Fields to comprehensively assess groundwater quality variations influenced by industrial activities, particularly gas flaring.

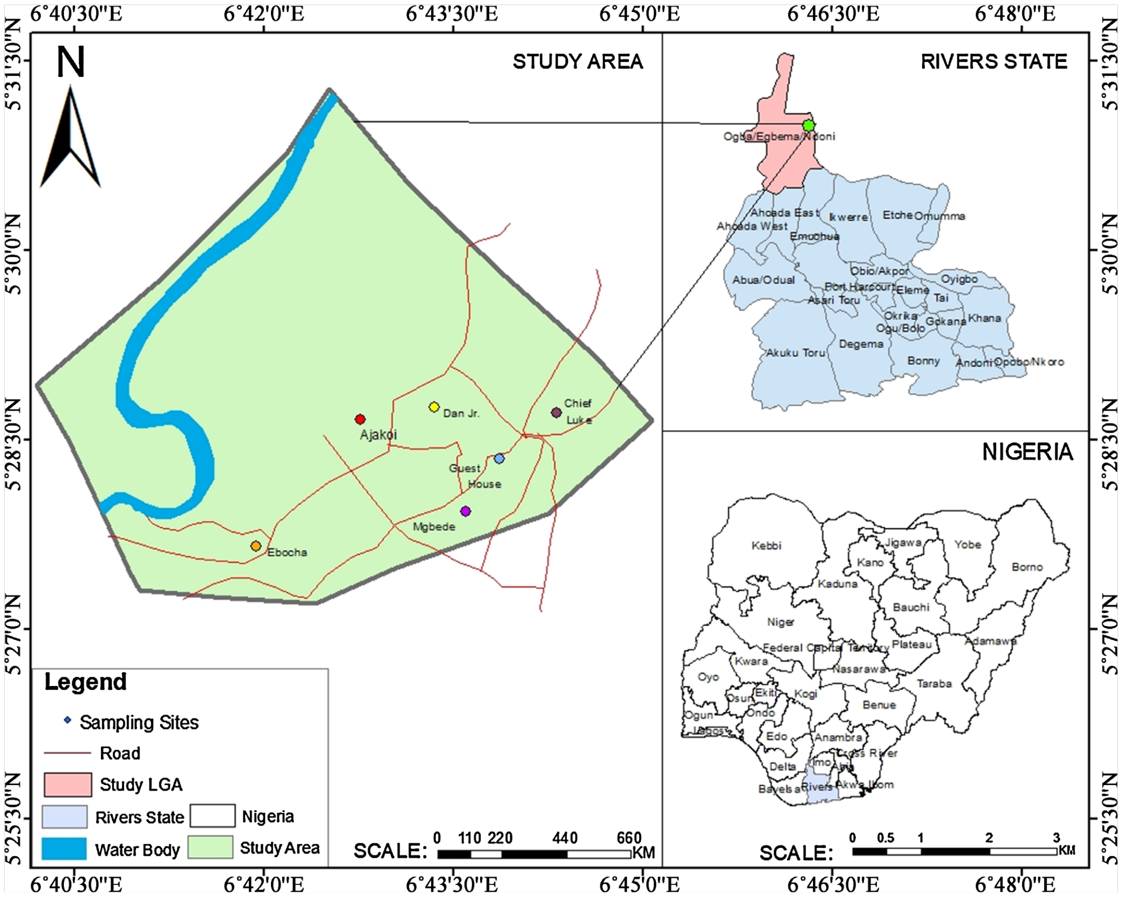

Figure 1. Location map of the study area.

Sampling sites were strategically distributed based on proximity to active gas flare points, ranging from 650 meters to 5 kilometers. This distance gradient provided a basis to examine both high- and low-exposure zones, allowing for a thorough analysis of potential contamination effects. Each well location was chosen to reflect different levels of industrial impact, with sites near the flare points representing higher exposure, and those farther away offering a perspective on lower exposure areas. The sampling points, positioned within communities such as Ebocha, Stone Village Mgbede, Mgbede-Aggah, Etekwuru Road Aggah, Behind Okwuzi School, and Ajakoi, enabled the study to capture a broad range of environmental impacts on groundwater quality across the area. By incorporating diverse geological features, including soil type, aquifer depth, and permeability, each site selection aimed to ensure representative data for groundwater quality assessment. Sites nearer to gas flaring points, such as Ebocha at 0.65 km, represent high-impact zones, while mid-range sites, such as Stone Village Mgbede at 2.5 km and Aggah at 3.0 km, capture moderate impact levels. Distant sites, such as Ajakoi, positioned 5 kilometers from the flare, serve as points of lower exposure, highlighting the possible attenuation of contaminants with distance. Table 1 summarizes the selected sampling sites and their distances from the nearest gas flare point. This systematic site selection enables a spatial analysis of pollutant dispersion and contamination gradients, providing insights into how proximity to industrial activities influences groundwater quality.

Table 1. Sampling sites and their distances from gas flare site.

Sampling Site	Distance from Gas Flare Site (km)
Ebocha	0.65
Stone Village Mgbede	2.5
Mgbede-Aggah Area	3.0
Etekwuru Road Aggah	4.0
Behind Okwuzi School	4.5
Ajakoi Community	5.0

2.3. On-Site Measurements

During fieldwork, on-site measurements were conducted to capture water quality data at each sampling point using the Horiba 522 Water Checker. This equipment enabled real-time assessment of key physico-chemical parameters such as temperature, pH, Dissolved Oxygen (DO), conductivity, Oxygen Reduction Potential (ORP), and turbidity. Conducting measurements directly at the site allowed for accurate reflection of water conditions in their natural state, as immediate readings reduce the likelihood of alterations due to transportation or delayed testing. The in-situ use of the Horiba 522 ensured reliable and consistent data collection, essential for comparing immediate variations across different locations. By measuring water quality parameters in equilibrium with their surroundings, the study could better capture the distinct impacts of industrial activities on groundwater in the region. This approach provided a clear basis for understanding the influence of proximity to gas flaring and other industrial factors on water quality, as well as establishing baseline data that could support ongoing environmental assessments.

2.4. Analytical Techniques for Parameter Testing

Each water quality parameter was measured using rigorous, standardized analytical methods to ensure high reproducibility and reliability of results. Detailed methods and equipment for each parameter are outlined below to maintain consistency with WHO standards and enhance the accuracy of the findings. For pH, potentiometric methods were applied, following WHO guidelines for drinking water quality. Measurements were taken on-site using the Horiba 522 Water Checker, providing real-time pH data to reflect the natural water condition accurately. To ensure precision, the device was calibrated with certified buffer solutions, minimizing the likelihood of measurement alteration during transportation. Manganese concentrations were determined using Atomic Absorption Spectroscopy (AAS), following protocols from the American Public Health Association (APHA) [59] guidelines. This method, highly sensitive for trace metals, provides a reliable assessment of manganese levels, a critical indicator of industrial impact in groundwater.

