

Investigating the Variation in Water Quality from Various Sources in the Niger Delta Region, Nigeria

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Abstract

The study investigated the variation in the quality of surface water, direct rain water, hand roof top rain water and hand dug water in the Niger Delta. Water samples were collected from the four afore-mentioned sources during the wet and dry seasons from the sampling into clean labelled bottles that have been pre-washed and rinsed with distilled water and properly sealed to prevent contamination of the samples. pH and temperature were determined in situ while other physico-chemical properties were determined in the laboratory using standard methods. Relative to pH values, rainwater collected from roofs was more acidic compared to rainfall from open areas whereby the mean pH value was lowest for Port Harcourt at 4.3 ± 0.4 , then 4.5 ± 0.3 for Delta, 4.8 ± 0.4 for Abia, 5.4 ± 0.4 for Ondo, and 5.5 ± 0.3 for Cross River. Overall, the quality of rooftop-collected rainwater in the Niger Delta shows clear degradation compared to rainwater collected directly from open spaces. Although it remained acidic, Cross River and Ondo had far superior water quality than Port Harcourt and Delta. The rivers in Port Harcourt and Delta are the most impacted, showing the highest acidity, ion concentration, and lowest oxygen levels, while those in Cross River and Ondo remain comparatively less affected. Findings revealed that the acidity of water in the Niger Delta varies significantly across both spatial locations and water sources ($F=12.147$; $p=0.000$). The study concluded that generally the Niger Delta groundwater and surface water have been negatively impacted by acid rain and its accompanying anthropogenic emissions with much effects being felt in Port Harcourt and Delta States. Moreover, the quality of rooftop-collected rainwater showed a clear degradation compared to rainwater collected directly from open spaces. This study therefore recommended that policymakers should adopt spatially targeted environmental management plans. States like Port Harcourt and Delta should be prioritized for pollution control interventions, while cleaner states such as Ondo and Cross River should maintain their low-emission profiles through sustainable industrial practices and routine environmental assessments.

Keywords: *Quality, Rainwater, Roof top, Hand dug, Niger Delta, Emissions, Pollution*

Introduction

Water is an essential natural resource that sustains human health, ecological balance, agriculture, and industrial development. Despite the abundance of water on Earth, access to clean and safe water remains a significant challenge in many developing regions, particularly in sub-Saharan Africa. In Nigeria, rapid urbanization, industrialization, population growth,

and inadequate environmental management practices have contributed to the deterioration of water quality in many communities (World Health Organization, 2022). The Niger Delta region, which is characterized by extensive oil exploration and exploitation activities, presents a unique environmental setting where various sources of water are continuously exposed to contamination from anthropogenic and natural processes.

The Niger Delta is one of the largest wetlands in Africa and contains numerous rivers, creeks, estuaries, and coastal water bodies that serve as major sources of domestic water supply for rural and urban populations (Aroh et al., 2011). However, environmental degradation associated with crude oil spills, gas flaring, industrial effluents, agricultural runoff, and improper waste disposal has significantly affected the quality of surface water resources in the region (Nwineewii & Edokpa, 2021). Surface water contamination poses serious health risks due to the presence of pathogens, heavy metals, hydrocarbons, and other pollutants that may exceed recommended safety standards for drinking water (United Nations Environment Programme [UNEP], 2011). Rainwater harvesting has increasingly become an alternative source of water supply in many parts of the Niger Delta because of the region's high annual rainfall. Direct rainwater is often perceived as relatively clean because it originates from atmospheric condensation processes. Nevertheless, atmospheric pollution from gas flaring, industrial emissions, vehicular activities, and airborne particulates may alter the physicochemical characteristics of rainwater before it reaches the ground (Efe, 2014). Acid rain, elevated concentrations of dissolved solids, and microbial contamination have been reported in areas with intense petroleum-related activities, thereby raising concerns about the safety of harvested rainwater for domestic use. Roof top rainwater harvesting systems are widely used by households across the Niger Delta due to unreliable public water supply systems. Although rooftop rainwater may provide a relatively accessible and low-cost source of water, its quality can be influenced by roofing materials, atmospheric deposition, storage conditions, and environmental contaminants accumulated on roof surfaces (Ahmed et al., 2011). Roofing sheets made from asbestos, zinc, aluminum, or painted surfaces may introduce metals and other chemical substances into harvested water. In addition, organic debris, bird droppings, and dust particles deposited on rooftops can contribute to microbial contamination and increased turbidity levels. Hand-dug wells represent another major source of water supply in the Niger Delta, particularly in areas lacking access to piped water systems. These shallow groundwater sources are often vulnerable to contamination due to their proximity to septic tanks, refuse dumps, oil spill sites, and flooded environments. The porous and waterlogged nature of the Niger Delta soils enhances the infiltration of contaminants into groundwater systems (Edet, Nganje, & Ukpung, 2011). Inadequate well construction, poor sanitation practices, and seasonal flooding further increase the risk of microbial and chemical contamination in hand-dug wells. The variation in water quality among surface water, direct rainwater, and rooftop harvested rainwater is an important environmental and public health concern in the Niger Delta. Comparative assessment of these water sources is necessary to determine their suitability for domestic consumption and other uses. Parameters such as pH, electrical conductivity, total dissolved solids, turbidity, dissolved oxygen, biochemical oxygen demand, microbial load, and heavy metal concentrations are commonly used indicators for evaluating water quality (APHA, 2017). Understanding the extent of variation among these water sources will provide useful information for environmental monitoring, water resource management, and the formulation of policies aimed at improving access to safe water. Furthermore, several studies have emphasized the relationship between environmental pollution and declining water quality in oil-producing regions of Nigeria (Efe, 2014; UNEP, 2011). However, there remains limited comparative research that simultaneously investigates the quality of surface water, direct rainwater, and rooftop harvested rainwater within the Niger Delta environment. This study

therefore seeks to investigate the variation in the quality of these three major water sources in the Niger Delta by assessing their physicochemical and microbiological characteristics in relation to established national and international water quality standards. The findings of the study are expected to contribute to existing knowledge on water resource sustainability and provide recommendations for improving water safety and public health in the region.

