



Evaluation of Ferrous Iron Concentration and Ecosystem and Water Resources Management Strategies for the Mitigation of Ferrous Iron Concentration in Bonny Island Underground Water, Rivers State, Nigeria

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Abstract

Groundwater is an important source of domestic and industrial water supply in Bonny Island, Rivers State, Nigeria, where intensive oil and gas activities occur within a sensitive coastal environment. This study evaluation of ferrous iron concentration and ecosystem and water resources management strategies for the mitigation of ferrous iron concentration in Bonny Island underground water, Rivers State, Nigeria. The study adopted a descriptive cross-sectional design complemented by field-based hydrochemical assessment. Five communities of Bonny Town, Ayambo, Oguede, Akiama and Finima were investigated. The population of the selected communities was 56,470, from which a minimum sample size of 397 was determined. However, 407 questionnaires were distributed and 361 valid responses were obtained, representing an 88.7% response rate. Groundwater samples were collected from selected shallow and deep wells and boreholes and analysed for iron concentration. Questionnaire data were analysed using descriptive statistics and Pearson's chi-square test. The results showed that respondents perceived hazard and effects management workshops as the most prominent groundwater protection strategy, with 73.7% positive responses, followed by water treatment workshops (68.4%) and HSE gap analysis (67.6%). Hydrochemical evidence showed increasing iron concentrations at some greater depths, with concentrations of 1.32 mg/L at 60 ft, 2.68 mg/L at 120 ft and 3.66 mg/L at approximately 1,500 ft. The test of the second hypothesis produced $\chi^2(16) = 78.34$, $p < .001$, indicating a statistically significant association between ecosystem protection/water resources management strategies and perceived mitigation of groundwater contamination. The study concludes that groundwater protection in Bonny Island requires integrated environmental monitoring, appropriate borehole siting and depth management, effective water treatment and strengthened regulatory enforcement.

Keywords: Ferrous Iron, Ecosystem Protection, Water Resources Management, Bonny Island, Niger Delta, Groundwater Contamination

Introduction

Groundwater constitutes an important source of domestic, commercial and industrial water supply in many communities, particularly where reliable surface-water sources are limited. Its quality is influenced by geological formations, groundwater flow, recharge processes, physicochemical conditions and human activities. Iron is one of the naturally occurring elements commonly found in groundwater, particularly under reducing conditions where ferrous iron (Fe^{2+}) remains soluble and mobile. When groundwater containing dissolved Fe^{2+} is exposed to atmospheric oxygen, oxidation may result in ferric iron precipitates, producing reddish-brown staining and other aesthetic and operational problems (Hem, 1985; APHA, 2017).

The occurrence of iron in groundwater is particularly relevant in coastal and sedimentary environments such as the Niger Delta. The geological composition of the region, organic-rich sediments, wetlands, groundwater conditions and extensive human activities can influence the mobilisation and distribution of iron. Previous investigations in the Niger Delta have documented concerns regarding elevated iron concentrations and groundwater quality. Recent research has also demonstrated the importance of hydrogeochemical processes, spatial characteristics and anthropogenic influences in understanding groundwater quality in Nigeria (Jolaosho et al., 2024; Iruoghene et al., 2024; Omeka et al., 2024).

Bonny Island presents a particularly important case because groundwater is used by residents and industries while oil and gas exploration, processing, transportation, construction and associated urban activities occur within the same environment. The interaction between natural hydrogeological conditions and anthropogenic activities creates the need for systematic groundwater assessment and environmental management. The study's field investigation identified ferrous iron in groundwater at particular depths, with concentrations increasing substantially in some deeper sources. The study also observed that some water sources were unsuitable for drinking without appropriate treatment.

Ecosystem protection and water resources management are therefore important components of groundwater conservation. Ecosystem protection encompasses environmental monitoring, hazard identification, environmental sensitivity assessment, environmental auditing, pollution prevention and conservation activities. Water resources management involves monitoring water quality, regulating abstraction, selecting appropriate groundwater sources, treating contaminated water and protecting aquifers from further deterioration. In Bonny Island, these measures are particularly relevant because groundwater quality has implications for household water supply, industrial operations, environmental sustainability and public health. The study therefore focuses specifically on the development of a water resources conservation plan to protect groundwater from Fe^{2+} contamination in Bonny Island, River State, Nigeria. The hypothesis states that effective formulation and implementation of ecosystem protection and water resources management strategies would not significantly mitigate groundwater contamination.

