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Assessment of the Spatial Distribution of Water Quality for Surface and Groundwater at Bonny Island, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The aim of the study was to assess the spatial distribution of water quality for surface and ground water at Bonny Island in Rivers State, Nigeria. Surface and Groundwater samples were collected from 9 sampling locations and analyzed for physicochemical parameters, heavy metals, and petroleum hydrocarbons. The contaminants in the surface and groundwater were measured using a variety of methods. Heavy metals in the water were measured using gas chromatography, PAHs were measured using Atomic Absorption Spectrophotometry (ASS) while THC were measured using HACH DR/890 colorimeter. The water quality index (WQI) was calculated using the Weighted Arithmetic Index Method while Principal Component Analysis was used to understand the distribution of the physicochemical parameters, heavy metals, and petroleum hydrocarbons. The results showed that the WQI for both surface and groundwater samples ranged from 55.22 – 125.39, indicating poor to unfit water quality for consumption. In contrast, a control location away from the industrial activities had good water quality with WQI between 35.19 and 45.77. Principal

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component analysis revealed that the surface water in the industrial area were contaminated with lead, Poly Aromatic Hydrocarbon (PAHs), Total Petroleum Hydrocarbon which indicate oil and gas activities. High chloride, nitrate and sulphate levels were also observed in surface water close to the NLNG plant. Limiting further contamination of the surface and groundwater can be achieved by constant effluent and plume stack monitoring by regulatory agencies. Industrial stakeholder should set up subsidized clinics to provide treatment for any gastrointestinal illnesses or renal damage suffered by residents.

Keywords: Water quality index; surface water; groundwater; groundwater contamination; physicochemical parameters; heavy metals; petroleum hydrocarbons; Oil & Gas Industry.

1. INTRODUCTION

The Bonny Island in the Niger Delta region in Nigeria has a thriving oil and gas industry with the presence of international oil corporations (IOCs) and the Nigerian Liquefied Natural Gas (NLNG). Although exploration of oil and gas is not done on the island, downstream operation such as refining, processing, transportation, and marketing of mainly gas products are prevalent on the island [1]. Oil and gas industry activities on the island have been reported to have very serious consequences on the surroundings and to the health of human [2,3]. Atonye [2] reported that residents in Bonny Island stated that they have suffered from skin irritation, headaches, irritation of the eyes and nausea. Odo et al. [3] in their study reported that prolonged exposure to gas flaring might result in renal damage. Several research studies have consistently reported water, land, food, and air pollution in the entire Bonny Island community [4,5,6,7,8]. Some of the pollutants that have been reported to be prevalent in places where oil and gas activities are done are heavy metals, phthalates, organochlorine pesticides, particulate matter, dioxins, organotin compounds, brominated flame retardants, polyfluorinated chemicals, PAHs, dioxin-like PCBs, and non-dioxin-like PCBs [9]. The presence of these pollutants in the aquatic and terrestrial ecosystem have been known to have very serious consequence as they tend to bioaccumulate in the marine organisms, plants and pollute water sources. The contamination of water resources particularly ground and surface water have also been reported to occur in other regions where oil and gas activities occur. Raimi and Ezugwu [10] reported that the surface and ground water in Ebocha-Obrikom Oil and Gas producing area of Rivers State, Nigeria was very polluted. They reported that the ground water was more impacted by chemical parameter than surface water. Nwankwo and Ogagarue [11] in their study reported that gas flaring affects the surface and groundwater. The reported that the surface water was generally acidic than the groundwater but stated that the groundwater had acceptable water quality. Su et al. [12] stated that the groundwater in the Oil and Gas Field of Dingbian County, Northwest China exceeded permissible drinking limit. They found out that ingestion of the groundwater was likely to have carcinogenic effect on adult and children.

