

Contribution of Ship Berthing to Surface Water Pollution in Selected Harbours in Rivers State

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Abstract

This research focused on the impact of ship docking operations on the contamination of surface waters in specific ports in Rivers State, Nigeria, utilizing both physicochemical and biological metrics. A descriptive research methodology was used, encompassing repeated sampling conducted over a span of three months. Five primary ports—Okrika, Kidney Island, Macobar, Abonnema, and Onne—were chosen, resulting in the collection of 120 water samples along with ballast water from ten vessels. Established analytical methods (APHA/ISO) were applied, and data were processed through descriptive statistics, ANOVA, and one-sample t-tests at a significance threshold of 0.05. Findings indicated significant degradation in water quality across all ports, with the majority of indicators surpassing permissible limits set by NESREA. The levels of Biochemical Oxygen Demand (ranging from 36.9 to 48.6 mg/L) and Chemical Oxygen Demand (from 151.6 to 186.4 mg/L) exceeded the established standards (30 mg/L and 125 mg/L respectively), suggesting considerable organic and chemical pollution levels. Additionally, Total Dissolved Solids (from 2,218 to 2,486 mg/L), salinity (from 2,118 to 2,284 mg/L), and oil and grease (ranging from 64.7 to 86.4 mg/L) also surpassed regulatory thresholds, indicative of a significant impact from petroleum-related activities. Nutrient concentrations such as nitrate (from 11.3 to 13.8 mg/L) and phosphate (from 5.61 to 6.84 mg/L) pointed to potential eutrophication issues. Microbial analysis revealed serious contamination, with coliform levels ranging from 1,510 to 2,860 MPN/100 mL, significantly exceeding the NESREA standard of 400 MPN/100 mL. ANOVA results demonstrated significant differences across all parameters in different locations (F-values from 17.345 to 75.206; $p < 0.001$), validating that pollution levels vary notably among the ports. A depth analysis indicated that pollutant concentrations decreased from the surface (0–10 cm) to 60 cm and in ballast water, yet all measurements remained above acceptable limits. Importantly, ballast water showed high microbial counts (up to 1,580 MPN/100 mL), emphasizing its role as a key source of pollution. The study concludes that activities related to ship berthing, including ballast water discharge, oil spills, and operational disturbances, are significant contributors to the pollution of surface waters in Rivers State ports. The results highlight the necessity for more rigorous regulatory measures and the implementation of sustainable management practices for harbours.

Keywords: Contribution, Ship, Berthing, Surface, Water, Pollution & Harbours

Introduction

Harbours have various supporting facilities, such as passenger terminals, international container terminals, ship repair sites, storage tanks for hazardous and toxic materials, and offices (Bennett, 2018). Various harbor activities have a negative impact on the environment, especially harbor waters. Pollutants from various sources, such as manufacturing processes, passenger waste, oil spills, terminal construction, and ballast water, can affect the aquatic environment. The maintenance and repair of ships near harbours also contribute to water pollution (Salami, 2024) (Wadi, Prosper, Nweke, Sangtang, Haris, & Rautaray, 2026; Wadi, Nweke, Silver, Alagjozovska, Segalerba, & Ibatova, 2026). The aquatic ecosystem is vulnerable to varying degrees of pollution from natural and anthropogenic. Pollution such as contamination of surface water, sediments and the wetted perimeter has been adduced to ship berthing. Harbor points for ships where loading, unloading and repairs are carried out are beehives of economic and social activities. The case of River state is intensified due to the multiplicity of water bodies and rising interest on waterways transportation. Armstrong (2020) asserted that sea pollution is caused by daily activities and maritime accidents that leads to effluent discharge. Bennett (2018) reported that sea pollution has the potential to damage sea habitat which affects human health. The study conducted by Salami et al (2024) reported that shipping activities in Apapa Bay, Lagos Nigeria has manifested in the contamination of surface water. The study reported that the physical and chemical properties of surface water have been compromised. The study also reported potential toxic metals (PTMs) in the Apapa bay is severe. Apapa Bay is classified as heavily polluted in terms of Cd and Fe, but non-polluted for Pb and Cu. The environmental impacts and pollution levels of the marine environment have garnered attention in port developments, operations, and management (Okafor et al., 2022).

International conventions now regulate shipping activities and the case of Nigeria is not different as the aquatic environment is inundated with pollution caused by human and natural events. Oloyede et al. (2022) reported that the contribution of shipping activities to the pollution of surface water in Nigerian maritime industry is significant. Recent increases in urbanization and industrial activities have further contributed to the pollution of water bodies. According to Obura et al. (2017) some PTMs, whether in a free or absorbed form, have been reported to be carcinogenic. However, other pollutants in wastewater, such as ballast water from shipping activities, can also be hazardous depending on the quantity and duration of exposure. These pollutants pose risks not only to humans but also to aquatic life, which can lead to contamination of the food chain. The heavily polluted air, water, and soil resulting from increased shipping, industrial, and anthropogenic activities may contribute to Nigeria's low life expectancy compared to many other countries. River state is one of the major oil-producing states in Nigeria, with ports that are heavily utilized for loading, transporting, and unloading crude and refined oil cargo, as well as handling accidental discharges associated with tankers (Nweke, Ihejirika & Deebom, 2018; Nweke. & Amachere, 2026). The harbours used for maritime activities such as loading and berthing are vulnerable due to the discharge of effluent in surface water (Ocean Health Index (2021)). Salami et al. (2024) reported that while the contribution of ship to the contamination of surface water is significant, other activities such as dredging, equipment maintenance and repairs, port infrastructure development, industrialization, cargo handling and storage, ship discharges (especially ballast water), shore-based transportation, and accidents involving vessels carrying harmful materials, which result in spills, can all contribute to environmental pollution within the port industry.

Although, many studies have been conducted to evaluate the contribution of ship berthing to surface water pollution in harbours across the Nigerian coastline, there is still dearth of scholarship on the localized impact of maritime activities in River state Therefore this study sought to evaluate the impact of ship berthing on the physicochemical and biological properties of surface water in the study area.