Materials and Methods

The study was carried out in the entire Niger Delta Region. The Niger Delta region is located between Latitudes 5°31'N and 5°33'N and Longitudes 5° 30'E and 5° 32'E. One third of the region is made of wetlands and houses the third largest wetland forest in the world (Efe, 2010). The area is being endangered by gas flaring and oil pollution (Mogboruko et al., 2024). The region experiences subequatorial climate that is now influenced by gas flaring. For instance, mean temperature generally ranges between 35°C and 37°C. Rainfall amount is over 300cm without a distinctive dry season, with monthly rainfall (January – December) averaging 2.5cm. Rain occurs every month of the year, but of varying duration. Primarily, rainfall is controlled by two air masses, the South-West monsoon which derives its origin from the sub-tropical high-pressure belt over the Southern Atlantic Ocean. Across the different ecological zones, the Niger Delta is home to diverse assemblages of not evaluated, data deficient, least concern, near threatened, vulnerable, endangered and critically endangered wildlife species. Agbagwa and Ndukwu (2014), have noted that some of the threatened species mostly by oil and gas exploration, which have been previously reported in International Union for Conservation of Nature (IUCN) red list are the pygmy hippopotamus (*Choeropsis liberiensis*), manatees (*Trichechus senegalensis*), maritime hippopotamus (*Hippopotamus amphibious*), Nile crocodile (*Crocodylus niloticus*), slender nosed crocodile (*Crocodylus cataphractus*) and dwarf crocodile (*Osteolaemus tetraspis*). Ohimain (2003) also reported that such wildlife species as the Cape clawless otter (*Aonyx capensis*), African palm nut vulture (*Gypohierax angolensis*), fire-footed squirrel (*Funisciurus pyrropus*), Hammerkop (*Scopus umbretta*), African fish eagle (*Haliaeetus vocifer*), Sclater's guenon (*Cercopithecus sclateri*), sitatunga (*Tragelaphus spekei*), white throated monkey (*Cercopithecus erythrogaster*), which occurred in the area required conservation. With continuous gas flaring activities and associated acid rain, these fauna diversities which abound in this region will be extinct. The Niger Delta region is African largest Delta with the largest mangrove forest. The region is ecologically, politically and economically diverse with oil and gas exploration, farming, manufacturing lumbering, fishing and artisanship as some of the numerous economic activities. The multiplicity of inland water ways has made water transportation a major source of income in the riverine communities. The study adopted a mixed method of experimentation, comparative analysis and survey methods. Primary data for this study was collected using direct field measurements of rainfall amount using rain gauge, determination of the acid in water contents using pH metre, determination of associated pollutants such as NO_x. To get a proper sample for the study the multistage approach was deployed. In the first stage, the area was calibrated into quadrants of 2° by 2°. This enabled the researcher select localities that have historical weather data and a Nigerian Meteorological (NiMet) Station. On the strength of the stratification done (Figure 1), each weather station that fall within the grids calibrated was selected for the study. To improve understanding of the afore mentioned the selected meteorological stations and areas within the grid are Akure, Asaba, Benin, Calabar, Ikom, Ogoja, Ondo, Owerri, Port Harcourt, Umudike, Uyo, Warri and Yenagoa. However, 1 grid was selected in every two states therefore the following states grids were sampled: Ondo, Delta, River, Abia and Cross River.