The contamination of the surface and groundwater in Bonny Island possess a unique challenge due to its geographical location. The availability of clean surface and groundwater sources on the island is vital as obtaining clean water from alternative means seem rather difficult. Given the potential impact of the oil and gas industry on the water quality in the Bonny Island region, this study aims to assess the water quality of the surface and ground water on the Island. Most researchers assessed the water quality solely by comparing the individual parameters with established standards. However, the Water Quality Index which is an indicator that takes all the individual contaminant parameters to output a single value that represent the quality of the water was used for assessing the water quality for this study. Also, the spatial distribution of the water quality was also analysed, as this give a clear insight of safe zone where clean water can be obtained from the Island.

2. METHODS

2.1 Study Area

The study was conducted on Bonny Island, an ancient coastal city and a Local Government Area (LGA) in Rivers State in southern Nigeria, on the Bight of Bonny [13]. The island is Bonny City, which is the capital of Bonny Kingdom. Much of the oil extracted onshore in Rivers State is piped to Bonny for export. The local government has an estimated population of 172,549 inhabitants who practice Christianity and traditional religion, which is characterized by high volume of oil and gas activities.

Bonny is positioned in the Niger Delta basin estimated to have a total volume of 37.4 billion barrels of oil and 202 trillion cubic feet (TCF) of gas [14]. The presence of this huge deposit of petroleum hydrocarbon is characterized by a high intensity of exploration, processing, and transportation of crude oil and its refined products. These activities have led to the contamination of the environment through the discharge of wastes, spillage through sabotage and accidental discharge, oil bunkering, and artisanal refining [15].

2.2 Samples

A quantitative research design method was adopted for the study. A quasi-experimental design was employed to assess the impact of the oil and gas operations on Bonny Island. Groundwater samples were collected from 9 sampling locations in Bonny Island as shown in Fig. 1. The names of the 9 sampling locations were Water well 6, Abalamabie, worker's camp, NLNG industrial area gate (IA), NLNG residential area gate (RA gate), Lighthouse, Finima Market, Shell gate and the Bonny Jetty. The sample locations were marked with GPS coordinates, and sampling was carried out seasonally over the twelve (12) calendar months, with samples taken in July and October 2022 for the wet season, and December 2022 and January 2023 for the dry season. Triplicate samples of water were collected twice in both wet and dry seasons.

2.3 Instrument Analysis

In order to obtain the concentrations of the physicochemical parameters, heavy metals and petroleum hydrocarbon, the following instruments were used:

2.3.1 Physiochemical parameters

A hand-held pH meter was used to measure pH by electrometry after calibrating with buffer solutions. Electrical conductivity was measured electronically using a conductivity meter calibrated with a potassium chloride standard solution. A HACH DR/890 Colorimeter was employed for measuring nitrate, phosphate, and sulphate concentrations using stored programs and specific reagent powder pillows (NitraVer 5 Nitrate, PhosVer 3 Phosphate, SulfaVer 4 Sulfate). Chloride was determined by titration, where water samples were measured into conical flasks, a potassium chromate indicator was added, and titration was performed with silver nitrate solution until a colour change from yellow to orange was observed. For sulphate, another titration method was used, involving heating the water samples with chromic acid, diluting, adding barium chloride dihydrate, barium diphenylamine-sulfonate, and titrating with ferrous ammonium sulphate solution and potassium dichromate until a maroon-red colour change occurred. A blank titration with distilled water was also performed.

2.3.2 Heavy metals

The concentrations of heavy metals (Hg, As, Pb, Cd, Ni, Cu, Cr, and V) in the groundwater samples were determined using atomic absorption spectrophotometry (AAS). The specific instrument used was a Varian AA 240 AAS, following the methods outlined by the American Public Health Association (APHA) and American Water Works Association (AWWA). The AAS was turned on, the desired element was selected, and the instrument was zeroed with distilled water and calibrated with standards of the element of interest. The water samples were then aspirated through the capillary tube and into the flame for atomization. The total metal concentrations were reported in ppm (mg/L) based on the readings obtained directly from the instrument.