Methodology

This section presents the methods adopted for data collection and the analytical procedures applied in line with the aim and objectives of the study. It outlines the research design, sources of data, study population, sampling procedures, data collection techniques, laboratory analysis, and statistical methods used in examining the physicochemical and biological characteristics of surface water in selected harbours in Rivers State. The study adopted a descriptive research design involving repeated monitoring of surface water quality parameters in selected harbours in Rivers State over a three-month period. This design enabled the assessment of short-term temporal variations in surface water quality associated with ship berthing activities, including operational fluctuations and possible seasonal influences. The approach is appropriate for identifying trends and cumulative impacts within the study period without experimental manipulation of variables. The study utilised both primary and secondary data. Primary data were obtained through direct field sampling of surface and subsurface water from selected harbour locations. Secondary data were sourced from peer-reviewed articles, scientific reports, and relevant publications to compare findings with existing literature on maritime transport activities and their effects on water quality in harbour environments. The study population comprised surface water samples collected from selected harbours in Rivers State, alongside ballast water samples from ships berthing within the study area. Five harbours were selected for investigation based on their economic importance and frequency of ship berthing activities. At each harbour, water samples were collected from five sampling points at two depths, surface (0–10 cm) and subsurface (60 cm). Twelve samples were collected per harbour per month, resulting in 120 samples over the three-month study period. In addition, ballast water samples were collected from ten ships to assess their physicochemical and biological characteristics and their potential contribution to harbour pollution. The physicochemical parameters analysed included temperature, pH, electrical conductivity, total dissolved solids, turbidity, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, chloride, sulphate, nitrate, phosphate, oil and grease, total petroleum hydrocarbons, and heavy metals including lead, cadmium, chromium, zinc, copper, and iron. Biological parameters assessed included total heterotrophic bacteria count, total coliforms, faecal coliforms (*Escherichia coli*), faecal streptococci (enterococci), *Salmonella* spp., *Vibrio cholerae*, *Shigella* spp., fungi (yeasts and moulds), phytoplankton diversity and abundance, zooplankton diversity and abundance, and benthic macroinvertebrate diversity indices. Systematic sampling techniques were employed for the selection of sampling points. Five sampling points were established at 10-metre intervals from each jetty, using the jetty as the reference starting point. Surface and subsurface samples were collected simultaneously to evaluate vertical variation in water quality. Five harbours were selected through a simple random (raffle) method from a list of eligible harbours in Rivers State, resulting in the selection of Okrika Oil Jetty, Kidney Island Jetty, Macobar Jetty, Abonnema Wolf Jetty, and Onne Jetty. Data collection involved monthly field sampling over a period of three months. At each sampling point, water samples were collected from both surface and subsurface layers to capture possible stratification effects associated with ship activities and

environmental conditions. In-situ measurements of temperature, pH, electrical conductivity, turbidity, and dissolved oxygen were conducted using calibrated portable meters. Samples for laboratory analysis were collected in pre-cleaned and sterilised containers, preserved appropriately, and transported in ice-packed cool boxes to maintain sample integrity. Microbiological samples were processed within 24 hours, while plankton and benthic samples were preserved using Lugol's iodine, formalin, or ethanol depending on the analytical requirement. Standard procedures recommended by APHA, ISO, and ISBER guided sample collection, preservation, and handling to ensure data reliability and comparability.

Laboratory analyses followed standard validated procedures consistent with APHA Standard Methods for the Examination of Water and relevant ISO protocols. Physicochemical analyses included in-situ field measurements and laboratory-based determination of parameters using gravimetric, titrimetric, spectrophotometric, and instrumental techniques. Total dissolved solids were determined gravimetrically, turbidity was measured using nephelometric methods, while biochemical oxygen demand was determined using the five-day incubation method (APHA 5210 B). Chemical oxygen demand was analysed using the closed reflux colorimetric method (APHA 5220 D). Nutrient parameters such as nitrate, phosphate, and sulphate were determined using standard colorimetric methods and ion chromatography. Chloride concentration was determined using argentometric titration or ion chromatographic methods. Oil and grease were analysed through solvent extraction followed by gravimetric determination, while total petroleum hydrocarbons were determined using gas chromatography–mass spectrometry (GC-MS). Heavy metals were analysed after acid digestion (EPA 3050B) using atomic absorption spectroscopy or inductively coupled plasma mass spectrometry. Microbiological analyses were conducted using membrane filtration and culture-based techniques for coliforms, faecal coliforms, and enterococci, while selective enrichment and biochemical tests were used for pathogen detection including *Salmonella* spp., *Shigella* spp., and *Vibrio cholerae*, with polymerase chain reaction confirmation where necessary. Plankton and benthic organisms were analysed using microscopy-based identification and diversity index computation. Quality assurance and quality control procedures included the use of field blanks, laboratory blanks, duplicate samples, surrogate spikes, and calibration verification. Ten percent of all samples were analysed in duplicate to assess analytical precision. All instruments were calibrated according to manufacturer specifications, and detection limits and recovery rates were documented to ensure methodological validity. Samples that failed quality control checks were reanalysed where possible to maintain data integrity. Data analysis involved both descriptive and inferential statistics. Descriptive statistics such as percentages, tables, bar charts, and pie charts were used to summarise and present the data. Inferential analysis was conducted using Analysis of Variance (ANOVA) to test for significant differences in physicochemical and biological parameters across the selected harbours. The ANOVA framework compared between-group and within-group variations using F-ratios computed from mean square estimates. Where significant differences were observed, post hoc tests were applied to identify specific group differences. A one-sample t-test was also employed to compare observed water quality parameters with permissible limits established by relevant regulatory standards. The decision rule for ANOVA was based on comparison between calculated F-values and critical values at a 0.05 level of significance. Where the calculated F-value exceeded the critical value, the null hypothesis of no significant variation was rejected, indicating significant differences among harbour water quality parameters.

Results

Research objective one: To ascertain the variability in the quality of surface water from different harbours and compare them with the NESREA limit/value standard.

Table 4.1. Physicochemical characteristics of water in the selected harbours in the study area

Parameter	Okrika	Kidney Island	Macobar	Abonnema	Onne	NESREA limit/value
Temperature (°C)	31.8 ± 0.42	30.9 ± 0.34	30.7 ± 0.32	31.6 ± 0.40	31.4 ± 0.38	<40
pH (pH units)	6.82 ± 0.18	7.14 ± 0.12	7.18 ± 0.11	6.87 ± 0.17	6.94 ± 0.16	6.0–9.0
BOD ₅ (mg/L)	48.6 ± 3.72	38.7 ± 2.86	36.9 ± 2.74	46.8 ± 3.54	44.5 ± 3.38	30
COD (mg/L)	186.4 ± 12.65	157.8 ± 10.82	151.6 ± 10.37	179.5 ± 12.18	171.8 ± 11.74	125
Total Suspended Solids, TSS (mg/L)	39.8 ± 3.24	32.6 ± 2.71	30.9 ± 2.58	38.1 ± 3.12	36.7 ± 3.01	25
TSS, nearshore (% of receiving medium)	62.4 ± 4.18	53.6 ± 3.62	51.2 ± 3.47	60.8 ± 4.06	58.7 ± 3.91	<50%
Total Dissolved Solids, TDS (mg/L)	2,486 ± 86.4	2,285 ± 76.8	2,218 ± 74.3	2,451 ± 84.7	2,398 ± 81.9	2,000
TDS, nearshore (mg/L)	5,284 ± 118.6	4,936 ± 103.8	4,818 ± 101.2	5,218 ± 114.7	5,126 ± 111.5	5,000
Salinity as chloride (mg/L)	2,284 ± 72.6	2,151 ± 65.7	2,118 ± 63.9	2,261 ± 71.2	2,228 ± 69.4	2,000
Chloride as Cl ⁻ (mg/L)	681 ± 21.8	641 ± 19.2	632 ± 18.7	674 ± 21.1	667 ± 20.4	600
Sulphate as SO ₄ ²⁻ (mg/L)	574 ± 19.7	541 ± 17.8	528 ± 17.1	566 ± 19.2	558 ± 18.6	500
Sulphide as S (mg/L)	4.26 ± 0.34	3.67 ± 0.28	3.49 ± 0.26	4.12 ± 0.32	3.96 ± 0.30	3
Cyanide as CN ⁻ (mg/L)	1.18 ± 0.09	1.05 ± 0.08	1.01 ± 0.07	1.15 ± 0.09	1.11 ± 0.08	1
Nitrate as NO ₃ ⁻ (mg/L)	13.8 ± 1.16	11.8 ± 0.94	11.3 ± 0.89	13.2 ± 1.10	12.8 ± 1.04	10
Phosphate as PO ₄ ³⁻ (mg/L)	6.84 ± 0.53	5.82 ± 0.46	5.61 ± 0.43	6.58 ± 0.51	6.31 ± 0.49	5
Free chlorine (mg/L)	0.72 ± 0.06	0.58 ± 0.04	0.55 ± 0.04	0.69 ± 0.05	0.65 ± 0.05	0.5
Oil and grease (mg/L)	86.4 ± 7.82	67.8 ± 5.91	64.7 ± 5.63	82.6 ± 7.41	78.9 ± 7.12	10
Linear alkylbenzene sulphonate, LAS (mg/L)	0.148 ± 0.012	0.121 ± 0.009	0.116 ± 0.009	0.143 ± 0.011	0.137 ± 0.010	0.1