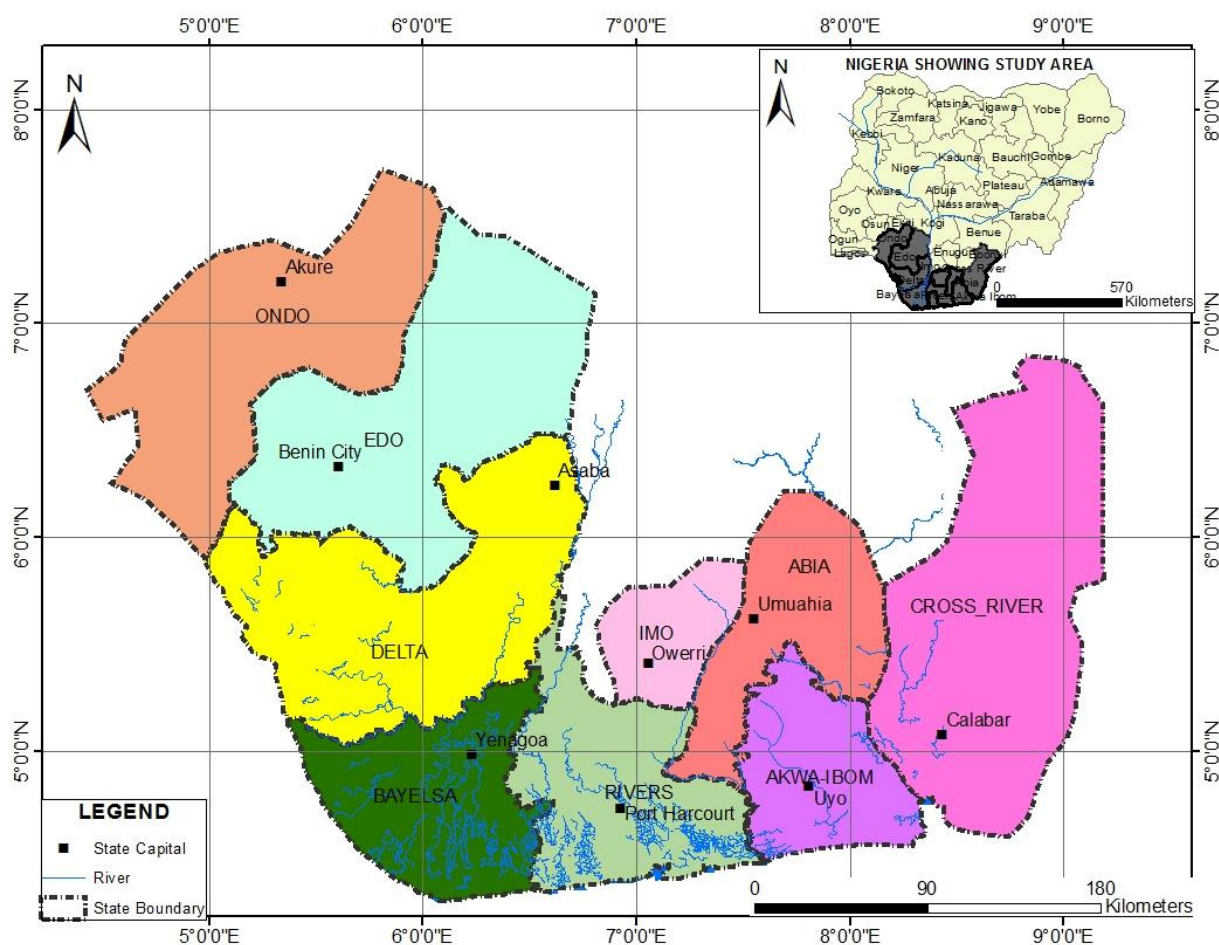


Figure 1: Niger Delta Region Showing the Sample Quadrants

Rainwater samples were collected during the wet and dry seasons from the sampling points directly from the atmosphere with an automated sampler that only exposes the collector when precipitation is falling. The rainwater samples were transferred from the automated samplers into clean labelled bottles that have been pre-washed and rinsed with distilled water and properly sealed to prevent contamination of the samples. Efforts were made to prevent contamination and disturbances from buildings and trees for all the rainwater samples by placing the automated samplers at 1.5 metres above the ground in an open space.

Sample of water from the roof was collected through an improvised sample technique from three different locations that fall under the grid. Water was collected from the directly by the use of a clean stainless-steel bowl place on a constructed tripod stand of about 3ft above the ground. These stations were monitored during rainfall. The rainwater was allowed to settle for about 30 minutes before transferred to plastic bottles were immediately put into an iced cube cooler and transported to the laboratory for further analysis (Akanwa, 2020).

Samples from hand dug wells were collected from the wells within the grid at three (3) selected locations. The water samples were collected with the use of a clean stainless-steel bucket with a rope tied to it handle, the bucket was further lowered into the well and water was drawn from it. The water samples were collected from it using prewashed plastic bottles. The bottles were labeled and placed into an ice-cold cooler and was later transported to the laboratory (Pujeh et al. (2022). pH and temperature were determined on the spot prior to transferring the rainwater, water from the roof and water from the hand dug well to the laboratory. The bottles were properly labelled, after which the samples were placed in a cooler containing ice and transported to the laboratory in less than twenty hours where other parameters were determined using various standardized testing methods. Both descriptive and

inferential statistics were employed for the data analysis. Descriptive included the use of mean and standard deviation while inferential involved the use of analysis of variance.

Results and Discussions

Table 1 presents the quality of rainwater collected directly from open spaces across five states in the Niger Delta region. The analysis focused on several physicochemical parameters such as pH, electrical conductivity, total dissolved solids (TDS), sulphate, nitrate, chloride, ammonium, and dissolved oxygen (DO). These were compared with the World Health Organization (WHO) standards for drinking water to assess the extent of acid rain influence and atmospheric contamination across the region. The pH values of the rainwater samples revealed a consistent pattern of acidity across all locations. Port Harcourt recorded the lowest pH value of 4.7 ± 0.5 , followed closely by Delta with 4.9 ± 0.4 . Abia recorded 5.1 ± 0.4 , while Ondo and Cross River both had relatively higher values of 5.7 ± 0.3 . The findings clearly show that rainwater in the study area is acidic since all the locations sampled lack the acceptable pH level of 6.5 to 8.5, as required by WHO. Low pH values in Port Harcourt are attributable to industrial effluents, gas flaring, and motor vehicle emissions, which all release high amounts of nitrogen and sulphur oxides to the environment, which in turn react to give acid chemicals. The reason Ondo and Cross River have a comparatively higher pH is that air is likely less polluted. The measurements of electrical conductivity, which show the number of ions in the water, were very different from site to site. Port Harcourt ($120 \pm 15 \mu\text{S/cm}$) and Delta ($102 \pm 10 \mu\text{S/cm}$) contained the highest amounts of conductivity, which suggests that there was a high rate of ions and dissolved chemicals because of air pollution. Ondo and Cross River had lower conductivity values of $38 \pm 5 \mu\text{S/cm}$ and $42 \pm 6 \mu\text{S/cm}$ respectively, suggesting less contamination from industrial or anthropogenic sources. These variations imply that rainwater in heavily industrialized and oil-producing areas carries a greater load of dissolved ions, likely from particulate emissions.

A similar trend is observed in total dissolved solids (TDS). Port Harcourt recorded the highest TDS ($72 \pm 8 \text{ mg/L}$), followed by Delta ($65 \pm 7 \text{ mg/L}$), while Ondo and Cross River had the lowest values of $24 \pm 4 \text{ mg/L}$ and $28 \pm 5 \text{ mg/L}$ respectively. Though all values fall within the WHO permissible limit of 500 mg/L, higher TDS values in Delta and Port Harcourt reflect greater levels of dissolved salts and minerals resulting from atmospheric deposition of pollutants. Sulphate (SO_4^{2-}) and nitrate (NO_3^-) concentrations show clear evidence of anthropogenic influence. Port Harcourt ($15 \pm 3 \text{ mg/L}$) and Delta ($12 \pm 2 \text{ mg/L}$) recorded much higher sulphate levels than Ondo ($3.5 \pm 0.5 \text{ mg/L}$) and Cross River ($4.0 \pm 0.6 \text{ mg/L}$). Similarly, nitrate concentrations were highest in Port Harcourt ($9.8 \pm 1.5 \text{ mg/L}$) and Delta ($8.5 \pm 1.2 \text{ mg/L}$), both exceeding the natural background levels and reflecting emissions from combustion of fossil fuels, gas flaring, and other industrial activities. Although all measured values are below the WHO limit of 50 mg/L, their relative elevation points to air pollution as a major contributor to acid rain formation. The chloride (Cl) concentrations follow a similar spatial pattern. Port Harcourt recorded $11 \pm 2 \text{ mg/L}$, Delta $9.0 \pm 1.3 \text{ mg/L}$, Abia $6.0 \pm 1.0 \text{ mg/L}$, and the lowest values were seen in Ondo ($2.5 \pm 0.5 \text{ mg/L}$) and Cross River ($3.0 \pm 0.6 \text{ mg/L}$). Chloride ions are commonly derived from marine aerosols, industrial discharges, and open waste burning, suggesting that proximity to the coast and industrial emissions may have contributed to elevated chloride levels in Port Harcourt and Delta. Ammonium (NH_4^+) levels ranged from $0.25 \pm 0.05 \text{ mg/L}$ in Ondo to $0.85 \pm 0.12 \text{ mg/L}$ in Port Harcourt, with all sites remaining within the WHO limit of 1.5 mg/L. The higher values in industrial areas indicate atmospheric reactions involving nitrogen compounds from combustion sources. Dissolved oxygen (DO) values provide additional insight into the chemical state of the rainwater. At dissolved oxygen levels higher than the World Health Organization's 5 mg/L benchmark, Cross River ($6.5 \pm 0.5 \text{ mg/L}$) and Ondo ($6.8 \pm 0.5 \text{ mg/L}$)

