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Impact of Anthropogenic Pressures on the Physico-Chemical Characteristics and Quality of Surface Water from Amadi Creek, Port Harcourt, Rivers State, Nigeria: Implication to Water Quality and Ecological Health

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Abstract: *The physico-chemical characteristics of surface water is a determinant factor for the overall health and functionality of aquatic ecosystems. This study aimed to assess the physico-chemical characteristics and water quality index of surface water from Amadi Creek, Port Harcourt, Rivers State, Nigeria. Monthly samples were collected from three stations (1. Marine base jetty, 2. Niger Delta Development Commission, NDDC water front and 3. Eastern bye-pass bridge) between June and August, 2023 using standard methods. Water quality was analysed using the Single factor index (SFI), Nemerow pollution index (NPI), water pollution index (WPI) and Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI). The results showed no significant monthly variation in most parameters measured except turbidity, THC and TOC, which recorded highest values (mean ± SD, ANOVA $p<0.05$) in August (turbidity: 48.33±23.71 NTU and THC: 5.42±3.00mg/L) and June (TOC: 0.65±0.05mg/L) respectively. Spatially, most physico-chemical characteristics were consistent across stations except for EC, ORP, salinity and TDS which were significantly decreased at the Eastern bye-pass bridge. Nutrients (phosphate, nitrate and sulphate) levels did not exhibit any spatial or temporal variations. Comparing average parameters values to permissible limits showed that DO, EC, pH, salinity, phosphate, nitrate was within the permissible limit while temperature, turbidity, BOD, THC and sulphate exceeded permissible limits set by Environmental Protection Authority (EPA) Victoria, European Union (EU) and National Environmental Standards and Regulations Enforcement Agency (NESREA). The SFI identified total hydrocarbon (9.47), Sulphate (6.54) and*

Total hydrocarbon (6.50) again as the dominant pollutant in Marine base jetty, NDDC water front and Eastern bye-pass bridge respectively. NPI and CCME-WQI classified water quality across stations as moderately polluted and marginally acceptable respectively, while WPI rated Marine based jetty as heavily polluted (WPI 7.33) and the other two stations as impure. In conclusion, while some physico-chemical parameters are within acceptable limits, elevated levels of temperature, turbidity, BOD, THC, and sulphate signify substantial anthropogenic pressure. Although, there were slight variations among the water quality indices (SFI, NPI, WPI, and CCME-WQI), all indices consistently identified Marine Base Jetty as the most polluted, primarily due to hydrocarbon and sulphate followed by Eastern bye-pass bridge then NNDC water front recording notable pollution. Immediate remediation is necessary to mitigate water quality degradation in Amadi Creek.

Keywords: Water quality index, CCME-WQI, Nemerow, single factor index, Marine-base Jetty

INTRODUCTION

The physico-chemical characteristics of surface water are important indicators to water quality and ecological health (APHA, 2012; Chukwu and Amachree 2018). Physico-chemical parameter influences biodiversity, productivity and overall functionality of aquatic ecosystems (Boyd, 2015). All aquatic life require water as a support system and as a medium for total well-being (Sikoki and Veen, 2004). Water quality monitoring employs the assessment of the physical, chemical, biology and hydrology characteristics of the water body (Chapman, 1996; Odiete 1999). Physico-chemical parameters such as pH, dissolved oxygen, salinity, and conductivity directly influence the growth, survival, reproduction, distribution of aquatic organisms, habitat selection (Francis *et al*., 2007; Uedeme-Naa *et al*., 2010; Zabbey and Hart 2014; Chukwu and Amachree, 2018; Lazarus *et al*., 2023); biological assessments such as analyzing microbial populations (Williams and Madise, 2018) and the condition of fish species (Ibim *et al*., 2020) gives insights into the ecological balance and potential contamination levels within the water body while, hydrological characteristics directly influence the physical, chemical, and biological conditions of aquatic ecosystems (Li e*t al.*, 2023).

Surface water bodies such as creeks play an essential role in sustaining ecological balance and providing water resources for domestic, industrial, agricultural, and recreational purposes (Morrison *et al*., 2001; Ogamba *et al*., 2015). Despite the significant importance of surface water quality, there have been increasing reports of environmental impacts occasioned by several anthropogenic pressure (Chebet *et al*., 2020). Some of these anthropogenic activities like discharges of industrial effluents, solid wastes, agricultural farms and urban runoffs, oil exploration and sewage discharges from households and poor environmental management have resulted in increased levels of pollutants such as hydrocarbons, heavy metals in surface water as well as overload the aquatic ecosystem with nutrients and microorganisms, further intensifying water quality degradation and human livelihood in most developing regions such as the Niger

Delta, Nigeria (Chindah *et al*., 2004; Nwankwoala, 2012; Yang *et al.*, 2020; Bedim-Godoy *et al.*, 2021). Over the years, water pollution has become endemic in most water bodies within the Niger delta axis of Nigeria (Nwankwoala, 2012; Emuedo *et al*., 2014; Odoemelam *et al*., 2019; Bodo *et al*., 2020; Okey-Wokeh and Wokeh, 2022), of which the Amadi-creek is not an exception (Ezeilo and Oba, 2016, Edori and Edori, 2021).