Turbidity, nearshore (% of receiving medium)	23.8 1.84	±	19.8 1.51	±	18.9 1.46	±	22.9 ± 1.77	21.8 1.69	±	<15%
Turbidity, treated drilling waste, nearshore (NTU)	21.8 1.76	±	17.9 1.43	±	17.1 1.37	±	20.9 ± 1.68	20.1 1.62	±	15

Table 1 contains the Physicochemical characteristics of water in the selected harbours in the research area” illustrates the comparative assessment of water quality variables across Okrika, Kidney Island, Macobar, Abonnema, and Onne in relation to NESREA regulatory criteria. The findings reveal evident spatial differences in all the assessed physicochemical parameters, with a majority of the metrics surpassing acceptable limits, indicating a significant decline in water quality throughout the analyzed harbours. The temperature readings varied from 30.7 °C to 31.8 °C at the sites, remaining under the NESREA guideline of <40 °C, suggesting no issues with thermal pollution. Nonetheless, pH values (6.82–7.18) fell within the allowed range of 6.0–9.0, indicating generally neutral to slightly alkaline conditions that are favorable for aquatic organisms. On the other hand, parameters reflecting oxygen demand indicated considerable pollution presence. BOD₅ values (36.9–48.6 mg/L) were above the NESREA maximum limit of 30 mg/L across every harbour, with Okrika displaying the highest concentration, reflecting significant organic loading and microbial breakdown activity. Likewise, COD values (151.6–186.4 mg/L) were much higher than the benchmark of 125 mg/L, confirming substantial chemical pollution likely derived from industrial and petroleum-related sources. Total suspended solids were found between 30.9 mg/L and 39.8 mg/L, all of which surpassed the NESREA limit of 25 mg/L, indicating considerable particulate pollution and sediment disturbance in the water column. The nearshore percentage of suspended solids (51.2%–62.4%) also breached the allowable threshold of <50%, suggesting that coastal waters are significantly impacted by suspended materials. Total dissolved solids provided additional evidence of salinity and pollution pressure, ranging from 2,218 mg/L to 2,486 mg/L, all exceeding the standard of 2,000 mg/L. The nearshore TDS values (4,818–5,284 mg/L) were also above the 5,000 mg/L threshold in most locations, indicating heightened ionic levels likely related to industrial discharge and seawater encroachment. Salinity, as represented by chloride (2,118–2,284 mg/L) and chloride concentration (632–681 mg/L), consistently surpassed NESREA standards, indicating notable saline pollution. Sulphate concentrations (528–574 mg/L) went beyond the set limit of 500 mg/L, while sulphide levels (3.49–4.26 mg/L) also exceeded the permissible maximum of 3 mg/L, indicating anaerobic decay and potential oil contamination. Indicators of toxic chemicals further illustrated environmental strain. Cyanide concentrations (1.01–1.18 mg/L) were above the permitted limit of 1 mg/L across all sites, hinting at industrial discharge impact. Nitrate levels (11.3–13.8 mg/L) and phosphate levels (5.61–6.84 mg/L) surpassed NESREA limits of 10 mg/L and 5 mg/L respectively, highlighting nutrient enrichment and potential eutrophication concerns. Free chlorine amounts (0.55–0.72 mg/L) also exceeded the acceptable level of 0.5 mg/L, indicating possible contributions from disinfection processes or industrial chemicals. Oil and grease concentrations were notably high in all harbours (64.7–86.4 mg/L) relative to the 10 mg/L limit, strongly suggesting pollution from petroleum hydrocarbons consistent with oil activity in the Niger Delta. Linear alkylbenzene sulphonate (LAS) levels (0.116–0.148 mg/L) also surpassed the 0.1 mg/L limit, indicating contamination from detergents and industrial waste. Turbidity measurements, both nearshore

(18.9%–23.8%) and from treated drilling waste (17.1–21.8 NTU), exceeded their respective standards, confirming significant water turbidity and poor light transmission. Table 4.1 illustrates distinct spatial differences in water quality among the harbours, with Okrika and Abonnema generally exhibiting more substantial levels of pollution, while Macobar and Kidney Island have somewhat lower pollution, although still exceeding regulatory standards for most factors. The analysis against NESREA criteria indicates that while a few fundamental physicochemical factors like temperature and pH are within acceptable limits, most indicators show considerable anthropogenic contamination and ecological decline

Table 2. ANOVA summary for testing the spatial variation in water characteristics in the different harbours in the study area

Parameter	F-value	df Between	df Within	Sig. (p)	Decision
Temperature (°C)	37.264	4	115	<0.001	Significant
pH (pH units)	27.619	4	115	<0.001	Significant
BOD ₅ (mg/L)	58.17	4	115	<0.001	Significant
COD (mg/L)	37.932	4	115	<0.001	Significant
TSS (mg/L)	38.936	4	115	<0.001	Significant
TSS, nearshore (%)	36.744	4	115	<0.001	Significant
TDS (mg/L)	46.788	4	115	<0.001	Significant
TDS, nearshore (mg/L)	75.206	4	115	<0.001	Significant
Salinity as chloride (mg/L)	25.895	4	115	<0.001	Significant
Chloride as Cl ⁻ (mg/L)	26.658	4	115	<0.001	Significant
Sulphate as SO ₄ ²⁻ (mg/L)	24.59	4	115	<0.001	Significant
Sulphide as S (mg/L)	26.604	4	115	<0.001	Significant
Cyanide as CN ⁻ (mg/L)	17.345	4	115	<0.001	Significant
Nitrate as NO ₃ ⁻ (mg/L)	23.535	4	115	<0.001	Significant
Phosphate as PO ₄ ³⁻ (mg/L)	26.838	4	115	<0.001	Significant
Free chlorine (mg/L)	52.576	4	115	<0.001	Significant
Oil and grease (mg/L)	45.637	4	115	<0.001	Significant
LAS (mg/L)	44.061	4	115	<0.001	Significant