2.3.3 Petroleum hydrocarbon

To determine the Total Hydrocarbon Content (THC) in water samples, a solvent extraction method was employed. 250 ml of the water sample was measured into a separatory funnel, and 25 ml of hexane was added. After vigorous shaking, the organic extract was collected by passing it through a column containing cotton wool, anhydrous sodium sulphate (a dehydrating agent), and silica gel (for cleanup). The THC was then measured using a HACH DR/890 Colorimeter with a stored program for THC. The colorimeter was zeroed with hexane before measuring the sample extracts.

The analysis of PAHs in the water samples was carried out using Gas Chromatography - Flame Ionization Detection (GC-FID). The organic extracts of the water samples were injected into the column of a Gas Chromatograph (HP 5890 Series II GC) using a hypodermic syringe. The separation of PAH compounds occurred as the vapor constituents partitioned between the liquid and gas phases within the column. The separated PAH compounds were then detected as they emerged from the column by the Flame

Ionization Detector (FID), which responds based on the composition of the vapor.

2.4 Data Analysis and Procedures

The data obtained from the analysis of physicochemical parameters, heavy metals, and petroleum hydrocarbons in the groundwater samples were subjected to statistical analysis using appropriate methods. Principal component analysis (PCA) was utilized to understand the spatial distribution of the water quality of the surface and ground water. The water quality index for surface and ground water were obtained using [16] method to obtain the WQI. Regression modelling was done by relating the WQI with the physiochemical parameters.

2.4.1 Water quality index (WQI)

The Weighted Quality Index was determined for this study by using the Weighted Arithmetic Index Method created by [16]. Earlier work of obtaining the water quality was done by [17] using a weighted arithmetic water quality measure but was refined by [16]. The formula for the water quality index using weighted arithmetic (WQI) is presented as eq. 1:

$$WQI = \sum_{i=1}^{n} \frac{W_i Q_i}{\sum_{i=1}^{n} W_i} \quad (1)$$

Where;
Q_i = Sub-Index of the *ith* parameter,
W_i = the unit weightage of the *ith* parameters
n = number of parameters
The ideal value for pH = 7, dissolved oxygen = 14.6 mg/l, and for other parameters, it is equal to zero [18].

According to [12] the value of Qi is calculated using eq. 2:

$$Q_i = \frac{(M_i - L_i)}{(S_i - L_i)} \times 100 \quad (2)$$

Where;
M_i = Observed value for physiochemical parameters,
Li = ideal value
S_i = standard value of the *ith* parameter.