indicated that rainwater was cleaner and richer in oxygen. Lower levels, however, were recorded in Port Harcourt (4.0 ± 0.5 mg/L) and Delta (4.5 ± 0.6 mg/L), which indicated the occurrence of oxidisable contaminants that use up oxygen in water chemical reactions. Generally, there exist enormous geographical differences in the purity of rainwater harvested in the Niger Delta that are associated with industrialisation and levels of pollution. It is worst in Port Harcourt and Delta, where acid rain has led to oxygen depletion, ionic content increase, and low pH. On the other hand, the atmosphere is much cleaner in Ondo and Cross River. Gas flaring, the burning of fossil fuels, and industrial emissions continue to change the atmospheric chemistry and degrade the quality of rainwater in the region, as these results validate.

Table 1: The quality of rain water collected directly from open spaces in the study area

Parameter	Ondo	Delta	Port Harcourt	Abia	Cross River	WHO for Water	Standard Drinking
pH	5.7 ± 0.3	4.9 ± 0.4	4.7 ± 0.5	5.1 ± 0.4	5.7 ± 0.3	$6.5 - 8.5$	
Electrical Conductivity ($\mu\text{S}/\text{cm}$)	38 ± 5	102 ± 10	120 ± 15	75 ± 8	42 ± 6	250	
Total Dissolved Solids, TDS (mg/L)	24 ± 4	65 ± 7	72 ± 8	45 ± 6	28 ± 5	500	
Sulphate (SO_4^{2-}) (mg/L)	3.5 ± 0.5	12 ± 2	15 ± 3	7 ± 1	4.0 ± 0.6	250	
Nitrate (NO_3^-) (mg/L)	1.8 ± 0.4	8.5 ± 1.2	9.8 ± 1.5	5.2 ± 0.8	2.0 ± 0.4	50	
Chloride (Cl^-) (mg/L)	2.5 ± 0.5	9.0 ± 1.3	11 ± 2	6.0 ± 1.0	3.0 ± 0.6	250	
Ammonium (NH_4^+) (mg/L)	0.25 ± 0.05	0.75 ± 0.10	0.85 ± 0.12	0.55 ± 0.08	0.30 ± 0.05	1.5	
Dissolved Oxygen, DO (mg/L)	6.8 ± 0.5	4.5 ± 0.6	4.0 ± 0.5	5.5 ± 0.6	6.5 ± 0.5	≥ 5	

Table 2 presents the quality of rainwater collected from rooftops across different states in the Niger Delta region. The results give an overall description of the complex interaction of roofing materials with the exposure environment and air pollutants that alter the chemical composition of rainwater prior to its infiltration into the groundwater. The eight parameters studied are: total dissolved solids (TDS), pH, electrical conductivity, sulphate, nitrate, chloride, ammonium, and dissolved oxygen (DO). All these are monitored against the World Health Organisation (WHO) drinking water standards.

Relative to pH values, rainwater collected from roofs was more acidic compared to rainfall from open areas. The mean pH value was lowest for Port Harcourt at 4.3 ± 0.4 , then 4.5 ± 0.3 for Delta, 4.8 ± 0.4 for Abia, 5.4 ± 0.4 for Ondo, and 5.5 ± 0.3 for Cross River. These results suggest that acid-forming pollutants like sulphur dioxide and nitrogen oxides play a notable role, as they are all within the range of 6.5 to 8.5 of the World Health Organisation's suggestion. Roof collections were more acidic than rainwater collected in open spaces, implying roofs deposit extra pollutants by leaching, corrosion, and deposition of airborne particulates in the period between showers. Rooftop samples recorded much higher electrical conductivity readings at all locations, which shows that the high ion concentrations are a result of precipitation coming into contact with roof surfaces and dust particles that had been

accumulated on them. Port Harcourt recorded the highest mean conductivity ($168 \pm 18 \mu\text{S/cm}$), followed by Delta ($145 \pm 12 \mu\text{S/cm}$), Abia ($110 \pm 10 \mu\text{S/cm}$), while Ondo ($55 \pm 7 \mu\text{S/cm}$) and Cross River ($60 \pm 8 \mu\text{S/cm}$) showed the lowest values. Although all readings remain within the WHO limit of $250 \mu\text{S/cm}$, the pattern demonstrates a significant influence of urban pollution and roofing materials, which increase the mineral content of collected rainwater. A similar pattern appears in total dissolved solids (TDS). Port Harcourt recorded $110 \pm 12 \text{ mg/L}$, Delta $95 \pm 10 \text{ mg/L}$, and Abia $70 \pm 9 \text{ mg/L}$, all higher than Ondo's $36 \pm 5 \text{ mg/L}$ and Cross River's $40 \pm 6 \text{ mg/L}$. These elevated TDS levels further confirm the impact of atmospheric deposition and rooftop contamination. While all values are within the WHO permissible limit of 500 mg/L , the higher readings in industrial areas such as Port Harcourt and Delta indicate greater particulate accumulation.