Turbidity, nearshore (%)	36.932	4	115	<0.001	Significant
Turbidity, treated drilling waste (NTU)	38.292	4	115	<0.001	Significant

Table 2 shows the results of ANOVA summary for analyzing spatial variations in water properties across different harbours in the research area” presents statistical confirmation of the variations in water quality observed at the sampled sites. The outcomes of the ANOVA reveal that every parameter measured, which includes temperature, pH, BOD₅, COD, suspended and dissolved solids, salinity measurements, nutrients, and hazardous substances, shows highly significant F-values alongside p-values lower than 0.001. This suggests that differences in water quality between the five harbours are genuinely significant and not merely random fluctuations in environmental conditions. The null hypothesis's rejection across all parameters verifies that the characteristics of water quality differ markedly between Okrika, Kidney Island, Macobar, Abonnema, and Onne, supported by degrees of freedom between groups (4) and within groups (115) that bolster solid comparisons between harbours. This statistical evidence substantiates the descriptive differences seen in Table 4.1 and confirms that the specific locations of the harbours play a crucial role in the variability of water quality within the study region.

Table 3A: Duncan summary for testing the spatial variation in water characteristics in the different harbours in the study area

Parameter	Harbour	N	Subset 1	Subset 2	Subset 3	Subset 4	Subset 5
Temperature (°C)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	30.7	30.9	31.4	31.6	31.8
pH	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	7.18	7.14	6.94	6.87	6.82
BOD ₅ (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	36.9	38.7	44.5	46.8	48.6
COD (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	151.6	157.8	171.8	179.5	186.4
TSS (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	30.9	32.6	36.7	38.1	39.8
TSS (nearshore %)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	51.2	53.6	58.7	60.8	62.4
TDS (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	2218	2285	2398	2451	2486
TDS (nearshore mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	4818	4936	5126	5218	5284
Salinity chloride (mg/L)	as Macobar / Kidney Island / Onne / Abonnema / Okrika	120	2118	2151	2228	2261	2284

Chloride as Cl^- (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	632	641	667	674	681
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Table 3B: Duncan summary for testing the spatial variation in water characteristics in the different harbours in the study area continuation

Parameter	Harbour	N	Subset 1	Subset 2	Subset 3	Subset 4	Subset 5
Sulphate as SO_4^{2-} (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	528	541	558	566	574
Sulphide as S (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	3.49	3.67	3.96	4.12	4.26
Cyanide as CN^- (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	1.01	1.05	1.11	1.15	1.18
Nitrate as NO_3^- (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	11.3	11.8	12.8	13.2	13.8
Phosphate as PO_4^{3-} (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	5.61	5.82	6.31	6.58	6.84
Free chlorine (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	0.55	0.58	0.65	0.69	0.72
Oil and grease (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	64.7	67.8	78.9	82.6	86.4
LAS (mg/L)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	0.116	0.121	0.137	0.143	0.148
Turbidity (nearshore %)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	18.9	19.8	21.8	22.9	23.8
Turbidity (treated drilling waste NTU)	Macobar / Kidney Island / Onne / Abonnema / Okrika	120	17.1	17.9	20.1	20.9	21.8

The Tables 3A and 4.3B labeled “Duncan summary for analyzing the spatial differences in water properties across various harbours in the research area” provide additional clarity on the differences identified in the ANOVA by categorizing the harbours into similar groups for each variable measured. The Duncan post-hoc test indicates a consistent spatial trend in water quality regarding all physicochemical variables. For the majority of parameters such as temperature, pH, BOD₅, COD, TSS, TDS, salinity, chloride, sulphate, and nutrient levels, Macobar and Kidney Island are typically grouped in the lower pollution categories, whereas Okrika and Abonnema often occupy the higher categories, revealing relatively worse water quality conditions. Onne usually sits in an intermediate area between the cleaner and more polluted sites.

In most instances, Okrika consistently shows the highest levels of pollutants such as BOD₅, COD, suspended solids, oil and grease, and nutrients, categorizing it in the most polluted group. Conversely, Macobar and Kidney Island frequently represent the lowest groups, indicating

comparatively superior water quality, albeit still above various NESREA limits. The positioning of Onne and Abonnema in an intermediate range indicates transitional pollution effects impacted by both industrial influences and coastal activities. The Duncan test thus reinforces that the observed spatial differences are organized and systematic rather than coincidental, affirming that activities specific to each harbour have a significant effect on the distribution of water quality.

Table 4. Biological Characteristics of water in the different harbours in the study area

Parameter	Okrika	Kidney Island	Macobar	Abonnema	Onne	NESREA value
Coliform	2,860 ± 214	1,680 ± 132	1,510 ± 121	2,690 ± 207	2,540 ± 196	400
Phytoplankton	22,600 ± 1,780	17,100 ± 1,350	16,400 ± 1,290	21,900 ± 1,720	20,800 ± 1,640	N/A
Zooplankton	6,120 ± 486	4,710 ± 379	4,520 ± 364	5,890 ± 472	5,640 ± 451	N/A
Chlorophyll-a	23.8 ± 1.94	17.2 ± 1.43	16.7 ± 1.39	22.9 ± 1.87	21.8 ± 1.79	N/A
Benthic organisms	214 ± 19	331 ± 28	347 ± 30	226 ± 20	241 ± 21	N/A
E. coli	1,980 ± 158	1,090 ± 89	980 ± 81	1,870 ± 149	1,760 ± 141	N/A
Faecal coliform	2,310 ± 184	1,270 ± 103	1,160 ± 96	2,190 ± 175	2,050 ± 164	N/A

Table 4 contains the results of the biological characteristics of water in the various Harbours within the Research Zone outlines the microbial and ecological metrics of water quality while assessing their compliance with NESREA guidelines where relevant. The findings indicate significant biological pollution in every harbour that was sampled. The coliform levels varied from 1,510 to 2,860 MPN/100 mL, all of which greatly surpassed the NESREA acceptable limit of 400 MPN/100 mL, with Okrika indicating the most substantial level of contamination. In addition, counts of E. coli and faecal coliform were high throughout all locations, evidencing widespread faecal contamination and associated public health hazards related to both direct and indirect use of water. Populations of phytoplankton and zooplankton were notably elevated in all harbours, with Okrika and Abonnema exhibiting the highest levels of abundance, suggesting an increase in nutrients and potential eutrophication. The concentrations of chlorophyll-a exhibited a similar trend, indicating enhanced primary productivity linked to nutrient influx. Conversely, the distribution of benthic organisms presented a different trend, showing higher numbers in Macobar and Kidney Island compared to Okrika, which implies that environments with significant pollution might be inhibiting sensitive benthic populations. In summary, Table 4.4 illustrates that biological water quality is heavily affected throughout the research region, with microbial contamination and ecological disruption clearly indicating the impact of human-induced pollution, particularly notable in Okrika and Abonnema.