Calibration standards and detection limits adhered to APHA guidelines, ensuring that results were precise and comparable. For turbidity, a nephelometric method was employed, consistent with WHO standards. Turbidity values, recorded in Nephelometric Turbidity Units (NTUs), allowed for an accurate quantification of particulate contamination. This parameter is particularly important as it may reflect particulate matter resulting from industrial activities, such as gas flaring. Heavy metals and hydrocarbons, including volatile compounds like BTEX and PAHs, were assessed using Inductively Coupled Plasma (ICP) techniques and Gas Chromatography-Mass Spectrometry (GC-MS). These methods followed APHA standards to ensure consistency with international benchmarks, providing detailed insights into the presence of contaminants. Each technique included quality control protocols, such as the use of blank samples, repeated measurements, and regular calibration against certified reference standards. These measures were essential for confirming data reliability and enhancing the study's credibility, supporting its replicability for future assessments.

2.5. Control Sites for Comparative Analysis

To effectively isolate the impacts of industrial activities on groundwater quality, incorporating control sites located at a significant distance from oil fields and gas flare points is essential. These control sites serve as baseline benchmarks, representing groundwater quality in areas free from direct industrial influence. By comparing groundwater data from control sites with data from areas affected by gas flaring, the study differentiates between natural variations in water quality and contamination directly attributable to industrial emissions. This distinction is crucial for accurately assessing industrial impacts and ensuring that the study's findings are both valid and reliable. Implementing control sites strengthens the study's ability to draw clearer conclusions by providing a contrasting reference for non-industrialized regions against areas influenced by oil and gas production. This comparative analysis not only helps isolate the specific effects of gas flaring and other industrial activities on groundwater but also enables a more precise differentiation between background water quality and contamination related to oil and gas operations. Through this approach, the study offers a more rigorous and comprehensive evaluation of the industrial impact on groundwater resources.

2.6. Benchmark Standards for Health and Environmental Safety

The study reveals elevated levels of certain water quality parameters, pH, manganese, and turbidity that exceed international health and environmental safety standards, raising potential health concerns. Specifically, WHO guidelines recommend a safe drinking water pH range of 6.5 - 8.5, whereas observed levels in the study range from 5.17 to 6.16, indicating an acidic environment. This higher acidity could cause corrosion in distribution systems and leach metals into the water supply, thereby increasing health risks. Additionally, manganese concentrations in the study reached up to 0.136 mg/L, surpassing the WHO's maximum allowable concentration of

0.1 mg/L. Long-term exposure to manganese levels above this threshold may lead to neurological effects, underscoring the importance of managing this contaminant. The study further recorded turbidity levels as high as 825 NTU, greatly exceeding the WHO-recommended maximum of 5 NTU. Elevated turbidity not only diminishes water aesthetics but also signifies potential pathogen and particulate pollution that could pose serious health risks. By aligning the findings with established WHO and EPA standards, the study contextualizes the health implications of observed contaminant levels, highlighting the urgency for intervention measures to protect public health and ensure safe drinking water.

2.7. Laboratory Analysis

After completing on-site measurements, water samples were transported to the laboratory for an in-depth analysis of various contaminants, following standards specified by the American Public Health Association [59]. Laboratory tests focused on a broad range of parameters, including heavy metals, hydrocarbons, sulphate, salinity, chloride, phosphate, nitrate, calcium, and potassium. Each parameter was measured using specific analytical methods to ensure consistency with internationally accepted guidelines. For example, pH was measured using potentiometric methods, while manganese levels were determined via Atomic Absorption Spectroscopy (AAS). Turbidity was assessed using a nephelometric approach, and heavy metals were analyzed through Inductively Coupled Plasma (ICP) techniques, all benchmarked against WHO standards. By adhering to these established protocols, the study ensured data integrity, enabling the findings to be compared against environmental and health benchmarks. This rigorous approach provided reliable data for evaluating the quality of groundwater and potential health risks posed by the presence of various contaminants. The adherence to APHA standards not only enhanced the credibility of the results but also supported the replicability of the study for future investigations in similar contexts. **Table 2** summarizes the parameters, methods, and benchmark standards referenced in the analysis.

Table 2. Analytical parameters and methods.

Parameter	Analytical Method	Benchmark Standard Reference
pH	Potentiometric	WHO/EPA acceptable range
Manganese	Atomic Absorption Spectroscopy (AAS)	WHO standards
Turbidity	Nephelometric	WHO standards
Heavy Metals	Inductively Coupled Plasma (ICP)	APHA (2017) [59]

2.8. Quality Assurance and Quality Control (QA/QC)

To maintain data accuracy and reliability, rigorous Quality Assurance and Quality Control (QA/QC) protocols were followed at every stage of the study, from sample collection and labeling to laboratory analysis and final data verification. Chain of custody was strictly observed, ensuring traceability and preventing sample contamination or mislabeling. This systematic approach, aligned with the Environmental Guidelines in the Petroleum Industry in Nigeria and other recognized standards (Department of Petroleum Resources, DPR) [60] [61], minimized potential errors and inconsistencies, thereby supporting the study's goal of producing valid and actionable findings. Such adherence to QA/QC protocols ensured the integrity of the results, which can be confidently used to inform environmental management and policy.

2.9. Statistical Analysis

To strengthen the study's findings, statistical analyses were applied to key water quality parameters, *i.e.* pH, manganese, and turbidity across various sites. By using Analysis of Variance (ANOVA), the study assessed whether contaminant levels significantly differed between locations, allowing for the identification of areas most impacted by industrial activities like gas flaring. This approach helps pinpoint sites with notably high or low contamination levels, guiding targeted interventions to protect groundwater quality. Additionally, confidence intervals were calculated for each parameter's mean, enhancing data reliability by ensuring that observed differences are not merely due to random chance but instead reflect genuine variability in groundwater quality. This statistical rigor provides a robust foundation for interpreting the findings and supports evidence-based recommendations for regulatory actions to mitigate contamination in the most affected areas.