Statement of the Problem

Groundwater contamination constitutes an important environmental challenge in areas experiencing intensive industrialisation and rapid urban development. In Bonny Island, the problem is compounded by the dependence of residents and industries on groundwater and the presence of extensive oil and gas activities. Although groundwater occurs beneath the island, its quality is not uniform across all sources. The study identified differences in iron concentrations according to groundwater depth and source, suggesting that groundwater abstraction without adequate hydrogeological assessment may expose users to elevated iron levels.

The problem is not limited to the presence of iron itself. Elevated iron affects the aesthetic quality and usability of water and may result in reddish-brown precipitation, staining of plumbing facilities and increased treatment requirements. The study reported an iron concentration of 3.66 mg/L in raw water from a deep borehole at Hospital Road Water Treatment Plant, compared with the World Health Organization guideline value of 0.3 mg/L. It also recorded 2.68 mg/L at a 120-ft source and 1.32 mg/L at a 60-ft source.

Despite these concerns, there is inadequate integration of groundwater-quality monitoring with ecosystem protection and water-resource management in the study area. Existing environmental management activities may be undertaken independently without being sufficiently linked to groundwater protection, borehole-depth management, hydrogeological assessment and treatment requirements.

The central problem addressed by this article is therefore whether effective ecosystem protection and water resources management strategies can contribute meaningfully to mitigating groundwater contamination by ferrous iron in Bonny Island. Addressing this problem is essential for developing evidence-based groundwater conservation measures that can protect water users while supporting sustainable industrial and community development.

Review of Literature

Theoretical Perspective

Three theories are relevant to understanding Fe^{2+} contamination and its mitigation in Bonny Island: Hydrogeochemical Evolution Theory, Redox Theory and Aquifer Vulnerability Theory.

a. Hydrogeochemical Evolution Theory explains groundwater chemistry as the product of interactions between groundwater and geological materials during groundwater movement. It is useful for understanding the contribution of iron-bearing geological materials to groundwater chemistry.

b. Redox Theory explains the transformation and mobility of iron under changing oxidation-reduction conditions. Under oxygen-deficient conditions, Fe^{3+} may be reduced to soluble Fe^{2+} , whereas oxygen exposure promotes oxidation and precipitation. The theory therefore provides an important explanation for the occurrence of dissolved ferrous iron in groundwater.

c. Aquifer Vulnerability Theory provides the principal framework for this article because it explains why some groundwater systems are more susceptible to contamination than others. Vulnerability is influenced by groundwater depth, geological formations, permeability, recharge conditions and human activities.

The theories collectively suggest that groundwater contamination is not determined by a single factor. Geological conditions determine the potential source of iron, redox conditions influence its mobility, while aquifer characteristics and human activities determine exposure and vulnerability. Consequently, effective mitigation requires an integrated water resources management approach.

Empirical Literature Review

Groundwater iron contamination may arise from both natural and anthropogenic processes. Natural sources include the weathering and dissolution of iron-bearing minerals within aquifer materials. The mobilisation of iron is strongly influenced by pH, dissolved oxygen, redox conditions, organic matter and groundwater residence time. Under reducing conditions, ferric iron can be converted to soluble ferrous iron, allowing it to remain in groundwater and move through aquifer systems (Hem, 1985; Appelo & Postma, 2005).

Research in different groundwater environments demonstrates that iron concentrations may vary substantially between wells and aquifer depths. The U.S. Geological Survey's assessment of the glacial aquifer system in the northern United States found considerable spatial variation in iron concentrations and identified relationships between iron occurrence, groundwater chemistry and reducing conditions (Groschen et al., 2009). Similar concerns have been reported in African groundwater systems, including South Africa, where iron-rich groundwater has been associated with geological conditions and groundwater chemistry (Demlie et al., 2014).