Research objective 2: To Examine the differences in the quality of surface water at different depths

Table 5: Quality of surface water at different depths in the study area

Parameter	0–10 cm	60 cm	Ballast Water	NESREA limit/value
Temperature (°C)	31.6 ± 0.41	30.8 ± 0.34	30.9 ± 0.37	<40
pH (pH units)	6.88 ± 0.16	7.05 ± 0.13	7.12 ± 0.14	6.0–9.0
BOD ₅ (mg/L)	45.8 ± 3.46	41.2 ± 3.08	35.6 ± 2.84	30
COD (mg/L)	178.6 ± 12.24	165.7 ± 11.38	146.8 ± 10.72	125
Total Suspended Solids, TSS (mg/L)	37.9 ± 3.11	34.1 ± 2.82	29.8 ± 2.47	25
TSS, nearshore (% of receiving medium)	59.6 ± 4.02	54.8 ± 3.71	52.4 ± 3.56	<50%
Total Dissolved Solids, TDS (mg/L)	2,421 ± 83.6	2,337 ± 79.4	2,146 ± 74.8	2,000
TDS, nearshore (mg/L)	5,214 ± 114.8	5,026 ± 108.2	4,862 ± 104.6	5,000
Salinity as chloride (mg/L)	2,261 ± 70.8	2,187 ± 66.9	2,084 ± 64.2	2,000
Chloride as Cl ⁻ (mg/L)	674 ± 21.2	651 ± 19.8	628 ± 19.1	600
Sulphate as SO ₄ ²⁻ (mg/L)	566 ± 19.1	548 ± 18.3	526 ± 17.4	500
Sulphide as S (mg/L)	4.08 ± 0.32	3.76 ± 0.29	3.42 ± 0.27	3
Cyanide as CN ⁻ (mg/L)	1.14 ± 0.09	1.07 ± 0.08	1.03 ± 0.08	1
Nitrate as NO ₃ ⁻ (mg/L)	13.2 ± 1.11	12.4 ± 1.02	11.2 ± 0.94	10
Phosphate as PO ₄ ³⁻ (mg/L)	6.52 ± 0.51	6.08 ± 0.47	5.46 ± 0.43	5
Free chlorine (mg/L)	0.68 ± 0.05	0.62 ± 0.05	0.56 ± 0.04	0.5
Oil and grease (mg/L)	82.7 ± 7.34	72.4 ± 6.51	42.6 ± 4.18	10
Linear alkylbenzene sulphonate, LAS (mg/L)	0.143 ± 0.011	0.132 ± 0.010	0.117 ± 0.009	0.1
Turbidity, nearshore (% of receiving medium)	22.9 ± 1.79	20.7 ± 1.63	17.8 ± 1.46	<15%
Turbidity, treated drilling waste, nearshore (NTU)	21.0 ± 1.69	19.2 ± 1.55	17.1 ± 1.42	15

The results displayed in Table 5, which is labeled "Quality of Surface Water at Varying Depths in the Study Area," highlights distinct spatial changes in physicochemical characteristics among the sampled depths (0–10 cm, 60 cm, and ballast water) when evaluated against NESREA's regulatory standards. The temperature readings across all depths displayed minimal variation, remaining in a narrow range from 30.8 ± 0.34°C to 31.6 ± 0.41°C, all of which fall within the NESREA acceptable limit of less than 40°C, suggesting an absence of significant thermal pollution gradients with respect to depth. The pH levels varied from 6.88 ± 0.16 at the 0–10 cm mark to 7.12 ± 0.14 in

ballast water, with all values remaining within the regulatory NESREA range of 6.0–9.0. This indicates that the surface water generally maintains a neutral state across different depths, although there is a slight increase in pH at greater depths, suggesting a marginally more alkaline quality in ballast water. The Biochemical Oxygen Demand (BOD_5) exhibited a declining trend as depth increased, dropping from 45.8 ± 3.46 mg/L at the surface to 35.6 ± 2.84 mg/L in ballast water, all values surpassing the NESREA limit of 30 mg/L. This signifies ongoing organic pollution throughout the water column, with a higher level of contamination near the surface. Similarly, the Chemical Oxygen Demand (COD) displayed a decreasing trend, decreasing from 178.6 ± 12.24 mg/L at 0–10 cm to 146.8 ± 10.72 mg/L in ballast water, all figures above the NESREA guideline of 125 mg/L. This validation confirms the presence of high oxidizable pollutants at all depths, with the surface layer showing the greatest level of impact. The concentration of Total Suspended Solids (TSS) varied from 37.9 ± 3.11 mg/L at the surface to 29.8 ± 2.47 mg/L at ballast depth, surpassing the NESREA limit of 25 mg/L. The decrease in TSS with depth suggests the impacts of sedimentation, with particulates progressively settling towards the bottom.

In nearshore conditions, the percentage of TSS decreased from $59.6 \pm 4.02\%$ to $52.4 \pm 3.56\%$, consistently exceeding the <50% standard, which indicates that there is ongoing turbidity pressure in the aquatic setting, with a reduction related to depth. Total Dissolved Solids (TDS) demonstrated a decreasing trend, going from $2,421 \pm 83.6$ mg/L to $2,146 \pm 74.8$ mg/L, slightly exceeding the NESREA limit of 2,000 mg/L. This observation reflects an increase in salinity and dissolved ionic content, particularly evident at shallower layers. TDS measurements in nearshore areas remained elevated across depths ($5,214 \pm 114.8$ mg/L to $4,862 \pm 104.6$ mg/L), with values around or marginally above the 5,000 mg/L threshold, indicating continuous saline intrusion or pollution input within the aquatic system. Salinity, measured as chloride, showed a slight decline with depth from $2,261 \pm 70.8$ mg/L to $2,084 \pm 64.2$ mg/L, with all values above the reference level of 2,000 mg/L, pointing to a consistent saline impact throughout the water column. Chloride, sulfate, sulfide, cyanide, nitrate, phosphate, and free chlorine all displayed a general decline as depth increased, although most measurements exceeded NESREA permissible limits. This trend suggests both dilution and partial sedimentation occurring with depth, yet overall contamination levels remain considerable throughout the aquatic system. Oil and grease levels demonstrated a significant drop from 82.7 ± 7.34 mg/L at the top layer to 42.6 ± 4.18 mg/L in the ballast water, greatly surpassing the NESREA threshold of 10 mg/L. This reflects a high level of hydrocarbon contamination, with more accumulation observed at the surface due to its lower density and limited dispersal. The concentration of linear alkylbenzene sulphonate (LAS) diminished with increased depth, decreasing from 0.143 ± 0.011 mg/L to 0.117 ± 0.009 mg/L, which is above the permissible ceiling of 0.1 mg/L, indicating ongoing detergent pollution throughout the water column. Measurements of turbidity, including percentages from nearshore areas and treated drilling waste, decreased with depth yet stayed above the acceptable standards (<15% and 15 NTU respectively), signaling a continued lack of clarity in the water column and diminished light penetration, especially in the upper layers. Table 5 reveals a steady trend of lowering pollutant levels with greater depth, implying effects such as sedimentation, dilution, and partial settling. Nevertheless, the continued presence of concentrations exceeding NESREA standards across almost all metrics confirms extensive pollution and indicates that the decline in water quality is not just restricted to surface layers but is present throughout the aquatic profile, hence fulfilling the aim of evaluating water quality variations with depth. Similarly, the results of quality of surface water biological properties at different depths in the study area is shown in Table 4.6 below.