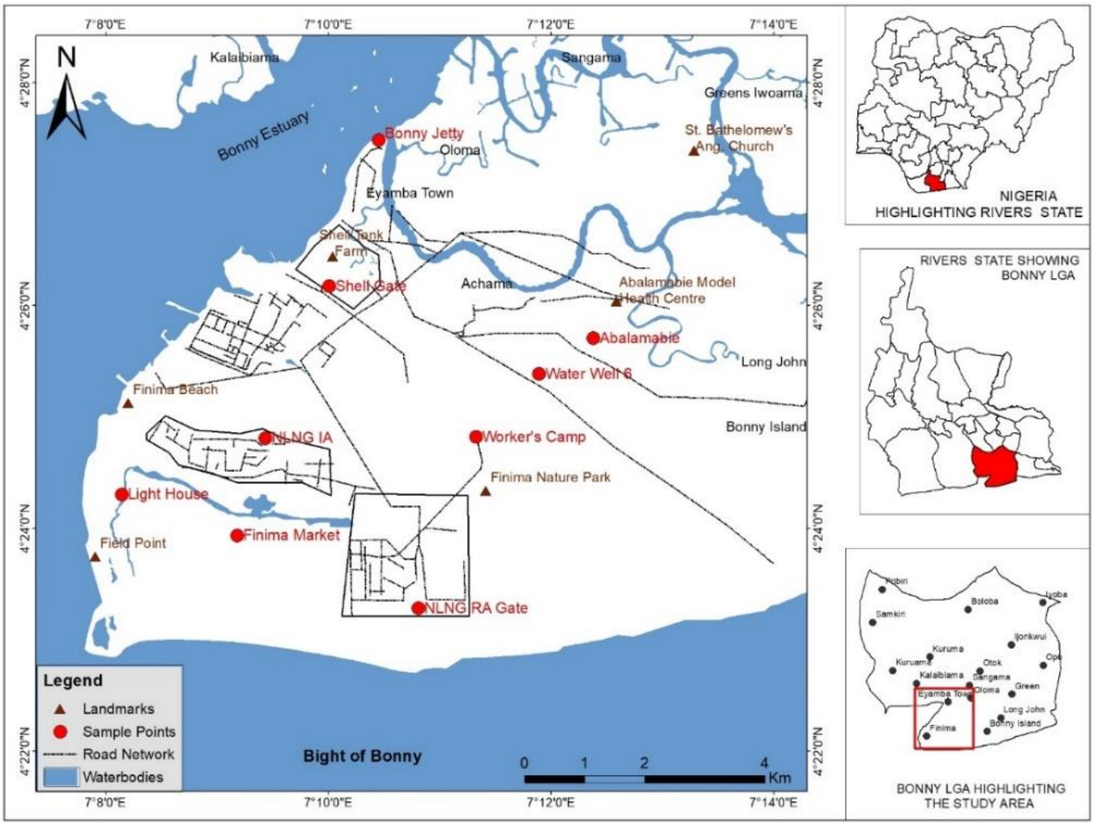

Fig. 1. Map of Bonny area showing the sampling location

3. RESULTS

3.1 Water Quality Assessment

The result of the water quality index of the surface and ground water samples for the 9 sampling locations is presented in Table 1. The result of the WQI for both the surface and ground water samples revealed poor water quality to unfit for consumption as their WQI ranged from 55.22 to 125.39. It was also noticed that the Control location had WQI ranging from 35.19 to 45.77 which indicated good water quality. The result indicates that the downstream activities from the oil and gas company might be contributing the poor water quality in the sampling locations as most of the sampling locations are situated close to where these industrial activities take place.

The result showed that the highest WQI was recorded at Light house surface water with WQI of 125.39 which is unfit for consumption. It was noticed that Finima had unfit water for consumption all year round. Also, NLNG RA surface water recorded the least WQI of 55.22 which was still rated to be poor water quality.

3.2 Spatial Distribution of the Physiochemical Parameters, Heavy Metal, Petroleum Hydrocarbon at Bonny Island

Principal component analysis (PCA) was employed to explore the relationships among various water quality parameters and sampling locations and the results are presented in Tables 2 and 3. The result of the Eigenvalues which represent the amount of variance explained by each principal component is presented in Table 2. The results show that the first principal component (F1) has the highest eigenvalue (2.869), explaining 17.933% of the variability. Subsequent components contribute progressively less to the total variance. The next five principal components had eigenvalues greater than 1 which aided in retaining the next five components. Based on the Eigenvalue criteria, the first six components were retained. The cumulative proportion of variance retained by the 6 components was 67.75% which adequately retained much of the information from the original dataset. Varimax rotation was applied to the initial solution. The varimax rotation aids in simplifying the interpretation of the factor loadings, revealing underlying patterns in the dataset.