Nigerian studies have also established the relevance of groundwater hydrochemistry to water-resource management. Research in Lagos and the Niger Delta has identified variations in groundwater quality and the occurrence of heavy metals and other chemical constituents. Recent hydrogeochemical studies have increasingly emphasised the need to integrate water chemistry, geological conditions and spatial assessment when evaluating groundwater quality (Jolaosho et al., 2024; Omeka et al., 2024).

The Bonny Island study extends this body of evidence by focusing specifically on Fe^{2+} occurrence at different groundwater depths and linking groundwater quality to environmental management strategies. The study found that shallow sources at approximately 3–24 ft had insignificant iron concentrations, whereas the 60-ft, 120-ft and approximately 1,500-ft sources showed substantially higher concentrations.

A major implication of the empirical literature is that groundwater protection cannot rely exclusively on treatment after abstraction. Prevention, monitoring and hydrogeological assessment are also necessary. Groundwater protection should therefore involve identifying vulnerable aquifer zones, monitoring groundwater quality, regulating potentially contaminating activities and ensuring that abstraction facilities are located at depths and locations capable of producing manageable-quality water.

Methodology

The study adopted a descriptive cross-sectional research design complemented by field-based hydrochemical assessment. The design enabled the researcher to collect questionnaire data from respondents and groundwater samples from selected sources without manipulating environmental conditions. Groundwater samples were collected from shallow and deep boreholes and wells and subjected to laboratory analysis. The investigation covered five selected communities in Bonny Island: Bonny Town, Ayambo, Oguede, Akiama and Finima. The communities were selected because of their geographical spread and the presence of oil and gas activities. The combined population of the selected communities was 56,470 as detailed in Table 1.

Using the Yamane formula at a 5% precision level, the minimum sample size was estimated at 397 respondents. However, 407 questionnaires were distributed, of which 361 were properly completed and returned, representing an 88.7% response rate (Table 2).

Table 1: Population of the Selected Communities

Community	Population
Bonny Town	18,520
Ayambo	9,550
Oguede	8,800
Akiama	9,000
Finima	10,600
Total	56,470

Source: Researcher's field survey (2026).

Table 2: Questionnaire Distribution and Retrieval

Respondent category	Distributed	Returned
Bonny Town residents/host community	93	84
Bonny Town oil staff/contractors	36	34
Ayambo residents/host community	47	38
Ayambo oil staff/contractors	22	18
Oguede residents/host community	48	41
Oguede oil staff/contractors	20	16
Akiama residents/host community	46	43
Akiama oil staff/contractors	21	19
Finima residents/host community	51	47
Finima oil staff/contractors	23	21
Total	407	361

Response rate = 88.7%.

Source: Researcher's Field Survey (2026).

Groundwater samples were collected from selected boreholes and wells at different depths. The study used purging before sampling to remove stagnant water and obtain a more representative groundwater sample. A battery-powered peristaltic pump and decontaminated sampling equipment were used. The collected samples were transported for laboratory analysis.

The study investigated iron concentration and related groundwater characteristics. Sampling included shallow domestic wells and deeper industrial water sources. The study reported that industrial water-treatment plants in Bonny Island obtained raw groundwater from depths of approximately 1,500 ft, while some domestic sources were between 60 and 120 ft.

Questionnaire responses were summarised using frequencies and percentages. Pearson's chi-square test was used to evaluate Hypothesis Two at the 0.05 significance level. The hypothesis tested whether respondents' perceptions of ecosystem protection and water resources management strategies were significantly associated with mitigation of groundwater contamination.

Findings

Groundwater Iron Concentrations

The hydrochemical assessment demonstrated that iron concentrations differed according to groundwater source and depth in table 3. The study recorded insignificant iron contamination in some shallow wells, while higher concentrations occurred in deeper sources.

The findings from Table 3 indicated that groundwater quality in Bonny Island cannot be assessed solely from the existence of a borehole. Depth, geological conditions and the specific aquifer zone accessed by the borehole are important considerations. The study reported that sources at 60 ft and above generally recorded higher iron concentrations.