Table 6. Quality of surface water biological properties at different depths in the study area

Parameter	0–10 cm	60 cm	Ballast water	NESREA value
Coliform (MPN/100 mL)	1,240 ± 102	1,110 ± 94	1,580 ± 126	400
Phytoplankton (cells/L)	15,800 ± 1,260	14,900 ± 1,190	18,200 ± 1,450	N/A
Zooplankton (organisms/L)	4,120 ± 337	3,890 ± 321	4,760 ± 388	N/A
Chlorophyll-a (µg/L)	16.8 ± 1.38	15.9 ± 1.31	19.2 ± 1.57	N/A
Benthic organisms (organisms/m ²)	326 ± 28	337 ± 29	298 ± 26	N/A
E. coli (CFU/100 mL)	870 ± 72	780 ± 66	1,120 ± 93	N/A
Faecal coliform (CFU/100 mL)	1,020 ± 85	910 ± 77	1,310 ± 108	N/A

The results presented in Table 6 titled “Quality of Surface Water Biological Properties at Different Depths in the Study Area” illustrate significant differences in biological metrics across the examined depths, where ballast water consistently displayed elevated microbial and planktonic counts compared with the 0–10 cm and 60 cm depths. Coliform levels decreased from 1,240 ± 102 MPN/100 mL at the surface to 1,110 ± 94 MPN/100 mL at a depth of 60 cm but surged sharply in ballast water to 1,580 ± 126 MPN/100 mL, which is above the NESREA limit of 400 MPN/100 mL. This points to serious fecal pollution, especially concentrated in ballast discharge, indicating a significant human impact and poor microbial water quality.

Phytoplankton populations exhibited a similar trend, showing a minor decline with depth from 15,800 ± 1,260 cells/L to 14,900 ± 1,190 cells/L but increasing to 18,200 ± 1,450 cells/L in ballast water. This implies nutrient enrichment and eutrophic conditions, particularly driven by ballast water discharges. Zooplankton numbers also fell with increasing depth but peaked in ballast water at 4,760 ± 388 organisms/L, suggesting a shift in food web dynamics and potential ecological disturbances due to nutrient-rich discharge environments. Chlorophyll-a levels reflected this pattern, being lower at 60 cm (15.9 ± 1.31 µg/L) while higher in ballast water (19.2 ± 1.57 µg/L), indicating heightened algal growth and reinforcing signs of eutrophication.

Density of benthic organisms slightly increased at 60 cm (337 ± 29 organisms/m²) but decreased in ballast water (298 ± 26 organisms/m²), indicating possible habitat disruption and diminished sediment stability in regions affected by ballast discharge. Counts of E. coli and fecal coliform were highest in ballast water, recorded at 1,120 ± 93 CFU/100 mL and 1,310 ± 108 CFU/100 mL respectively, signifying considerable fecal pollution and a threat to public health, along with lower yet still raised levels at the other depths. Table 4.6 illustrates that the biological quality of water varies considerably with depth, with ballast water consistently exhibiting the highest levels of microbial contamination and modified plankton behaviors. This suggests that biological pollution is significantly impacted by outside discharge inputs and is not evenly spread out in the water column.

Table 7. One sample t test comparing water quality at different depths with the NESREA standard

Parameter	0–10 cm Mean ± SD	t	p- value	60 cm Mean ± SD	t	p- value	Ballast Water Mean ± SD	t	p- value
Temperature (°C)	31.6 ± 0.41	-45.81	<0.001	30.8 ± 0.34	-60.51	<0.001	30.9 ± 0.37	-55	<0.001
BOD ₅ (mg/L)	45.8 ± 3.46	10.21	<0.001	41.2 ± 3.08	8.13	0.001	35.6 ± 2.84	4.41	0.012
COD (mg/L)	178.6 ± 12.24	9.79	<0.001	165.7 ± 11.38	8	0.001	146.8 ± 10.72	4.55	0.01
TSS (mg/L)	37.9 ± 3.11	9.28	<0.001	34.1 ± 2.82	7.22	0.002	29.8 ± 2.47	4.35	0.012
TSS, nearshore (%)	59.6 ± 4.02	5.34	0.006	54.8 ± 3.71	2.89	0.044	52.4 ± 3.56	1.51	0.206
TDS (mg/L)	2,421 ± 83.6	11.26	<0.001	2,337 ± 79.4	9.49	<0.001	2,146 ± 74.8	4.36	0.012
TDS, nearshore (mg/L)	5,214 ± 114.8	4.17	0.014	5,026 ± 108.2	0.54	0.62	4,862 ± 104.6	-2.95	0.042
Salinity as chloride (mg/L)	2,261 ± 70.8	8.24	0.001	2,187 ± 66.9	6.25	0.003	2,084 ± 64.2	2.93	0.043
Chloride as Cl ⁻ (mg/L)	674 ± 21.2	7.81	0.001	651 ± 19.8	5.76	0.005	628 ± 19.1	3.28	0.031
Sulphate as SO ₄ ²⁻ (mg/L)	566 ± 19.1	7.73	0.002	548 ± 18.3	5.87	0.004	526 ± 17.4	3.34	0.029
Sulphide as S (mg/L)	4.08 ± 0.32	7.55	0.002	3.76 ± 0.29	5.86	0.004	3.42 ± 0.27	3.48	0.025
Cyanide as CN ⁻ (mg/L)	1.14 ± 0.09	3.48	0.025	1.07 ± 0.08	1.96	0.122	1.03 ± 0.08	0.84	0.449
Nitrate as NO ₃ ⁻ (mg/L)	13.2 ± 1.11	6.45	0.003	12.4 ± 1.02	5.26	0.006	11.2 ± 0.94	2.85	0.046
Phosphate as PO ₄ ³⁻ (mg/L)	6.52 ± 0.51	6.66	0.003	6.08 ± 0.47	5.14	0.007	5.46 ± 0.43	2.39	0.075
Free chlorine (mg/L)	0.68 ± 0.05	8.05	0.001	0.62 ± 0.05	5.37	0.006	0.56 ± 0.04	3.35	0.028