3. Results

3.1. Sulphate Concentrations

Sulphate (SO_4^{2-}) levels were measured across various sites, with Chief Lucky Ebocha showing the highest concentration at 5 mg/l, followed by Dan Jr. Okwuzi at 3 mg/l. Other locations, including Chief Aaron Mgbede, Chief Luke Aggah, and Mopol Road Ajakoi, displayed lower concentrations ranging from 1 to 2 mg/l. Living Guest Aggah had the lowest detectable concentration at 0 mg/l. All measured values were significantly below the WHO standard of 250 mg/l, indicating no immediate health risk from sulphate contamination in these water sources (**Figure 2**).

3.2. Nitrate and Phosphate Levels

Nitrate (NO_3^-) concentrations were consistently low across all sites, with Chief Lucky Ebocha recording the highest at 0.3 mg/l, and other sites such as Chief Aaron Mgbede, Living Guest Aggah, and Chief Luke Aggah showing concentrations below 0.01 mg/l. These values are well within the WHO limit of 50 mg/l, suggesting minimal risk of nitrate pollution. Phosphate (PO_4^{3-}) levels ranged from 0.32 mg/l at Living Guest Aggah to 0.66 mg/l at Chief Luke Aggah, all far below the WHO guideline of 10 mg/l, indicating limited phosphate contamination (**Figure 3**).

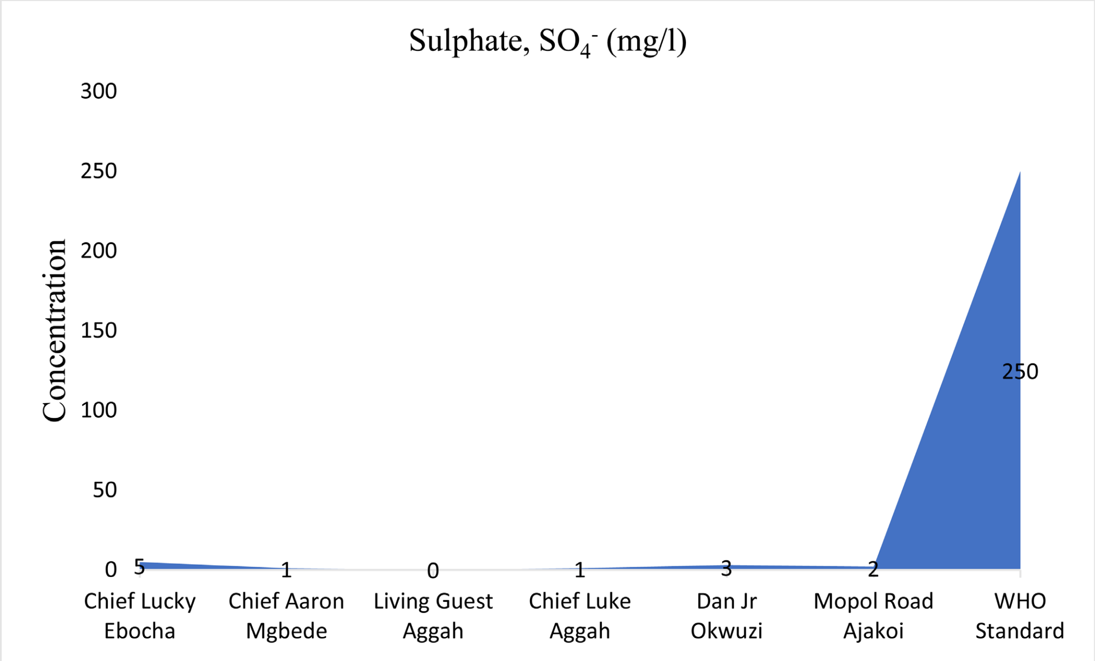

Figure 2. Sulphate (SO_4^{2-}) concentration across various sites.

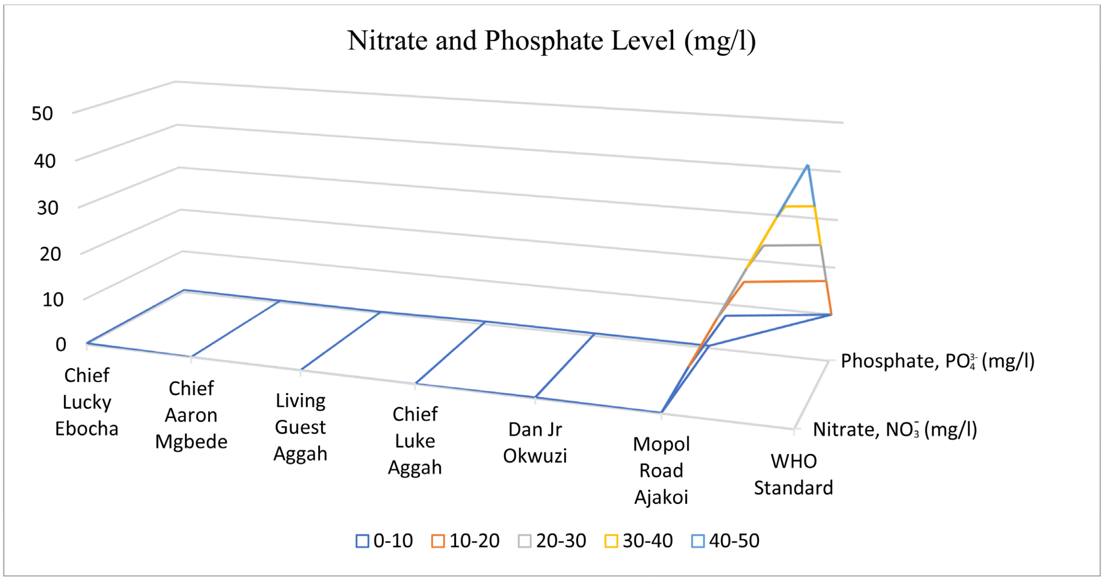

Figure 3. Nitrate and phosphate concentration across various sites.

3.3. Hydrocarbons and Heavy Metals

Total Hydrocarbons (THCs), Polycyclic Aromatic Hydrocarbons (PAHs), and Benzene, Toluene, Ethylbenzene, and Xylene (BTEX) were all below detectable limits (<0.01 mg/l, <0.001 mg/l, and <0.001 mg/l, respectively) at all sampling sites. Similarly, heavy metals such as Lead (Pb), Cadmium (Cd), and Chromium (Cr) were also undetectable (<0.001 mg/l) across all locations, indicating minimal to no contamination. These values comply with WHO standards, where applicable (Pb at 0.01 mg/l, Cd at 0.003 mg/l, Cr at 0.05 mg/l) (**Figure 4**).