Table 3: Selected Groundwater Iron Concentrations by Depth

Water source	Approximate depth	Iron concentration (mg/L)	Interpretation
New Jerusalem shallow well	3 ft	Insignificant	Low
Macaulay domestic well	24 ft	Insignificant	Low
Bina Pure Water Plant	60 ft	1.32	Elevated
Nourish Pure Water Plant	120 ft	2.68	Elevated
Hospital Road Water Treatment Plant	1,500 ft	3.66	Highly elevated
Akiama Water Treatment Plant	~1,500 ft	>3.00	Highly elevated
Finima Water Treatment Plant	~1,500 ft	>3.00	Highly elevated

Source: Researcher's field survey and laboratory analysis (2065).

Perceived Condition of Water Sources

Respondents also provided assessments of the suitability of available water sources.

Table 4: Perceived Condition of Water Sources in Bonny Island

Perceived condition	Frequency	Percentage (%)
Fit for drinking and other domestic purposes	87	24.3
Fit for other domestic purposes only	209	58.4
Unfit for drinking and other domestic purposes	62	17.3
Total	358	100.0

Source: Researcher's field survey (2026).

The results in Table 4 indicated that only 24.3% of respondents considered available water fit for drinking and other domestic purposes, while 58.4% considered it suitable only for other domestic uses and 17.3% regarded it as unsuitable for both drinking and other domestic purposes.

Ecosystem Protection and Water Resources Management Strategies

The study examined respondents' perceptions of environmental and groundwater protection activities.

Table 5: Perceived Effectiveness of Ecosystem Protection and Groundwater Management Strategies

Strategy	SA	A	N	D	SD	Positive Response (%)
HSE gap analysis	146	98	61	19	37	67.6
Environmental Sensitivity Index mapping	125	76	84	32	44	55.7
Water treatment workshop	154	93	48	39	27	68.4
Hazard and effects management workshop	137	129	32	41	22	73.7
Groundwater protection strategies workshop	104	107	83	38	29	58.4
Total	666	503	308	169	159	—

SA = Strongly Agree; A = Agree; N = No Idea; D = Disagree; SD = Strongly Disagree.

Note: Positive response represents Strongly Agree + Agree.

Source: Researcher's field survey (2026).

From Table 5, the highest positive response was recorded for hazard and effects management workshops (73.7%), followed by water treatment workshops (68.4%) and HSE gap analysis (67.6%). Environmental Sensitivity Index mapping recorded 55.7%, while groundwater protection strategies workshops recorded 58.4%.

Test of Hypothesis Two

H₀₂: The formulation and effective implementation of ecosystem protection and water resources management strategies in Bonny Island will not significantly mitigate groundwater contamination in the study area.

The data from Table 5 were utilized in testing the hypothesis. The data were inputted into the computer with the SPSS software and the results were obtained.

Table 6: Observed Frequencies for Hypothesis Two

Management strategy	SA	A	N	D	SD	Total
HSE gap analysis	146	98	61	19	37	361
Environmental Sensitivity Index mapping	125	76	84	32	44	361
Water treatment workshop	154	93	48	39	27	361
Hazard and effects management workshop	137	129	32	41	22	361
Groundwater protection strategies workshop	104	107	83	38	29	361
Total	666	503	308	169	159	1,805

Source: Researcher's field survey (2026).

Table 7: Pearson Chi-Square Test of Hypothesis Two

Statistic	Result
Pearson χ^2	78.34
Degrees of freedom	16
p-value	< .001
Cramér's V	0.104
Decision	Reject H_{02}
Significance level	0.05

Source: SPSS version 27

Interpretation: The calculated Pearson chi-square value of 78.34 with 16 degrees of freedom is statistically significant at $p < .001$. Therefore, H_{02} is rejected. This indicates a statistically significant association between the ecosystem protection/water resources management strategies and respondents' perceptions concerning mitigation of groundwater contamination.

The magnitude of Cramér's V (0.104) indicates that the association is **small**, meaning that although the relationship is statistically significant, the management strategies explain only a modest degree of variation in the categorical response pattern. Consequently, the result should not be interpreted as evidence that the strategies alone cause a reduction in groundwater contamination.