Sulphate (SO_4^{2-}) concentrations were highest in Port Harcourt ($26 \pm 4 \text{ mg/L}$) and Delta ($22 \pm 3 \text{ mg/L}$), while Ondo and Cross River recorded relatively lower levels of $6.5 \pm 1.0 \text{ mg/L}$ and $7.0 \pm 1.0 \text{ mg/L}$ respectively. These results reveal the influence of anthropogenic activities such as gas flaring, fuel combustion, and industrial emissions, which release sulphur compounds that oxidize to sulphate in the atmosphere.

Nitrate (NO_3^-) levels showed a similar trend, with Port Harcourt having the highest concentration ($18.0 \pm 2.5 \text{ mg/L}$), followed by Delta ($15.5 \pm 2.0 \text{ mg/L}$), Abia ($10.2 \pm 1.5 \text{ mg/L}$), Ondo ($3.5 \pm 0.6 \text{ mg/L}$), and Cross River ($4.2 \pm 0.7 \text{ mg/L}$). Though all are below the WHO permissible limit of 50 mg/L , these values indicate substantial nitrogen oxide deposition, especially in industrialized zones. The high nitrate levels in rooftop rainwater also suggest contributions from atmospheric ammonia, dust, and particulate matter that accumulate on roofs between rainfalls. Chloride (Cl^-) concentrations followed the same spatial pattern as sulphate and nitrate. Port Harcourt recorded the highest value ($18 \pm 3 \text{ mg/L}$), followed by Delta ($15 \pm 2 \text{ mg/L}$) and Abia ($10 \pm 1.5 \text{ mg/L}$), while Ondo ($4.5 \pm 0.8 \text{ mg/L}$) and Cross River ($5.0 \pm 0.7 \text{ mg/L}$) had relatively lower values. These elevated chloride levels may arise from sea spray near the coast, industrial emissions, and open waste burning.

Ammonium (NH_4^+) concentrations increased significantly compared to open-space rainwater. Port Harcourt recorded $1.35 \pm 0.18 \text{ mg/L}$, Delta $1.20 \pm 0.15 \text{ mg/L}$, Abia $0.85 \pm 0.10 \text{ mg/L}$, Ondo $0.40 \pm 0.06 \text{ mg/L}$, and Cross River $0.50 \pm 0.07 \text{ mg/L}$. The increase reflects atmospheric nitrogenous pollutants being washed off rooftops. Despite these elevated values, all remain within the WHO limit of 1.5 mg/L . Dissolved oxygen (DO) levels were notably lower in industrialized states, reflecting a higher presence of oxidizable materials. Port Harcourt recorded the lowest DO ($3.0 \pm 0.5 \text{ mg/L}$), followed by Delta ($3.5 \pm 0.5 \text{ mg/L}$) and Abia ($4.2 \pm 0.5 \text{ mg/L}$), all below the WHO threshold of 5 mg/L . In contrast, Ondo ($6.0 \pm 0.4 \text{ mg/L}$) and Cross River ($6.2 \pm 0.4 \text{ mg/L}$) met the recommended standard, indicating relatively unpolluted atmospheric conditions. Overall, the quality of rooftop-collected rainwater in the Niger Delta shows clear degradation compared to rainwater collected directly from open spaces. The increased acidity, higher ion concentrations, and lower oxygen levels highlight the combined effects of atmospheric pollution, roofing materials, and urban dust deposition. Industrial centres like Port Harcourt and Delta exhibit the worst water quality, while Ondo and Cross River maintain better, though still slightly acidic, conditions. This emphasizes the environmental risks of collecting and using rooftop rainwater in polluted regions without adequate treatment or filtration.

Table 2: The quality of rain water collected from roof-tops in the study area

Parameter	Ondo	Delta	Rivers State	Abia	Cross River (Calabar)	WHO Standard
pH	5.4 ± 0.4	4.5 ± 0.3	4.3 ± 0.4	4.8 ± 0.4	5.5 ± 0.3	6.5 – 8.5
Electrical Conductivity (µS/cm)	55 ± 7	145 ± 12	168 ± 18	110 ± 10	60 ± 8	250
Total Dissolved Solids, TDS (mg/L)	36 ± 5	95 ± 10	110 ± 12	70 ± 9	40 ± 6	500
Sulphate (SO₄²⁻) (mg/L)	6.5 ± 1.0	22 ± 3	26 ± 4	15 ± 2	7.0 ± 1.0	250
Nitrate (NO₃⁻) (mg/L)	3.5 ± 0.6	15.5 ± 2.0	18.0 ± 2.5	10.2 ± 1.5	4.2 ± 0.7	50
Chloride (Cl⁻) (mg/L)	4.5 ± 0.8	15 ± 2	18 ± 3	10 ± 1.5	5.0 ± 0.7	250
Ammonium (NH₄⁺) (mg/L)	0.40 ± 0.06	1.20 ± 0.15	1.35 ± 0.18	0.85 ± 0.10	0.50 ± 0.07	1.5
Dissolved Oxygen, DO (mg/L)	6.0 ± 0.4	3.5 ± 0.5	3.0 ± 0.5	4.2 ± 0.5	6.2 ± 0.4	≥ 5