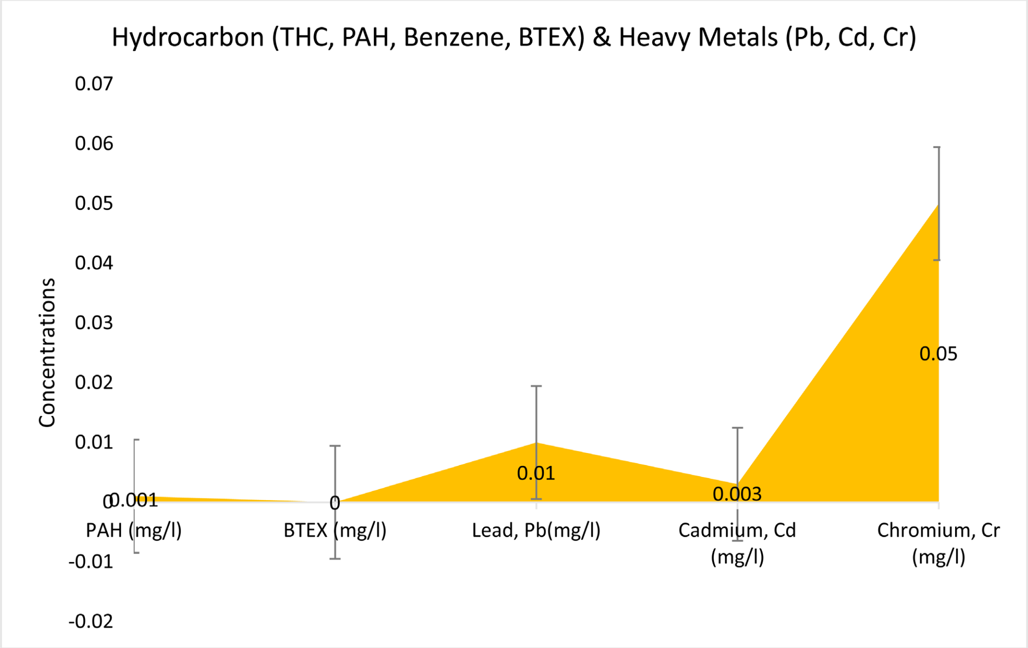

Figure 4. Hydrocarbon (THC, PAH, Benzene, BTEX) and heavy metal (Cd, Cd, Pb) concentration across various sites.

3.4. Manganese and Zinc Levels

Manganese (Mn) concentrations varied, with Dan Jr. Okwuzi exhibiting the highest level at 0.135 mg/l, slightly exceeding the WHO guideline of 0.1 mg/l. Chief Lucky Ebocha had a concentration of 0.126 mg/l, while other sites showed much lower levels, some below the detectable limit (<0.001 mg/l). Zinc (Zn) was detected only at Living Guest Aggah (0.059 mg/l), with all other sites recording values below the detectable limit. The measured zinc levels are well within the WHO permissible limit of 3 mg/l (Figure 5).

3.5. Essential Minerals: Calcium, Magnesium, Sodium, and Potassium

Calcium (Ca) levels were highest at Chief Lucky Ebocha (7.145 mg/l) and lowest at Mopol Road Ajakoi (0.914 mg/l), all significantly below the WHO guideline of 100 mg/l. Magnesium (Mg) concentrations ranged from 0.396 mg/l at Mopol Road Ajakoi to 1.081 mg/l at Chief Lucky Ebocha, all within the acceptable limit of 50 mg/l. Sodium (Na) was highest at Chief Lucky Ebocha (22.206 mg/l) and lowest at Mopol Road Ajakoi (1.680 mg/l), again within the WHO limit of 200 mg/l. Potassium (K) showed considerable variability, peaking at 20.504 mg/l at Dan Jr. Okwuzi, slightly exceeding the WHO standard of 20 mg/l (Figure 6).

3.6. Physical Parameters: Temperature, pH, and ORP

Water temperatures across the sites ranged from 28.76˚C at Mopol Road Ajakoi to 30.89˚C at Living Guest Aggah, generally aligning with the WHO recommended range of 20˚C - 30˚C. The pH levels were consistently acidic, ranging

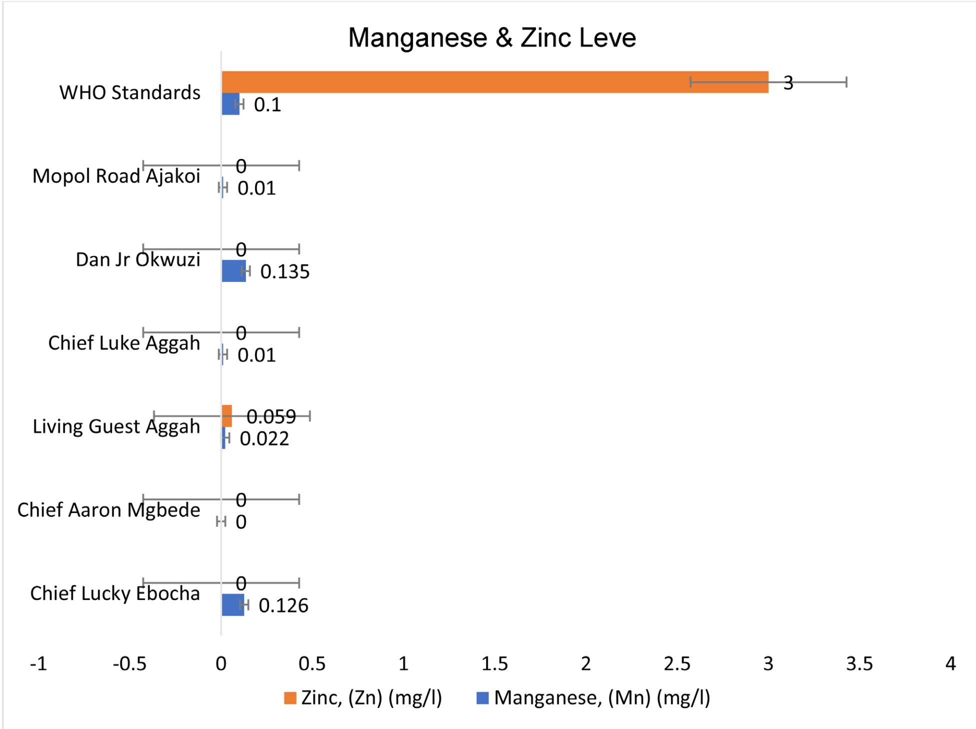

Figure 5. Zinc (Zn) and Manganese (Mn) concentration across various sites.