Table 1. Water quality of different sample water from the study area and the control sample

Sampling Locations	July	October	December	January
Ablamabie surface water	86.20	93.25	101.52	95.89
Ablamabie shallow wells	86.56	70.99	93.46	106.25
Water well-6 shallow well	105.72	60.26	76.61	63.38
Finima surface water	107.46	114.23	101.38	112.21
NLNG RA surface water	71.22	65.15	67.89	55.22
NLNG IA surface water	78.65	69.69	65.80	83.41
Bonny Jetty surface water	117.67	87.87	100.28	73.40
Light House ground water	115.61	99.39	118.00	70.41
Light House surface water	106.61	125.39	66.28	73.40
Workers Camp surface water	82.16	86.80	66.28	73.40
Control (BUC)	**38.07**	**45.77**	**39.40**	**35.19**

WQI rating: 0-25=Excellent water quality, 26-50=Good water quality, 51-75=Poor water quality, 76-100=Very poor water quality, >100 unfit for consumption. Source: Brown et al. 1972

Table 2. Eigenvalue and Proportion of Variance

Principal Components	Eigenvalue	Before Varimax		After Varimax	
		Variability (%)	Cumulative %	Variability (%)	Cumulative %
F1	2.869	17.933	17.933	16.917	16.917
F2	2.774	17.339	35.272	14.255	31.172
F3	1.742	10.889	46.161	13.948	45.120
F4	1.341	8.380	54.541	8.339	53.460
F5	1.070	6.690	61.231	7.030	60.490
F6	1.044	6.528	67.759	7.270	67.759

The result of the factor loading is presented in Table 3. Factor loadings indicate the strength and direction of the relationship between variables and principal components. In interpreting the results, values greater than 0.45 are often considered significant. For example, Dissolved Oxygen (DO) had a loading of 0.673 on the fifth factor (D5), indicating a strong positive association. pH had a loading of 0.535 on the first factor (D1), suggesting a substantial contribution to this component. TDS and EC exhibited high loadings on multiple factors, reflecting their influence on various components. After varimax rotation, variables with loadings greater than 0.45 on a given component were retained. For instance, four physiochemical parameters namely pH, TDS, EC, and phosphate were retained on the first principal component. Five parameters namely nitrate, cadmium, lead, TPH, and PAH were retained on the second principal component. Two parameters namely Chloride and sulphate were on the third principal components. Just chromium was retained on the fourth principal component. DO, Iron, and TPH were retained on the fifth principal component. Temperature was retained on the sixth principal component.

The result of the biplot which show the distribution of the physiochemical parameter concentration in the various sampling locations are shown in Figs. 2 and 3. The result from Fig. 2 revealed that the surface water samples obtained from the jetty had higher concentration of TDS, pH, EC, and phosphate compared to other sampling locations. Residential Area surface water also had elevated TDS, pH, EC and phosphate than the other sampling locations. The industrial area surface water had the highest concentration of lead, PAH, TPH, and Nitrate than any other sampling locations.

The result from Fig. 3 showed that surface water from the Finima had highest concentrations of chloride and sulphate. Also, the surface water at light house also had elevated chloride and sulphate. The surface water at the jetty had elevated DO while the ground water at light house had elevated iron concentrations.

3.3 Regression Modelling

The model developed related the WQI with the physiochemical parameters, heavy metal, and petroleum hydrocarbon. The result of the developed model is presented in Tables 4 and 5. The developed model aids in obtaining the WQI when the physiochemical parameters, heavy metals, or petroleum hydrocarbon are known. The first model related the WQI with the variables in principal component 1 (pH, TDS, EC, Phosphate) as shown in Table 4. The result from the model development showed that those parameters were not good predictors of the WQI due to their low-performance metrics. The coefficient of determination for the dry and wet seasons were 0.42 and 0.36 respectively and the mean square errors were relatively high.