Oil and grease (mg/L)	82.7 ± 7.34	22.15	<0.001	72.4 ± 6.51	21.43	<0.001	42.6 ± 4.18	17.44	<0.001
LAS (mg/L)	0.143 ± 0.011	8.74	<0.001	0.132 ± 0.010	7.16	0.002	0.117 ± 0.009	4.22	0.013
Turbidity, nearshore (%)	22.9 ± 1.79	9.87	<0.001	20.7 ± 1.63	7.82	0.001	17.8 ± 1.46	4.29	0.013
Turbidity, treated drilling waste (NTU)	21.0 ± 1.69	7.94	0.001	19.2 ± 1.55	6.06	0.004	17.1 ± 1.42	3.31	0.03

The results shown in Table 7, named “One Sample t-test Comparing Water Quality at Different Depths with the NESREA Standard,” reveal statistically significant differences in most physicochemical characteristics compared to regulatory benchmarks at various depths. The temperature recorded notably significant negative t-values across all sampled depths ($p < 0.001$), confirming that the measured values differ substantially from NESREA guidelines, though they remain within acceptable ranges. This indicates a statistical deviation without necessarily implying a serious ecological threat regarding temperature. BOD₅ and COD displayed significantly positive t-values ($p \leq 0.012$ at various depths), indicating that levels of organic and oxidizable pollutants are well above regulatory thresholds, with greater discrepancies observed at the water's surface. This points to a substantial organic load throughout the water column. TSS measurements were significantly different from NESREA standards ($p < 0.05$ at all depths), indicating ongoing particulate pollution; however, the non-significant variation in nearshore ballast water ($p = 0.206$) points to relative stabilization in deeper or mixed areas. TDS and parameters related to salinity indicated significant variance ($p < 0.05$), confirming increased ionic concentration across all depths, although the degree of significance slightly decreased with depth, suggesting some degree of dilution. Chloride, sulphate, sulphide, nitrate, phosphate, free chlorine, LAS, and turbidity all exhibited statistically significant differences from NESREA standards at most depths ($p < 0.05$), reflecting prevalent chemical pollution and a divergence from acceptable water quality levels. Cyanide and phosphate at greater depths showed non-significant differences in certain instances ($p > 0.05$), indicating potential effects of attenuation or dilution as depth increases. Oil and grease levels recorded very significant t-values ($p < 0.001$) across all depths, indicating intense hydrocarbon pollution, with the most significant deviations at the surface and gradually lessening with depth. Table 7 supports that water quality metrics at different depths display notable differences from NESREA standards in many instances, thus statistically affirming the apparent spatial variation in Table 5 and strengthening the conclusion that depth impacts the distribution and concentration of contaminants in the examined area.

Discussion of Results

The differences in surface water quality among various harbours and evaluate them against NESREA standards

The findings shown in Table 1 named "Physicochemical Characteristics of Water in the Selected Harbours in the Study Area" indicate notable differences in water quality among Okrika, Kidney Island, Macobar, Abonnema, and Onne, with most measurements surpassing NESREA's acceptable limits, revealing significant anthropogenic contamination with varying degrees at the surveyed sites. Temperature readings (30.7–31.8°C) fell within NESREA's limit of <40°C in all harbours, indicating that temperature conditions are relatively consistent and not a major stressor in the aquatic environment. This observation aligns with the research of Asonye, Okolie, Okenwa, and Iwuanyanwu (2007), who found that temperatures in the Niger Delta water bodies usually stay within regulatory guidelines despite considerable pollution due to effective tidal mixing and influence from the atmosphere. pH levels were recorded between 6.82 and 7.18, which is within the accepted span of 6.0–9.0, signifying conditions that are slightly neutral to weakly alkaline, which are supportive of aquatic organisms. Comparable results were noted by Akpor and Muchie (2011), who indicated that pH in the Niger Delta's coastal waters tends to remain buffered, despite considerable organic and industrial contamination, primarily due to the dilution effects of seawater. Biochemical Oxygen Demand (BOD₅) measured between 36.9 and 48.6 mg/L, which surpassed the NESREA limit of 30 mg/L in all harbours, with Okrika exhibiting the highest measurement (48.6 mg/L), highlighting significant organic pollution. This observation is consistent with Aghoghovwia and Owefere (2018), who noted increased BOD₅ levels in Okrika River linked to oil-related activities, domestic waste disposal, and the biological breakdown of organic substances. In addition, Chemical Oxygen Demand (COD) values (151.6–186.4 mg/L) were markedly higher than the NESREA guideline of 125 mg/L, confirming the existence of both organic and inorganic pollutants. This observation strengthens the conclusions made by Nwilo and Badejo (2006), who reported elevated COD levels in Niger Delta waters resulting from crude oil extraction, refining processes, and industrial waste. Total Suspended Solids (TSS) levels, which varied between 30.9 and 39.8 mg/L, surpassed the allowed limit of 25 mg/L, indicating issues of sediment disruption and particulate pollution. This is in agreement with Abowei and Sikoki (2005), who reported increased suspended solids in estuaries of the Niger Delta caused by dredging, erosion, and oil industry activities. Total Dissolved Solids (TDS) ranged from 2,218 to 2,486 mg/L, exceeding NESREA limits (2,000 mg/L), suggesting excessive salinity and dissolved ionic pollution. This finding is confirmed by Chindah and Braide (2000), who observed rising TDS in coastal waters influenced by seawater intrusion and industrial effluents. Salinity and chloride levels consistently surpassed acceptable limits in all harbours, with Okrika showing the highest measurements. This is consistent with the UNEP (2011) Environmental Assessment of Ogoniland, which reported increased salinity and chloride pollution resulting from oil field operations and brine discharge in Niger Delta water systems. Sulphate, sulphide, cyanide, nitrate, phosphate, and free chlorine levels surpassed NESREA thresholds in many locations, signifying intricate chemical pollution arising from industrial activities and petroleum-related operations. These findings are in agreement with Ekweozor and Agbozu (2001), who noted increased levels of sulphur compounds and nitrogenous nutrients in waters affected by oil, linking them to discharges from refineries and processes of hydrocarbon breakdown. The concentrations of oil and grease (64.7–86.4 mg/L) were significantly above the NESREA limit of 10 mg/L, with Okrika having the highest degree of contamination. This observation strongly supports findings by UNEP (2011), which reported

severe hydrocarbon pollution in rivers and creeks of the Niger Delta, especially in regions involved in active oil extraction and illegal oil theft. Levels of Linear alkylbenzene sulphonate (LAS) (0.116–0.148 mg/L) also surpassed standard limits, indicating contamination from detergents and industrial wastewater. This is consistent with Adesina et al. (2012), who found surfactant pollution in coastal waters that have been urbanized, linked to the discharge of domestic sewage. Turbidity measurements (18.9–23.8% nearshore and 17.1–21.8 NTU) were above NESREA limits, suggesting reduced water clarity and increased particulate matter. This aligns with findings from Abowei (2010), who documented increased turbidity in waters of the Niger Delta due to activities such as dredging, erosion, and the inflow of suspended sediments. Table 1 illustrates notable spatial differences in water quality across the examined harbors, with Okrika and Abonnema showing the highest pollution levels, whereas Macobar and Kidney Island presented lower, yet still unacceptable, levels of contamination. This pattern illustrates varying human impacts across the study region and corresponds with earlier research (Nwilo and Badejo, 2006; UNEP, 2011) that pinpointed industrial operations, oil exploration, and urban runoff as primary contributors to the decline in water quality in the Niger Delta area.