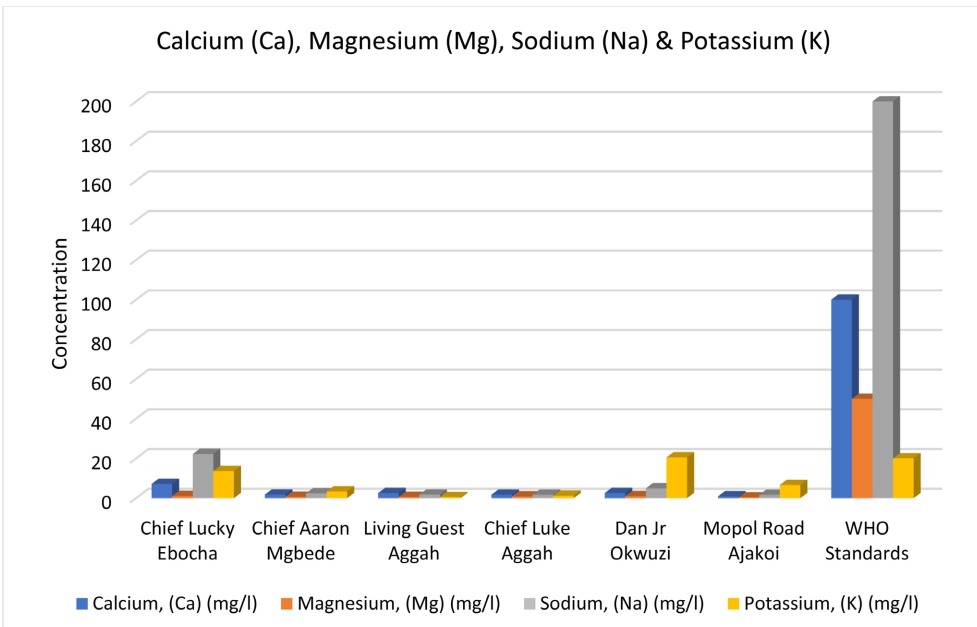

Figure 6. Calcium (Ca), Magnesium (Mg), Sodium (Na) and Potassium (K) concentration across various sites.

from 5.17 at Living Guest Aggah to 6.16 at Mopol Road Ajakoi, below the WHO recommended range of 6.5 - 8.5. Oxidation-Reduction Potential (ORP) values varied widely, from 9 mV at Chief Lucky Ebocha to 284 mV at Dan Jr. Okwuzi, with some values falling outside the typical range of 200-600 mV recommended by

WHO (Figure 7).

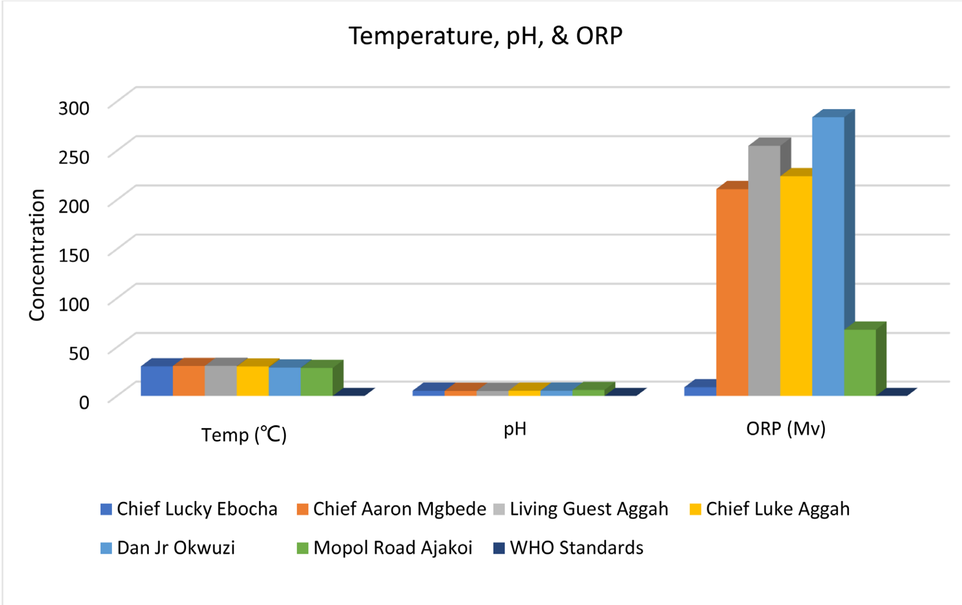

Figure 7. Temperature, pH and ORP level across various sites.

3.7. Conductivity, Turbidity, and Dissolved Oxygen

Conductivity readings were low, ranging from 0.04 uS/cm at Living Guest Aggah to 0.192 uS/cm at Chief Lucky Ebocha, indicating low ionic content. Turbidity values were notably high at Chief Lucky Ebocha (37.3 NTU) and Mopol Road Ajakoi (825 NTU), significantly exceeding the WHO guideline of 5 NTU, suggesting potential particulate contamination. Dissolved Oxygen (DO) levels were satisfactory across all sites, ranging from 5.5 mg/l at Chief Luke Aggah to 6.22 mg/l at Dan Jr Okwuzi, all above the WHO minimum standard of 5 mg/l (Figure 8).

3.8. Total Dissolved Solids and Salinity

Total Dissolved Solids (TDSs) were consistently low, with values ranging from 0.022 mg/l at Living Guest Aggah to 0.106 mg/l at Chief Lucky Ebocha, well below the WHO threshold of 600 mg/l. Salinity measurements showed variability, with significant readings at Chief Lucky Ebocha (100 mg/l) and Chief Aaron Mgbede (500 mg/l), while other sites recorded negligible salinity levels. These values are all within the acceptable range set by WHO, ensuring the water's palatability and safety for consumption (Figure 9).