Table 3. Factor loading

Parameters	D1	D2	D3	D4	D5	D6
Dissolved Oxygen	0.257	-0.214	-0.151	-0.113	0.673	0.104
pH	0.535	-0.333	0.074	0.470	0.023	-0.153
TDS	0.934	0.022	0.063	-0.086	0.029	0.083
EC	0.935	0.015	0.056	-0.080	0.032	0.083
Temp	0.114	0.033	0.148	0.057	0.045	0.886
TSS	0.330	-0.127	-0.311	0.190	-0.323	0.264
Chloride	0.226	-0.122	0.832	0.010	-0.073	0.176
Phosphate	0.537	0.186	-0.264	0.056	0.139	-0.087
Nitrate	0.188	0.450	0.541	-0.284	0.182	0.200
Sulphate	-0.171	0.303	0.796	0.041	-0.090	0.002
Iron	-0.005	-0.013	-0.446	-0.258	-0.465	0.230
Cadmium	-0.145	0.738	-0.086	0.308	-0.050	-0.138
Lead	0.109	0.659	0.191	0.099	-0.205	0.086
Chromium	-0.151	0.096	0.005	0.858	-0.016	0.103
TPH	-0.114	0.464	-0.293	0.081	0.484	0.294
PAH	0.116	0.747	0.246	-0.217	0.042	0.075

The second model developed related the WQI with the variables in principal component 2 (Nitrate, Cadmium, lead, PAH, TPH) as shown in Table 5. The result from Table 5 indicated that those set parameters were good predictors of the WQI. The coefficient of determination for the dry and wet seasons were 0.83 and 0.96 respectively. The mean square errors obtained for both the dry and wet seasons were 116.84 and 25.54 respectively.

Table 4. Model relating the WQI to factor 1 (pH, TDS, EC, Phosphate)

Model form	Season	Model Equation	Goodness of fit
WQI = f(pH, TDS, EC, Phosphate)	Dry	WQI = 274.19 – 24.72pH + 0.055TDS – 74.64phosphate	$R^2 = 0.42$ MSE = 243.57
	Wet	WQI = 130.15 – 5.26pH + 0.47TDS – 0.23EC - 26.12phosphate	$R^2 = 0.36$ MSE = 318.23

Table 5. Model relating the WQI to factor 1 (Nitrate, Cadmium, lead, PAH, TPH)

5	Season	Model Equation	Goodness of fit
WQI =f(nitrate, Cd, Pb, PAH, TPH)	Dry	WQI = 50.59 + 17.84nitrate – 1.46Cd – 5.51Pb + 153.54TPH – 126.94PAH	$R^2 = 0.83$ MSE = 116.84
	Wet	WQI = 65.70 + 10.25nitrate – 3.76Cd +31.75Pb – 33.60TPH + 1.15PAH	$R^2 = 0.96$ MSE = 25.54