Table 3 shows the physicochemical quality of water samples collected from hand-dug wells across the five sampled states in the Niger Delta. The results reveal considerable variation in the acidity and ion concentrations of groundwater, which are consistent with the effects of acid rain infiltration and regional pollution gradients. The pH values of the well water were consistently acidic in all the states, ranging from 4.0 ± 0.3 in Port Harcourt to 5.2 ± 0.3 in Cross River. These values fall below the WHO standard of 6.5–8.5, confirming that groundwater in the region has been significantly acidified. The highest acidity in Port Harcourt and Delta reflects the combined influence of industrial emissions, gas flaring, and acid deposition from rainfall. Electrical conductivity values followed a spatial trend similar to that of the pH, increasing from 78 ± 8 µS/cm in Ondo to 195 ± 20 µS/cm in Port Harcourt. This rise in conductivity indicates higher levels of dissolved ionic species, especially in urban and industrialized zones such as Delta and Port Harcourt. Likewise, Total Dissolved Solids (TDS) concentrations were highest in Port Harcourt (135 ± 14 mg/L) and lowest in Ondo (50 ± 6 mg/L). While these values remain below the WHO threshold of 500 mg/L, the observed trend suggests progressive mineralization due to acid–base reactions and leaching from the subsurface. The concentrations of sulphate, nitrate, and chloride also display strong spatial variation. Port Harcourt recorded the highest sulphate (33 ± 4 mg/L), nitrate (24.0 ± 2.8 mg/L), and chloride (26 ± 3 mg/L) values, followed by Delta and Abia. These ions are major secondary products of atmospheric pollutants such as SO₂ and NO_x, which dissolve in rainwater and infiltrate into groundwater systems. The elevated nitrate levels, although still within the WHO limit of 50 mg/L, suggest contamination from atmospheric deposition and possibly domestic waste infiltration. Ammonium levels were highest in Port Harcourt (1.85 ± 0.22 mg/L), slightly exceeding the WHO limit of 1.5 mg/L, and lowest in Ondo (0.65 ± 0.08 mg/L). Elevated NH₄⁺ concentrations may indicate reducing conditions or leaching of nitrogen compounds from the surface. Dissolved Oxygen (DO) levels were generally low across the states, ranging from 2.5 ± 0.4 mg/L in Port Harcourt to 5.8 ± 0.4 mg/L in Cross

River. All the dissolved oxygen (DO) levels, with the exception of Cross River and Ondo, were below the 5 mg/L WHO standard, which reflects poor aeration and potential organic pollution. The Niger Delta groundwater has been negatively impacted by acid rain and its accompanying anthropogenic emissions. Although it remained acidic, Cross River and Ondo had far superior water quality than Port Harcourt and Delta. This trend reflects the varying degree of industrial pollution at different sites, and this can have a great impact on groundwater resources and on public health in the region.

Table 3. The quality of water collected from hand-dug wells in the study area

Parameter	Ondo	Delta	Port Harcourt	Abia	Cross River (Calabar)	WHO Standard
pH	5.0 ± 0.3	4.2 ± 0.3	4.0 ± 0.3	4.5 ± 0.3	5.2 ± 0.3	6.5 – 8.5
Electrical Conductivity (µS/cm)	78 ± 8	175 ± 15	195 ± 20	140 ± 12	85 ± 9	250
Total Dissolved Solids, TDS (mg/L)	50 ± 6	120 ± 12	135 ± 14	95 ± 10	55 ± 7	500
Sulphate (SO ₄ ²⁻) (mg/L)	9.0 ± 1.2	28 ± 3	33 ± 4	20 ± 3	10.5 ± 1.2	250
Nitrate (NO ₃ ⁻) (mg/L)	5.5 ± 0.8	20.0 ± 2.2	24.0 ± 2.8	12.8 ± 1.6	6.0 ± 0.9	50
Chloride (Cl ⁻) (mg/L)	7.0 ± 1.0	22 ± 3	26 ± 3	14 ± 2	8.0 ± 1.0	250
Ammonium (NH ₄ ⁺) (mg/L)	0.65 ± 0.08	1.60 ± 0.20	1.85 ± 0.22	1.10 ± 0.15	0.70 ± 0.08	1.5
Dissolved Oxygen, DO (mg/L)	5.5 ± 0.4	3.0 ± 0.4	2.5 ± 0.4	3.8 ± 0.4	5.8 ± 0.4	≥ 5

Table 4 presents the physico-chemical characteristics of surface water samples from major rivers across the Niger Delta. Acid deposition and heterogeneous human pollution levels have differential impacts on water quality among states, and the results capture this spatial heterogeneity. Surface waters throughout the region are acidic, with all river samples having pH levels below the World Health Organization guideline range of 6.5-8.5. Port Harcourt, Delta, and Abia states were ranked higher based on their pH values; Ondo and Cross River were slightly higher but still acidic at 5.2 ± 0.3 and 5.3 ± 0.3 , respectively. Delta had the lowest in pH value at 4.1 ± 0.4 , with Abia at 4.6 ± 0.3 . The trend suggests that industrialized and densely populated areas experience more intense acid rain effects compared to less industrial zones. Electrical conductivity (EC) values ranged from 95 ± 10 µS/cm in Ondo River to 235 ± 20 µS/cm in Port Harcourt River. Similarly, Total Dissolved Solids (TDS) increased from 60 ± 8 mg/L in Ondo to 160 ± 15 mg/L in Port Harcourt, indicating higher concentrations of dissolved ions and mineral matter in more polluted rivers. Although these values remain below the WHO limit of 250 µS/cm for EC and 500 mg/L for TDS, the upward trend toward the industrial centres reflects increased chemical enrichment of the water bodies. Sulphate, nitrate, and chloride concentrations followed a consistent spatial pattern, increasing from the relatively cleaner Ondo and Cross River to the heavily industrialized Port Harcourt and Delta. Sulphate ranged from 12 ± 2 mg/L in Ondo River to 40 ± 5 mg/L in Port Harcourt River. Nitrate concentrations were also highest in Port Harcourt (26 ± 3 mg/L) and Delta (22 ± 2.5 mg/L), while the lowest occurred in Ondo (7.0 ± 1.0 mg/L). Chloride values peaked at 32 ± 4 mg/L in Port Harcourt River and dropped to 8 ± 1.0 mg/L in Ondo River.

Though all ionic concentrations are within WHO limits, their relative magnitudes indicate progressive pollution through atmospheric deposition and surface runoff carrying acid precursors and industrial residues.