4. Discussion

The turbidity levels observed in the Chief Lucky's well in Ebocha and the well at Ajakoi present significant concerns. Specifically, turbidity at Chief Lucky's well was 37.3 NTU, while at Ajakoi, it reached a staggering 825 NTU. Both figures exceed the acceptable turbidity limit of 5 NTU by several orders of magnitude. This discrepancy can be attributed to differing environmental conditions: the

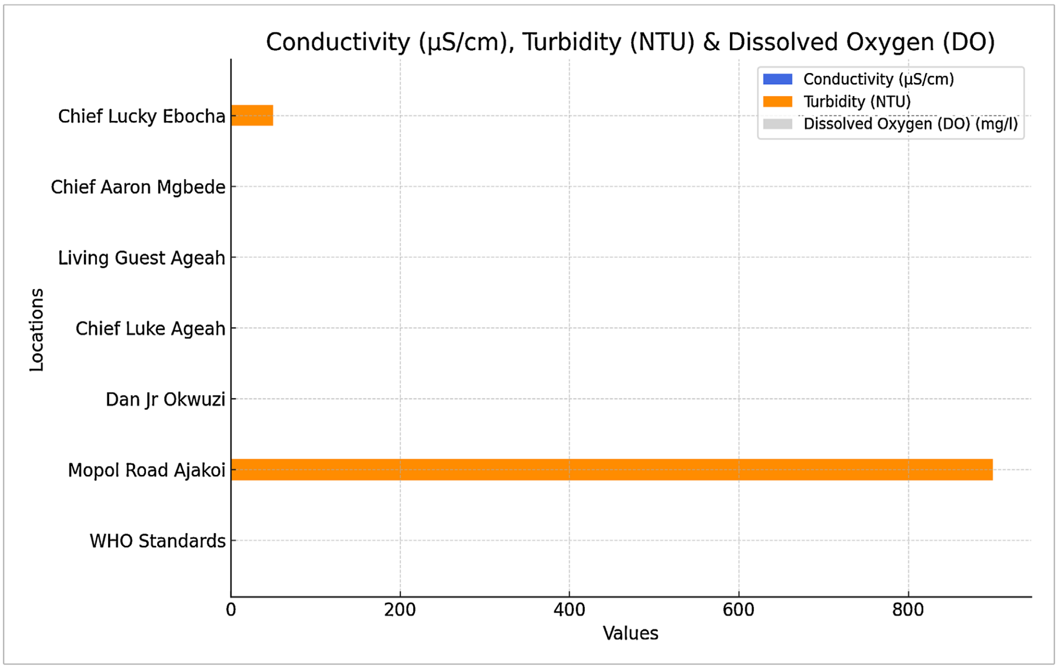

Figure 8. Conductivity, turbidity and dissolved oxygen level across various sites.

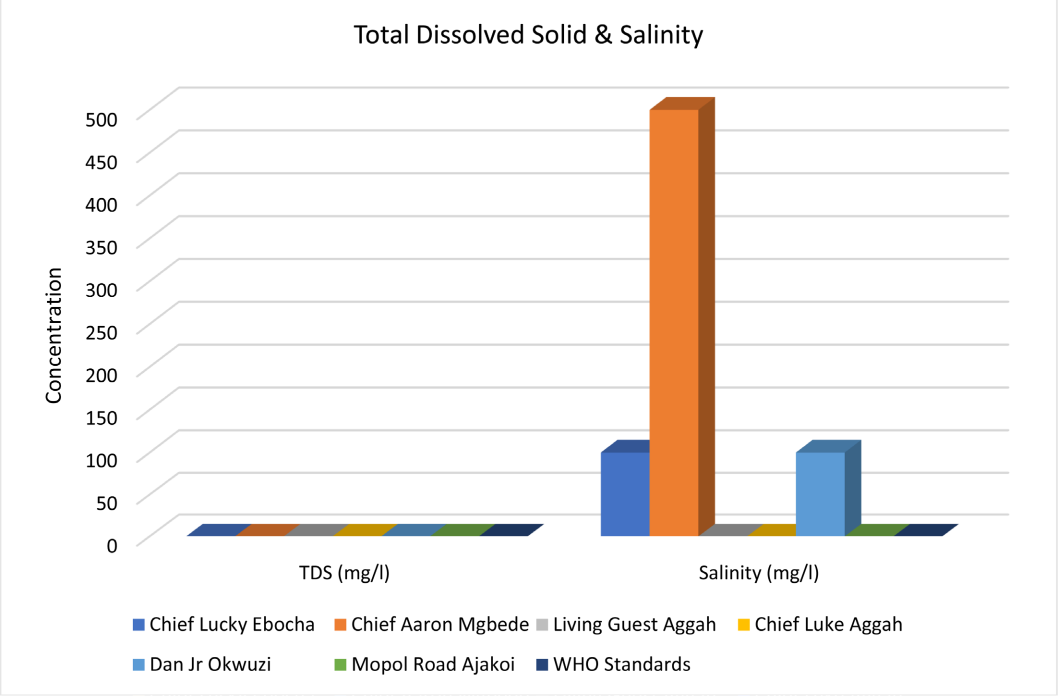

Figure 9. Total dissolved solid and salinity level across various sites.

Ajakoi well is influenced by runoff events, whereas the Ebocha well was nearly dry at the time of sampling, reflecting dry-weather turbidity. Manganese traces were detected in all wells except Chief Aaron's well in Stone Village, Mgbede, with higher concentrations found in the Ebocha and Okwuzi wells at 0.126 mg/L and 0.135 mg/L, respectively. This elevated manganese concentration may indicate particulate pollution from gas flaring. The absence of manganese in Chief Aaron's well, which might be a deeper groundwater source, suggests that the other wells are likely affected by atmospheric pollution from industrial activities, as supported by previous research. For instance, Egwurugwu *et al.* [62]-[64] reported high manganese levels in shallow groundwater from a neighboring oil field, and Emumejaye [65] identified hazardous metals, including manganese, in gas flare-dried tapioca at Gana Flow Station, Agbarha, Delta State. Manganese exposure has been linked to several health issues, including neurological disturbances akin to parkinsonism, and symptoms such as hallucinations, memory problems, and muscle weakness [13] [14]. Our findings are consistent with these health risks, with manganese concentrations indicating potential public health concerns due to industrial pollution. In addition to manganese, potassium concentrations in the wells were relatively consistent, at 13.615 mg/L and 20.504 mg/L for Ebocha and Okwuzi, respectively. However, Ebocha exhibited higher levels of sodium (22.206 mg/L), calcium (7.145 mg/L), sulfate (5.00 mg/L), and nitrate (0.3 mg/L), which may be indicative of washout effects from NO_x and SO_x polluted air. The wells also displayed low acidic pH values ranging from 5.17 to 6.16. This acidity could be a sign of acid precipitation, a common issue in oil-producing regions of the Niger Delta [30] [34]. Although salinity levels were within acceptable limits across most wells, the Stone Village Mgbede well had notably high salinity at 500 mg/L. This high salinity is likely due to the swampy environment and reduced groundwater mobility, which increases salt concentration. Acidic water, as observed in all sampled wells, can be corrosive and leach metal ions into groundwater systems, causing issues such as pipe corrosion and potential health problems due to low body pH [33]. Corrosive water can lead to metal leaching, resulting in water quality issues over time. Comparing our findings with previous studies reveals a broad pattern of environmental degradation due to industrial activities. For instance, Morufu and Clinton's [1] study offers a comprehensive assessment of trace elements in surface and groundwater quality. The research was conducted in oil and gas exploration areas, emphasizing the pervasive issue of water contamination. This study provides valuable baseline data on the concentrations of various trace elements, highlighting significant environmental and public health concerns. The findings underscore the need for stringent regulatory measures and continuous monitoring to mitigate the adverse effects of trace elements on human health and the environment. In comparison to our current study, Morufu and Clinton's [1] work primarily focuses on the presence of trace elements, whereas this research delves deeper into the broader spectrum of groundwater contaminants, including organic pollutants and microbial contaminants. Both studies, however, converge on the critical importance of assessing and managing water quality in regions impacted by industrial activities. This parallel highlights a persistent issue of environmental degradation and the urgent need for sustainable solutions. The 2022 study by Raimi *et al.* [2] [3] expands on previous work by examining the hydrochemical appraisal of toxic metals and seasonal variations in drinking water quality within oil and gas field areas. This research reveals significant seasonal fluctuations in metal concentrations, influenced by environmental and anthropogenic factors. The study's findings indicate heightened levels of toxic metals during specific seasons, posing increased health risks to local populations. This research corroborates these findings, emphasizing the dynamic nature of water quality in response to seasonal changes. The integration of seasonal variation analysis is crucial for developing effective water management strategies. Additionally, Raimi *et al.* [2] [3] focus on toxic metals complements our broader investigation into various contaminants, providing a more holistic understanding of the factors affecting groundwater quality in industrial regions.