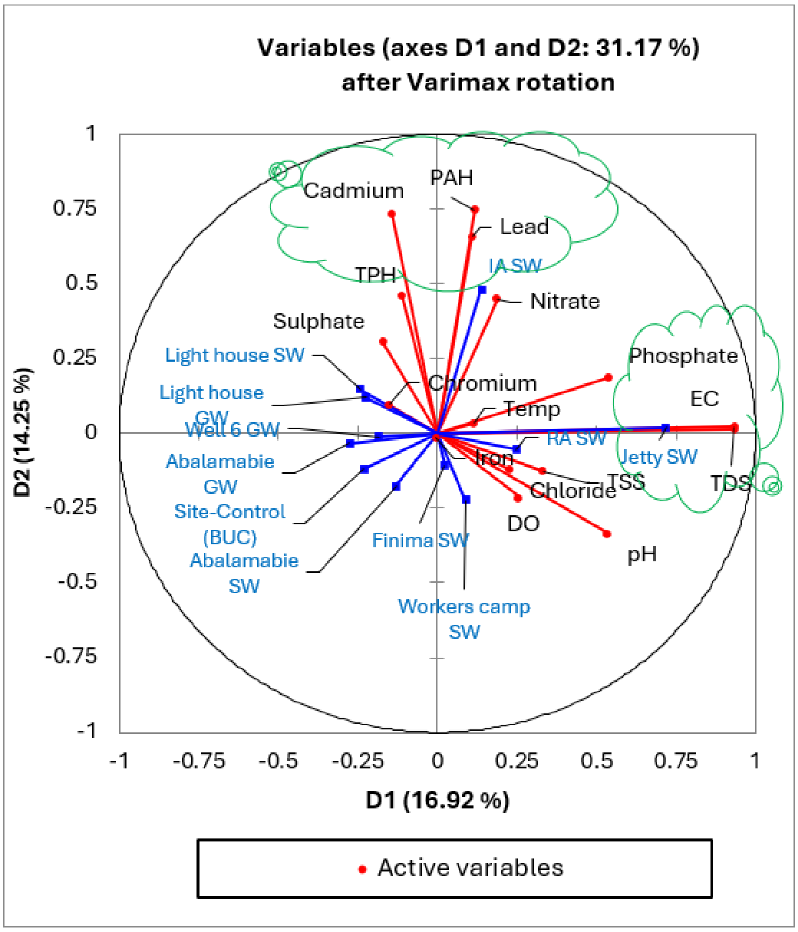

Fig. 2. Biplot showing the distribution of the physiochemical parameters at the different sampling location

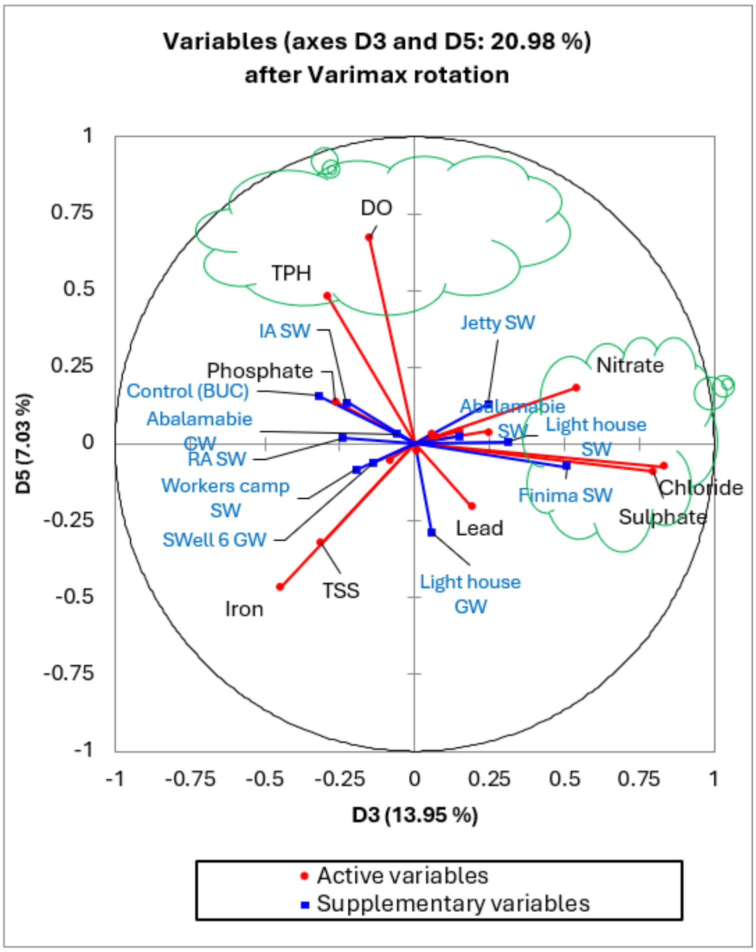

Fig. 3. Biplot showing the distribution of the physiochemical parameters at the different sampling location

4. DISCUSSION

The water quality index (WQI) found in the sampling locations ranged from 55.22 to 125.39 indicating that the surface or groundwater had either poor or unfit water for human consumption. Notably, the Light House surface water exhibited the highest WQI of 125.39, categorized as unfit for consumption, while Finima, home to the Nigeria Liquefied Natural Gas (NLNG) plant, had unfit water quality throughout the year. The water quality where oil and gas activities occur in Bonny Island were mostly unfit for consumption. The poor water quality where downstream oil and gas activities take place can be attributed to hydrocarbon contamination and heavy metal pollution of the water sources. The relatively good water quality at a control site on Bonny Island provided evidence in stating that downstream activities might be a contributing factor to the poor water quality. Nwankwoala and Omofuophu [7] reported extremely high levels of total petroleum hydrocarbons (TPH) in groundwater samples around the Bonny oil and gas terminal, exceeding regulatory intervention limits by over 34 times.