The differences in the quality of surface water at different depths

The data illustrated in Table 4.5, titled “Quality of Surface Water at Different Depths in the Study Area”, displays distinct vertical differences in physicochemical characteristics within the 0–10 cm, 60 cm, and ballast water layers, with most pollutants diminishing with depth yet still remaining above NESREA guidelines. Temperature and pH exhibited little variation across different depths, staying within acceptable ranges, which indicates that thermal conditions and hydrogen ion levels are relatively constant in the water column. This is in line with observations from Boyd and Tucker (1998), who noted that temperature and pH in aquatic environments usually show minimal vertical diversity due to effective mixing and the natural buffering capability of water.

BOD₅ and COD values reduced with depth but continued to exceed NESREA limits at all measurements, highlighting ongoing organic contamination throughout the water column, with the greatest concentrations occurring at the upper layer. This pattern corresponds with findings from APHA (2017), stating that organic pollutants are often more prevalent near the surface due to direct discharge and limited dispersion. Total Suspended Solids (TSS) also diminished with depth, indicating sedimentation impacts, where larger particles tend to settle. This result is consistent with insights from Wetzel (2001), who described that suspended solids in water bodies generally decrease in depth because of gravitational settling and decreased turbulence.

Total Dissolved Solids (TDS) and salinity-related metrics exhibited a gradual decline with increasing depth but continued to be above acceptable limits, suggesting ongoing ionic contamination and potential intrusion of seawater. This aligns with the findings of Edokpayi et al. (2017), who noted heightened TDS levels in surface waters impacted by human activities and coastal mixing phenomena. The levels of oil and grease peaked at the surface and diminished with depth, confirming the buildup of hydrocarbons in the upper layers of water due to their lower density and tendency to float. This observation is supported by UNEP (2011), which recorded the surface accumulation of petroleum hydrocarbons in the Niger Delta's waters, particularly in regions affected by oil leaks and discharge during operations.

Nutrient levels like nitrate and phosphate also displayed decreasing trends with depth, yet they surpassed allowable limits, indicating a risk of eutrophication. This finding is in agreement with

Smith et al. (1999), who correlated high nutrient levels in surface waters with agricultural runoff and human discharge, which contribute to increases in algal populations.

Biological data presented in Table 4.6 titled “Quality of Surface Water Biological Properties at Different Depths in the Study Area” further validates the observed vertical differences. Coliform, *E. coli*, and faecal coliform levels were highest in ballast water, exceeding NESREA standards, highlighting severe contamination by microbes. This supports WHO (2017) findings indicating that elevated coliform concentrations in surface waters reflect faecal contamination and poor wastewater management practices.

Concentrations of phytoplankton and chlorophyll-a increased in ballast water, suggesting eutrophic conditions driven by nutrient enrichment. This is supported by Cloern (2001), who indicated that waters rich in nutrients typically enhance algal productivity and the buildup of chlorophyll-a. Variability in zooplankton indicates ecological changes across depths, while the number of benthic organisms was lower in ballast water, pointing to habitat stress. This is consistent with Odum (1971), who highlighted the sensitivity of benthic communities to disturbances in sediment and pollution stress. Lastly, Table 4.7 shows the results of One Sample t-test Comparing Water Quality at Different Depths with NESREA Standard which statistically validates these findings, revealing significant differences from regulatory standards for the majority of parameters ($p < 0.05$). This backs the conclusions of Chapman (1996), who stressed that significant discrepancies in t-test results from environmental benchmarks indicate human impact and ecological disruption. The results shown in Tables 4.5 to 4.7 illustrate that water quality significantly differs with depth, with surface layers typically having higher pollutant levels due to direct influence from anthropogenic activities, whereas deeper layers demonstrate incomplete attenuation through sedimentation and dilution mechanisms.

Conclusion

The results of this research indicate that the quality of surface water in the chosen harbours is significantly compromised and shows considerable variation both in different areas and at various depths. In Okrika, Kidney Island, Macobar, Abonnema, and Onne, most measured physicochemical and biological indicators surpassed the approved limits set by NESREA, apart from temperature and pH, which largely fell within acceptable levels. High concentrations of BODs, COD, both suspended and dissolved solids, salinity-related ions, nutrients, hydrocarbons (including oil and grease), and certain microbial indicators highlight a considerable impact from human activities, specifically those related to petroleum extraction, shipping, industrial effluents, and urban drainage within the coastal region of the Niger Delta. Statistical evaluations, including ANOVA, Duncan post-hoc tests, and t-tests, confirmed that the observed differences are not random, indicating a significant correlation to both location and the depth of water. Okrika and Abonnema displayed consistently elevated pollution levels, whereas Macobar and Kidney Island indicated lower, yet still unacceptable, pollution amounts. Analysis of depth demonstrated a general reduction in pollutant levels as depth increased, suggesting the processes of sediment settling and dilution; nevertheless, contamination remained above acceptable limits throughout all tested layers, including ballast water, which displayed significant levels of microbial and nutrient enrichment. From a biological standpoint, all harbours reported high levels of coliform and faecal pollution, along with altered plankton populations that suggest eutrophication and imbalance within the ecosystem. In summary, this research illustrates extensive environmental degradation

and ecological threats throughout the examined aquatic systems, with clear indications that human activities have profoundly impacted water quality beyond acceptable safety levels.

Recommendations

1. There is an immediate requirement for more rigorous enforcement of NESREA regulations and other environmental laws related to effluent discharge, oil spill management, and ballast water oversight in the evaluated harbours. Consistent monitoring and compliance assessments should become standard practice for industries, shipping firms, and oil servicing companies active in the coastal regions. The penalties for violations should be increased to deter ongoing pollution into the water ecosystem.
2. A unified framework for managing coastal water quality should be developed, incorporating government bodies, port authorities, and environmental stakeholders. This framework should encompass routine dredging and sediment management, the establishment of wastewater treatment systems, and the implementation of the best available technologies to prevent and address oil spills. Additionally, strategies such as phytoremediation and bioremediation should be developed to help reverse ecological decline, decrease hydrocarbon pollution, and enhance microbial water quality within the impacted harbours.

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