Discussion of Findings

The study demonstrates that groundwater contamination by ferrous iron is an important water-quality concern in Bonny Island. The laboratory results show a clear difference between some shallow sources and deeper groundwater sources. Shallow wells at approximately 3–24 ft recorded insignificant iron concentrations, whereas concentrations increased to 1.32 mg/L at 60 ft, 2.68 mg/L at 120 ft and 3.66 mg/L at approximately 1,500 ft in the Hospital Road Water Treatment Plant.

The occurrence of elevated iron at different depths supports the relevance of hydrogeological assessment in groundwater development. A deeper borehole should not automatically be regarded as producing better-quality water. Rather, the quality of abstracted groundwater depends on the particular aquifer zone accessed, geological materials encountered and groundwater chemistry. This is particularly important in Bonny Island, where the study indicates that iron-bearing formations can influence groundwater quality.

The respondents' perceptions further demonstrate the importance of management interventions. Hazard and effects management workshops received the highest positive response (73.7%), indicating relatively strong recognition of their importance. Water treatment workshops and HSE gap analysis also received high positive responses. These findings suggest that environmental-management programmes can contribute to awareness and preparedness for groundwater-quality problems which is in consonance with the findings of Jolaosho et al., 2024 and Omeka et al., 2024.

However, the relatively lower positive responses for Environmental Sensitivity Index mapping and groundwater protection strategy workshops indicate that some potentially important preventive measures may not be sufficiently institutionalised. Effective groundwater management requires moving beyond general environmental awareness towards systematic mapping of sensitive groundwater zones, routine monitoring, hydrogeological investigations and specific groundwater-protection plans.

The significant chi-square result provides statistical evidence of an association between the management strategies and respondents' perceptions of mitigation. However, the small Cramér's V indicates that the relationship is modest. This distinction is important. Statistical significance demonstrates that the observed response patterns are unlikely to be independent, but it does not establish that the management strategies

directly caused the observed groundwater-quality conditions. Actual mitigation requires longitudinal groundwater monitoring and direct measurement of changes in iron concentrations following implementation of management interventions.

The findings are consistent with the broader understanding that groundwater-quality management requires an integrated approach combining hydrogeological assessment, environmental regulation, pollution prevention and treatment. The study's theoretical framework similarly indicates that geological processes, redox conditions and aquifer vulnerability interact to influence groundwater iron behaviour.

Conclusion

The study concludes that ferrous iron contamination is present in groundwater in Bonny Island and that its concentration varies among groundwater sources and depths. Some shallow sources recorded insignificant iron concentrations, whereas several deeper sources recorded concentrations considerably above the WHO guideline value of 0.3 mg/L. The findings demonstrate that groundwater abstraction and development in Bonny Island require careful hydrogeological assessment rather than reliance on depth alone.

The study also establishes that ecosystem protection and water resources management strategies are important components of groundwater conservation. Respondents particularly recognised hazard and effects management workshops, water treatment workshops and HSE gap analysis as important environmental-management activities.

The statistical test of the hypothesis produced a significant association, $\chi^2(16) = 78.34$, $p < .001$, leading to rejection of the null hypothesis. Nevertheless, the small Cramér's V of 0.104 indicates that the association is modest. The result therefore supports the relevance of integrated management but does not establish a direct causal effect of the strategies on groundwater contamination.

Effective groundwater protection in Bonny Island should consequently combine preventive environmental management with groundwater-quality monitoring, hydrogeological expertise, appropriate borehole siting and depth selection, water treatment and stronger regulation of activities capable of affecting groundwater resources.

Recommendations

- 1. Establish routine groundwater-quality monitoring.** Government agencies, industries and relevant environmental institutions should establish regular monitoring programmes for Fe^{2+} and other important groundwater-quality parameters across Bonny Island. Monitoring should be undertaken at different depths and locations to identify changes in groundwater quality over time.
- 2. Develop a groundwater protection and conservation plan.** Bonny Island should have a dedicated groundwater management framework identifying vulnerable aquifer zones, groundwater-quality monitoring points, acceptable abstraction practices, pollution-control measures and emergency responses to contamination.
- 3. Strengthen hydrogeological assessment before borehole construction.** Borehole development should be preceded by hydrogeological investigations capable of identifying aquifer characteristics and groundwater zones with lower iron concentrations. The study specifically recommends that groundwater users extract water from aquifer zones with manageable iron levels.
- 4. Provide appropriate water treatment facilities.** Given the elevated iron concentrations reported in some sources, robust treatment systems should be provided where groundwater is intended for potable use. The treatment process should be designed according to the actual raw-water characteristics.
- 5. Strengthen industrial environmental regulation.** Oil and gas companies and other industrial operators should be subjected to continuous environmental monitoring and stricter compliance requirements relating to groundwater protection, waste management and pollution prevention.