The principal component analysis (PCA) shed light on the potential sources of contamination. Higher concentrations of parameters like total dissolved solids (TDS), pH, electrical conductivity (EC), and phosphates were observed in surface water samples from the Jetty and residential areas, suggesting impacts from domestic and industrial effluents. Meanwhile, elevated levels of lead, polycyclic aromatic hydrocarbons (PAHs), TPH, and nitrates in the Industrial area surface water pointed towards contributions from oil and gas activities. Furthermore, the high chloride and sulphate levels observed in surface water samples from Finima and Light House could be linked to the impacts of the NLNG plant and associated operations. The finding from this study have shown that industrial activities, particularly those related to oil and gas production, consistently contribute to poor water quality in Bonny Island.

Drinking contaminated groundwater which is unfiltered and untreated can result in serious health challenges. Odo et al. [3] in their study measured some renal function markers in the blood of residents who stayed at Finima in Bonny. The result from their study showed that residents in Bonny Island had significantly higher levels of creatine, urea, and cystatin-C levels than people from a control group (areas without oil and gas activities). Odo et al. [3] attributed the increase in the renal markers concentration in residents to prolonged exposure to gas flaring, but multiple exposure paths might have been the result of such elevated concentration. The higher level of creatine, urea, and cystatin C levels in the blood of residents in Finima indicates that a good number of them might be suffering from kidney damage because of the oil and gas activities occurring in that area. Damage to the kidney limits its filtering capability of waste products like creatine and urea. Treatment of the groundwater for residents in Bonny Island is paramount to limit the adverse health effects of consuming contaminated drinking water. The result from the model development showed that nitrate cadmium, lead, TPH, and PAH had a good relationship with the WQI. Surface or groundwater with elevated concentrations of these five parameters is likely to have poor water quality and vice versa.

5. CONCLUSION

The study assessed the spatial distribution of water quality for surface and ground water at Bonny Island in Nigeria, which has a thriving oil and gas industry. The results showed that the water quality in areas near the oil and gas operations were poor to unfit for consumption, with water quality indices ranging from 55.22 to 125.39. In contrast, the control location away from the industry had good water quality with indices between 35.19 and 45.77. The findings demonstrate the significant impact of the oil and gas industry on the water resources in Bonny Island with the water in areas surrounding the industrial operations being unsuitable for drinking.

Interventions are urgently required to mitigate the contamination of the water sources and in other to ensure the availability of clean water for the local population. Potential measures that can be taken to reduce the pollution of the surface and groundwater are constant monitoring of effluent discharge and plume stack monitoring by regulatory agencies. Regulatory agencies should attach penalties to companies that discharge effluent above the safe limit. The IOC and NLNG who are the industrial stakeholders can ensure that effective water treatment plants are setup especially within the industrial area to help in the purification of water. Policy makers should be concerned with mandating the establishment of water treatment plants especially in region where oil and gas activities occur. Given the persistent issue of poor water quality on Bonny Island, industrial stakeholders should also set up subsidized clinics to provide treatment for any gastrointestinal illnesses, renal damage or other health issues arising from contaminated water sources. While this study provides valuable insights to surface and groundwater contamination, there are limitations that should be acknowledged. The study only employed the use of 9 sampling locations. Additional sampling location within close proximity can provide more accurate assessment of the water quality within a specific region. Further research is needed to investigate the long-term impacts of water contamination on human health and ecosystems, as well as to explore innovative and sustainable solutions for water treatment and resource management in industrial areas.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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