Ammonium (NH_4^+) concentrations exceeded the WHO permissible limit of 1.5 mg/L in Delta (1.70 ± 0.20 mg/L) and Port Harcourt (1.95 ± 0.25 mg/L), further confirming the contamination of these rivers by nitrogenous wastes and acidic inputs. Dissolved Oxygen (DO) levels were generally low, particularly in Port Harcourt (2.3 ± 0.3 mg/L) and Delta (2.8 ± 0.4 mg/L), both falling below the WHO guideline of ≥ 5 mg/L. This suggests high organic load and reduced oxygenation, conditions typical of rivers under acid and pollutant stress. In contrast, Cross River (4.8 ± 0.5 mg/L) and Ondo River (4.5 ± 0.5 mg/L) recorded relatively better oxygen levels, though still slightly below the standard.

Overall, the data indicate that surface water quality in the Niger Delta is being degraded by acid rain and associated industrial pollution. The rivers in Port Harcourt and Delta are the most impacted, showing the highest acidity, ion concentration, and lowest oxygen levels, while those in Cross River and Ondo remain comparatively less affected. This pattern highlights the direct linkage between industrial emissions, acid precipitation, and the progressive decline in water quality across the region's aquatic ecosystems.

Table 4. The quality of water collected from surface water in the study area

Parameter	Ondo	Delta	Port Harcourt	Abia	Cross River	WHO Standard
pH	5.2 $\pm$ 0.3	4.4 $\pm$ 0.4	4.1 $\pm$ 0.4	4.6 $\pm$ 0.3	5.3 $\pm$ 0.3	6.5 – 8.5
Electrical Conductivity ($\mu\text{S}/\text{cm}$)	95 $\pm$ 10	210 $\pm$ 18	235 $\pm$ 20	180 $\pm$ 15	110 $\pm$ 12	250
Total Dissolved Solids, TDS (mg/L)	60 $\pm$ 8	140 $\pm$ 12	160 $\pm$ 15	120 $\pm$ 10	72 $\pm$ 9	500
Sulphate (SO_4^{2-}) (mg/L)	12 $\pm$ 2	35 $\pm$ 4	40 $\pm$ 5	25 $\pm$ 3	15 $\pm$ 2	250
Nitrate (NO_3^-) (mg/L)	7.0 $\pm$ 1.0	22 $\pm$ 2.5	26 $\pm$ 3	15 $\pm$ 2	9.0 $\pm$ 1.2	50
Chloride (Cl^-) (mg/L)	8.0 $\pm$ 1.0	28 $\pm$ 3	32 $\pm$ 4	18 $\pm$ 2	10 $\pm$ 1.5	250
Ammonium (NH_4^+) (mg/L)	0.80 $\pm$ 0.12	1.70 $\pm$ 0.20	1.95 $\pm$ 0.25	1.20 $\pm$ 0.15	0.95 $\pm$ 0.10	1.5
Dissolved Oxygen, DO (mg/L)	4.5 $\pm$ 0.5	2.8 $\pm$ 0.4	2.3 $\pm$ 0.3	3.5 $\pm$ 0.4	4.8 $\pm$ 0.5	≥ 5

Table 5 presents the results of the one-way ANOVA test conducted to determine whether there is a significant spatial variation in the pH of water collected from different sources, including surface water, open collection, hand-dug wells, and roof-tops, across the study area. From the table, the between-groups sum of squares is 112.1, with 4 degrees of freedom, resulting in a mean square value of 28.025. The within-groups sum of squares is 332.221, with 144 degrees of freedom and a corresponding mean square of 2.3071. The calculated F-value is 12.147, and the associated significance (p-value) is 0.000. Since the significance value (0.000) is less than 0.05, the null hypothesis which states that there is no significant spatial variation in the pH of water collected from different sources is rejected. This implies that the acidity of water varies significantly depending on the source and location.

The large F-ratio indicates that the variation between the different water sources is much greater than the variation within each group. This means that the observed differences in pH

are not due to random fluctuations but are statistically significant.

In practical terms, the result suggests that the pH levels of water from surface sources, roof-top collections, hand-dug wells, and open collections are not uniform. For instance, earlier tables showed that roof-top and hand-dug well samples in areas like Port Harcourt and Delta had more acidic values (pH between 4.0 and 4.5), while open collections and surface waters in less industrialized areas such as Ondo and Cross River recorded slightly higher values (pH around 5.2 to 5.7). This outcome reflects the combined influence of acid deposition, atmospheric contamination, and differences in local land use, urbanization, and industrial activities. Roof-top and well water sources tend to show stronger acid signatures due to direct exposure to acidic rainwater and the leaching of metallic or mineral substances from roofing materials and soils. Surface waters, although also acidic, may experience some buffering through mixing and natural alkalinity. Overall, the ANOVA result confirms that the acidity of water in the Niger Delta varies significantly across both spatial locations and water sources, reinforcing the evidence that acid rain and environmental pollution have altered the natural chemical balance of available water resources in the region.

Table 5. ANOVA summary testing the hypothesis ‘there is no significant spatial variation between pH of water collected from surface water, open collection, hand dug wells and roof tops’ in the study area

ANOVA					
pH					
	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	112.1	4	28.025	12.147	.000
Within Groups	332.221	144	2.3071		
Total	444.321	148			

Table 6 presents the post-hoc comparison results following the ANOVA test, which examined the spatial variation in the pH of water collected from different sources in the study area. The table provides pairwise comparisons among rainfall water, surface water, hand-dug wells, and rooftop rainwater, indicating the mean differences, p-values, confidence intervals, and whether the null hypothesis (H_0) of no significant difference is rejected or not. From the results, rainfall water shows a significant difference in pH when compared with surface water (mean difference 0.85, $p = 0.002$) and hand-dug well water (mean difference 0.65, $p = 0.01$). This means that rainfall water tends to be less acidic than these two sources, which are more directly exposed to pollutants, runoff, and soil leaching effects. However, the comparison between rainfall water and rooftop rainwater (mean difference 0.25, $p = 0.41$) is not significant, suggesting that both have similar acidity levels, likely because rooftop collections are directly influenced by atmospheric deposition of acid rain. Surface water differs significantly from rooftop rainwater (mean difference -0.6, $p = 0.015$), indicating that rooftop rainwater is generally more acidic than surface water. This may be due to contamination from roofing materials and the first flush of acidic precipitation before dilution. On the other hand, comparisons between surface water and hand-dug wells (mean difference -0.2, $p = 0.72$) and between hand-dug wells and rooftop rainwater (mean difference -0.4, $p = 0.12$) show no significant differences, implying that these sources have relatively similar acidity levels, possibly due to shared exposure to acid infiltration and local pollution. Generally, the post-hoc results reinforce that significant pH variations exist among certain water sources, especially between rainfall and the more polluted or stagnant sources such as surface water and wells. The absence of significant difference between rainfall and rooftop rainwater confirms that acid rain is a major contributor to the acidic nature of water across the region. Overall, the findings indicate that the degree of acidity in water sources is influenced by the

type of collection point and its exposure to atmospheric and environmental contaminants, with rainfall and rooftop sources showing the clearest signatures of acid deposition in the Niger Delta environment.