6. Institutionalise environmental sensitivity mapping. Environmental Sensitivity Index mapping should be integrated into groundwater planning and development-control decisions so that environmentally sensitive groundwater and ecological areas receive stronger protection.

7. Increase community participation and environmental awareness. Host communities should be involved in groundwater monitoring, reporting of suspected contamination and environmental-protection programmes. Community knowledge can complement technical monitoring and improve early detection of groundwater-quality problems.

8. Promote coordination among institutions. Relevant government agencies, oil and gas operators, local authorities, community organisations and hydrogeological professionals should establish a coordinated groundwater-management mechanism for Bonny Island.

Limitations of the Study

The study has several limitations that should be considered when interpreting its findings. First, the investigation focused on five selected communities in Bonny Island and therefore may not represent groundwater conditions across all communities in Bonny Local Government Area. Second, the questionnaire component was cross-sectional, meaning that respondents' perceptions were obtained during the study period and may not capture long-term changes in environmental-management practices.

Third, the study combined perceptions of residents and oil and gas personnel/contractors. Although this provides a broader perspective, these groups may have different experiences and knowledge of environmental-management practices. Fourth, groundwater iron concentrations are influenced by complex geological and hydrochemical processes, meaning that questionnaire responses alone cannot establish a direct causal relationship between management strategies and actual changes in contamination.

Finally, fieldwork was affected by community reluctance, security challenges and difficulties associated with accessing some locations. The researcher addressed these challenges through community engagement, local assistance and repeated field visits.

References

- American Public Health Association. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). American Public Health Association.
- Appelo, C. A. J., & Postma, D. (2005). *Geochemistry, groundwater and pollution* (2nd ed.). CRC Press.
- Demlie, M., Hingston, E., & Mnisi, Z. (2014). A study of the sources, human health implications and low-cost treatment options of iron-rich groundwater in northeastern KwaZulu-Natal, South Africa. *Journal of Geochemical Exploration*, 144, 504–510.
- Fetter, C. W. (2018). *Contaminant hydrogeology* (3rd ed.). Waveland Press.
- Garrels, R. M., & Christ, C. L. (1965). *Solutions, minerals, and equilibria*. Harper & Row.
- Groschen, G. E., Arnold, T. L., Morrow, W. S., & Warner, K. L. (2009). *Occurrence and distribution of iron, manganese, and selected trace elements in groundwater in the glacial aquifer system of the northern United States*. U.S. Geological Survey Scientific Investigations Report 2009–5006.
- Hem, J. D. (1985). *Study and interpretation of the chemical characteristics of natural water* (3rd ed.). U.S. Geological Survey Water-Supply Paper 2254.
- Iruoghene, O., Odesa, G. E., Eyankware, M. O., & Efetobo, O. (2024). A comprehensive review of the high iron concentrations reported in groundwater in the Niger Delta sedimentary basin.
- Jolaosho, T. L., Mustapha, A. A., & Hundeyin, S. T. (2024). Hydrogeochemical evolution and heavy metal characterization of groundwater from southwestern Nigeria: An integrated assessment using spatial, indexical, irrigation, chemometric, and health risk models. *Heliyon*, 10(19), e38364.

- Omeka, C. O., et al. (2024). [Groundwater quality and hydrogeochemical assessment study]. *Environmental Science and Pollution Research*, 31, 22284–22307.
- Standards Organisation of Nigeria. (2015). *Nigerian standard for drinking water quality (NIS 554:2015)*. Standards Organisation of Nigeria.
- World Health Organization. (2022). *Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda*. World Health Organization.