Like many coastal environments within the Niger Delta, Amadi Creek, situated in Port Harcourt, Rivers State, Nigeria, serves as an important resource sustaining fishing activity, transportation, open defeacation, disposal of sewage, industrial and domestic wastes for the surrounding communities but has become increasingly vulnerable to anthropogenic stressors (Zabbey and Hart, 2014; Chukwu and Amachree, 2018). Escalating industrial activities, urbanization, and anthropogenic pressures have raised concerns about the creek's water quality and overall ecological health. Degradation of water quality in Amadi Creek has profound implications for both the environment and public health. While elevated levels of pollutants can lead to the disruption of aquatic ecosystems, loss of biodiversity, and the proliferation of waterborne diseases; communities depending on the creek for domestic and recreational purposes are at increased risk of exposure to harmful contaminants.

Previous studies on Amadi creek and surrounding creeks have documented the impact of oil pollution, waste disposal, and other anthropogenic activities on the water quality and aquatic life (Izonfuo and Bariweni, 2001; Ideriah *et al*., 2010; Ekubo and Abowei, 2011; Adiele *et al.*, 2019; Ibim *et al*., 2020). Despite these studies, there is a paucity of recent and detailed investigations on the physico-chemical characteristics and quality of surface water in Amadi Creek, particularly in light of expanding industrial and urban activities in Port Harcourt. This study aimed at assessing the physico-chemical characteristics and quality of surface water from Amadi Creek, Port Harcourt, Rivers State, Nigeria. The findings will contribute to understanding the current state of the creek, add to existing literatures critical data necessary for sustainable management practices mitigating pollution, protecting aquatic life, preserving the ecological integrity of the creek, ensuring the health and well-being of local communities amidst the challenges posed by industrialization and urban development.

MATERIALS AND METHODS

Study Area

The study was carried out along Amadi Creek (Fig 1, a tidal, brackish water creek) Port Harcourt Local Government (PHALGA) Rivers State, Nigeria. The study area used to be a mangrove swamp but industrialization, urbanization and other human activities has changed the situation of the environment. Like many coastal environments within the Niger Delta, Amadi Creek is an important resource which sustains fishing activities, transportation, open defeacation, disposal of sewage, industrial and domestic wastes for the communities around the Trans-Amadi Industrial area near the creek. Amadi creek flows from Okrika town down to Mini-Ewa, Rumuobiakani through Woji, Oginigba, Okujagu communities and then empties into the Bonny River, enroute to the Atlantic Ocean (Ezeilo and Dune, 2012; Amachree *et al*., 2025).

Sampling Stations

Three sampling stations (Fig 1.) were established within the study area. The stations were chosen based on ecological settings and human activities in the area. The stations included: Station 1 (Marine base Jetty) with latitude 4°46'8''N and longitude 7°1'49''E is an open water area. Activities found within station 1 includes human settlement, waste disposal, boat fabrication, industrial waste discharge, transportation and fishing; Station 2 (NDDC water front) with latitude 4°46'18''N and longitude 7°1'17''E is an area with a dead end (i.e., water movement occurs through a single route), Activities within station 2 includes; human settlement, block industry, boat fabrication and repair, direct sewage and domestic disposal, and fishing activities and; Station 3 (Eastern bypass bridge,) with latitude 4°47'11''N and longitude 7°1'16''E is located beneath the Eastern Bypass Bridge around the Koko-Ama community axis. Activities includes; human settlement, waste disposal, recreational and fishing activities.