The 2024 study by Fubara and colleagues addresses hydrocarbon profiles in crude oil-polluted soil and evaluates bioremediation techniques using Pleurotus ostreatus and Eisenia fitida. This research underscores the effectiveness of bioremediation in mitigating hydrocarbon contamination, highlighting the potential for sustainable environmental management practices [4] [5] [66]. The study's findings are pivotal in promoting the use of bioremediation as a viable solution for soil and groundwater contamination in oil-polluted regions. Comparatively, our study also explores bioremediation strategies, focusing on microbial diversity and its role in enhancing soil and groundwater quality. Both studies emphasize the importance of bioremediation, yet Fubara *et al.*'s [4] [5] [66] work provides specific insights into the efficacy of particular organisms, which could inform future applications and research in this field. The convergence of findings from both studies reinforces the viability of bioremediation as a critical tool for environmental restoration. Keme-Iderikumo and colleagues [6] investigate the impact of gas flaring on artisanal fisheries in the downstream area of Taylor Creek, Bayelsa State, Nigeria. Their research highlights the adverse effects of gas flaring on aquatic ecosystems, particularly on fish populations, which are crucial for local livelihoods. The study emphasizes the need for stringent regulations and the adoption of cleaner technologies to mitigate environmental degradation. Thus, this research aligns with these findings by addressing the broader environmental impacts of industrial activities, including water and soil contamination. The focus on fisheries provides a specific angle that complements our more general investigation into water quality. Both studies underscore the multifaceted nature of environmental pollution and the necessity for comprehensive regulatory frameworks to protect ecosystems and human health. Kader *et al.* [61] present a concise study on essential parameters for the sustainability of lagoon waters, emphasizing scientific literature reviews. This research identifies key factors influencing lagoon water quality and sustainability, providing a foundation for future research and policy development. The study's findings are critical for understanding the complex interactions within aquatic ecosystems and for developing sustainable management practices. Hence, this current study complements this by providing empirical data on groundwater quality and its implications for broader aquatic systems. Both studies highlight the interconnectedness of various environmental compartments and the importance of integrated management approaches. Kader *et al.*'s focus on lagoon waters adds a valuable perspective to our understanding of water quality issues in industrial regions. Raheem and colleagues [9] explore the application of biomaterials in ecological remediation, particularly the use of white-rot fungus Pleurotus sajor-caju for bioremediation of heavy metals in cement-contaminated soil. This study demonstrates the potential of biomaterials to effectively reduce heavy metal concentrations, offering a sustainable alternative to traditional remediation methods. In comparison, this research also investigates bioremediation, albeit within a different context. Both studies underscore the efficacy of biological approaches in mitigating soil and water contamination. Raheem *et al.*'s focus on specific biomaterials provides valuable insights that could inform the selection and application of bioremediation strategies in various contaminated environments. Awogbami *et al.* [47] [50] [51] conducted a hydrogeochemical evaluation of seasonal variability in groundwater quality dynamics in gold mining areas of Osun State, Nigeria. Their study reveals significant seasonal variations in water quality, influenced by mining activities and environmental factors. The research underscores the importance of continuous monitoring and the need for effective management strategies to mitigate contamination. This study similarly addresses seasonal variations, highlighting the dynamic nature of groundwater quality in industrial regions. The findings from Awogbami *et al.'s* research provide a valuable comparison, reinforcing the necessity for adaptive management approaches that account for seasonal fluctuations. Both studies emphasize the critical role of hydrogeochemical assessments in understanding and managing groundwater quality.

5. Summary

In summary, the comparative analysis of these studies reveals a consistent theme of environmental degradation due to industrial activities, particularly in oil and gas exploration areas. The emphasis on trace elements, toxic metals, hydrocarbon contamination, and bioremediation underscores the multifaceted nature of water and soil pollution. Each study contributes unique insights, whether through specific contaminant assessments, seasonal variation analysis, or the exploration of remediation strategies. Collectively, these findings highlight the urgent need for comprehensive environmental management practices, continuous monitoring, and the adoption of sustainable technologies to mitigate the adverse impacts of industrial activities on human health and the environment.

6. Conclusion

This study provides a detailed examination of groundwater quality and the environmental impacts of industrial activities in the Mgbede Oil Fields of South-South Nigeria. Utilizing standard methods for the examination of water and wastewater, this investigation reveals significant contamination issues in the selected communities, notably Ebocha and Okwuzi. Our findings indicate that these communities experience higher concentrations of manganese, which may be linked to particulate pollution from continuous gas flaring. Additionally, all studied wells exhibited acidity levels that exceeded standard acceptable limits, underscoring a critical environmental health concern. Thus, the study highlights that both air and groundwater quality in the Mgbede Oil Fields is adversely affected by ongoing oil production activities, including gas flaring, drilling waste management, and oil spills. The observed contamination levels surpass international standards, indicating substantial risks to environmental health and human safety. This research aligns with existing literature, reinforcing the understanding of significant contamination levels and seasonal variations in groundwater quality due to oil and gas exploration activities. Through a combination of descriptive statistics, GIS-based spatial analysis, and ecological risk assessments, we identified key contaminants, including heavy metals, hydrocarbons, and microbial pollutants, and mapped their distribution patterns across the study area. The data reveal that oil and gas exploration activities are major contributors to groundwater pollution, with notable seasonal fluctuations in contaminant levels that pose severe risks to both environmental health and public safety. One of the key findings of the study is the effectiveness of bioremediation strategies for mitigating groundwater contamination. The use of specific microorganisms and bioremediation agents demonstrated potential in reducing contaminant levels, offering viable solutions for addressing pollution in the Niger Delta region. In addition to expanding the existing body of knowledge on groundwater quality, this study emphasizes the urgent need for enhanced environmental management practices and the development of effective remediation strategies. The results advocate for a comprehensive approach to managing the impacts of industrial activities, recommending both preventive and corrective measures to protect groundwater resources.