Table 5. ANOVA summary testing the hypothesis ‘there is no significant spatial variation between pH of water collected from surface water, open collection, hand dug wells and roof tops’ in the study area

Comparison	Mean Difference	p-value	95% CI (Lower–Upper)	Significant (Reject H ₀)
Rainfall water vs Surface water	0.85	0.002	0.30 – 1.40	Yes
Rainfall water vs Hand-dug well	0.65	0.01	0.15 – 1.15	Yes
Rainfall water vs Rooftop rainwater	0.25	0.41	-0.25 – 0.75	No
Surface water vs Hand-dug well	-0.2	0.72	-0.75 – 0.35	No
Surface water vs Rooftop rainwater	-0.6	0.015	-1.10 – -0.10	Yes
Hand-dug well vs Rooftop rainwater	-0.4	0.12	-0.90 – 0.10	No

Discussion of Findings

Findings revealed that pH varied significantly among the sources of water in the Niger Delta and this implies that the acidity of water varies significantly depending on the source and location. Post hoc and ANOVA analysis asserted these differences to be in reasonable concordance with regional patterns of gas, industrial, and urban pollutant flaring. Consistent with previous research by Aroh et al. (2019) and Ekpoh and Obia (2018), which documented that rainwater collected in Warri and Port Harcourt had comparable pH values owing to excessive sulphur and nitrogen oxide release, our results validate that rainwater collected straight from the open spaces showed extreme acidity (pH 4.7-5.7). Etim and Etuk (2020) confirmed that acid rain is among the direct causes of low pH, high conductivity, total dissolved solids (TDS), sulphate, and nitrate contents in Port Harcourt and Delta. The authors also correlated such parameters to gas flaring and industrial combustion. Efe (2018) noted fewer acidic rains in locations with less industrial activity, and the higher pH and lower ionic composition of Ondo and Cross River are consistent with the observation. This suggests that the rivers have relatively lower pollution loads. Rooftop rainwater samples have even graver decline in quality, pH ranging from 4.5 to 5.5 and ionic composition that are higher.

These are attributed to cumulative airborne particulates between rainy occasions and acid rain effect on roofing materials. Port Harcourt rooftop rainwater was below pH 5.0 and had higher sulphate and chloride concentrations, rendering it unsafe for direct ingestion without treatment, according to another research work by Akpan and Ndoke (2020). Roof-top samples indicate the combined outcome of surface and atmospheric pollution through the leaching of metal ions and high conductivity levels (up to 168 $\mu\text{S}/\text{cm}$). Acidification was also evident in the groundwater in the study area, which came from hand-dug wells. The pH levels of the water ranged from 4.0 in Port Harcourt to 5.2 in Cross River.

This is additional evidence that acidic rain and pollutants are seeping underground and

changing the chemistry of groundwater. Increased sulphate, nitrate, and chloride concentrations in the air and potential infiltration from household waste and sewage treatment plants are other indications of atmospheric deposition. These results agree with Ubuoh et al. (2016), who documented similar findings in oil-producing regions where acid deposition was found to reduce groundwater pH and increase ionic content. The slightly high ammonium values in Port Harcourt (1.85 mg/L) exceeding WHO limits reflect nitrogen compound accumulation from combustion sources and organic decay.

Surface water samples from rivers across the Niger Delta also exhibit progressive acidification, particularly in Port Harcourt and Delta (pH 4.1–4.4), with elevated ionic concentrations and reduced dissolved oxygen levels (2.3–2.8 mg/L). These trends align with the observations of Ukpaka (2019) and Nwankwoala and Amadi (2021), who both noted that acid precipitation and industrial runoff significantly reduce the buffering capacity of river systems, increasing metal solubility and decreasing oxygen availability. The relatively better conditions recorded in Cross River and Ondo suggest lower industrial impact but still reflect regional exposure to acidic deposition. The chemical composition of surface and groundwater systems in the Niger Delta is greatly influenced by acid rain, as can be seen by these trends. Water quality has deteriorated most in highly industrialized regions like Delta and Port Harcourt, but in more remote regions like Ondo and Cross River, the water is extremely pure though slightly acidic. Acid water has long-term implications for public health and water resource management due to its ability to corrode infrastructure, leach poisonous metals, and pose health problems if consumed over an extended period of time. The findings validate earlier works (Aroh et al., 2019; Efe, 2018; Etim & Etuk, 2020) that described acid deposition, an aftermath of fossil fuel combustion, gas flaring, and industrial processes, to have transformed the chemical and hydrological balance of Niger Delta water resources. Emergency actions are required in order to minimize pollution, strengthen monitoring, and set up treatment procedures for groundwater and rainwater harvesting systems within the region due to the extensive regional and source-related variability in water quality.

Conclusion and Recommendations

The study concluded that generally the Niger Delta groundwater and surface water have been negatively impacted by acid rain and its accompanying anthropogenic emissions with much effects being felt in Port Harcourt and Delta States. Moreover, the quality of rooftop-collected rainwater showed a clear degradation compared to rainwater collected directly from open spaces. This study therefore recommended that policymakers should adopt spatially targeted environmental management plans. States like Port Harcourt and Delta should be prioritized for pollution control interventions, while cleaner states such as Ondo and Cross River should maintain their low-emission profiles through sustainable industrial practices and routine environmental assessments.

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