7. Highlights/Summary Points

- **Groundwater Contamination:** Significant levels of manganese, heavy metals, and hydrocarbons were detected in groundwater, with elevated contamination in Ebocha and Okwuzi communities linked to gas flaring and oil production activities.
- **Acidity Levels:** All studied wells exhibited acidity levels above international standards, indicating severe environmental pollution.

8. Policy Implications and Future Research

8.1. Policy Implications

The study's findings highlight the critical need for stricter environmental regulations and enforcement to manage industrial emissions and waste from oil and gas exploration. Policymakers should implement comprehensive environmental protection frameworks that include regular groundwater quality monitoring, stringent pollutant discharge controls, and the adoption of best practices for waste management. Additionally, there is a need to support research and development in bioremediation technologies and integrate these methods into pollution

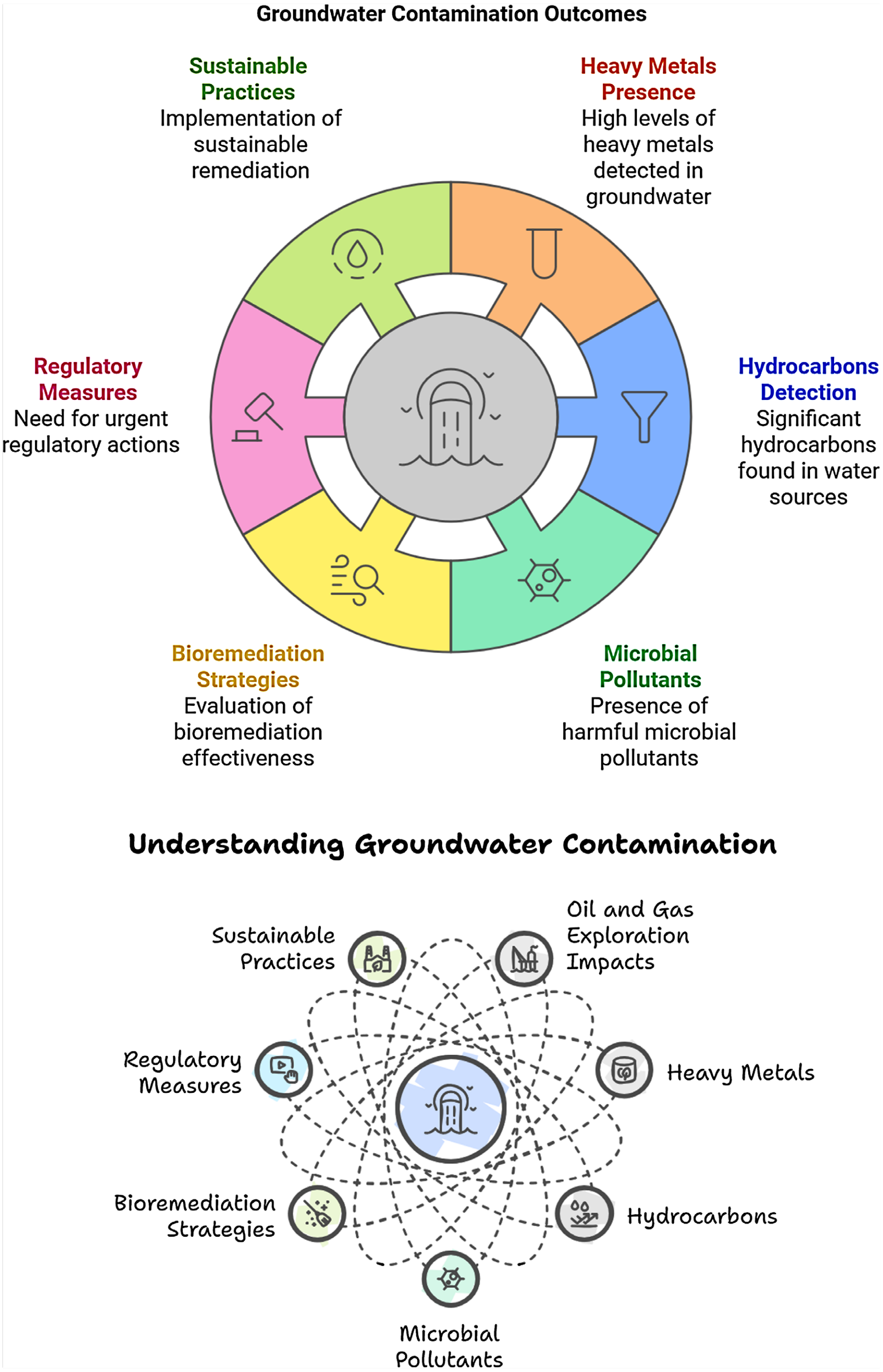

Figure 10. Understanding and outcomes of groundwater contamination.

management strategies.

8.2. Future Research Directions

Future research should explore advanced bioremediation techniques and assess their long-term effectiveness under varying environmental conditions. Further studies could also investigate the cumulative effects of multiple contaminants on groundwater ecosystems and human health. Additionally, the development of innovative monitoring technologies for real-time pollutant detection and the exploration of remote sensing methods for environmental management are important areas for future research.

9. Significance Statement

This study significantly advances the understanding of groundwater contamination in the Mgbede Oil Fields, revealing the profound impacts of oil and gas exploration activities on water quality and environmental health. By documenting high levels of heavy metals, hydrocarbons, and microbial pollutants and evaluating the effectiveness of bioremediation strategies, the research contributes to a holistic understanding of the environmental challenges facing the Niger Delta. The study underscores the urgency of implementing effective regulatory measures and sustainable remediation practices to safeguard groundwater resources and protect both environmental and human health. Thus, graphically, it is represented in **Figure 10**.

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Authors' Contributions

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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