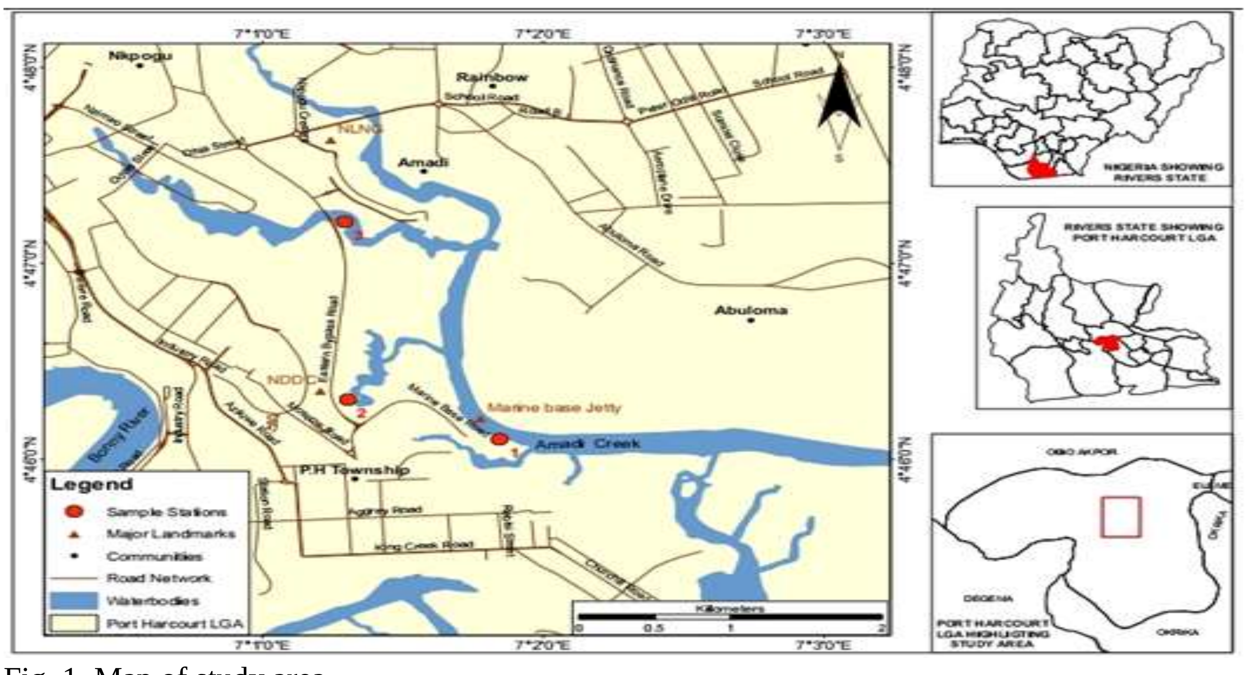

Fig. 1. Map of study area

Water sample collection and determination of physico-chemical characteristics

Water samples were monitored for physico-chemical characteristics once a month in the three stations for a period of three months (June-August 2023). Samples were collected monthly during ebb tide. Physico-chemical characteristics such as temperature (°C), dissolved oxygen- DO (mg/L), pH, salinity (‰), electrical conductivity- EC (µS/cm), Oxidation-reduction potential- ORP (mV), turbidity (NTU) and Total dissolved solids- TDS (mg/L) were measured *in situ* with a multi-meter (HI98194 HANNA produced in Woonsocket, RI, USA). Water samples for total organic carbon- TOC (mg/L) and Total hydrocarbon concentration- THC (mg/L) were collected in pre-acid-washed glass bottles (5% nitric acid, double rinsed with distilled water, dried and labeled accordingly prior to the sampling day). Water samples for nutrients (Phosphate, Nitrate and Sulphate) analysis was collected in 1 litre plastic bottle while, water samples for Biochemical oxygen demand, BOD_5 were collected in amber bottle and taken to laboratory for analysis of the individual parameters according to standard procedures set by the American Public Health Association (APHA, 2012).

Water quality indices

WQI transforms the analytical (measured) data into a single value which represents the overall water quality of the particular water body. In the present study ten parameters (Temperature, DO, EC, pH, salinity, BOD, THC, Phosphate, Nitrate and Sulphate) with appropriate standards were chosen for the analysis using four water quality indices viz: Single Factor Index (SFI), NEMEROW Pollution Index (NPI), Water Pollution Index (WPI) and Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI).

a. Single Factor Index

The single factor index method was applied to assess the pollution degree of individual environmental parameters and evaluates whether each parameter exceeds the standard or permissible limits in the surface water (Yan *et al*., 2016). This method highlighted the parameters contributing the most to the pollution at each station. The Single Factor index was calculated with the equation:

$$\boldsymbol{P} = \frac{\boldsymbol{Ci}}{\boldsymbol{Si}} \qquad \text{Equation 1}$$

Where:

Pi is the pollution index for a single parameter; Ci represents the measured average concentration of parameter; Si the standard or permissible limit of the value of the parameter. The results derived Single Factor Index is interpreted as Pi ≤ 1 when parameter is within permissible limits and Pi > 1 when parameter exceeds the permissible limit, indicating its contribution to the pollution.

NEMEROW Pollution Index

The Nemerow Pollution Index was used to assess the combined effects of all the parameters on the surface water quality, considering both the worst-case scenario (maximum individual pollution index, P_{max}) and the average pollution condition (P_{mean}). NPI was calculated with the equation:

$$P_N = \sqrt{\frac{P_i^2 max + P_i^2 mean}{2}} \qquad \text{Equation 2}$$

Where,

P_N is Nemerow pollution index; Pi mean is the arithmetic mean of the pollution index of all the pollutants (average pollution level) and Pi (max) is the maximum pollution index among the pollutants, based on the single pollution index at each station. The results of the NPI is interpreted in terms of pollution degree as PN <1 insignificant pollution (clean); 1≤ PN < 2.5

slightly polluted (low); 2.5 ≤ PN < 7 moderate and PN > 7 heavy (Zhu et al., 2017; Li et al., 2020).

Water Pollution Index, WPI
Water pollution index was used to assess water pollution by averaging the ratios of measured values to their permissible limits and normalising it by the number of analyses. This method was developed to protect aquatic life and assess water quality by applying guidelines. It was calculated with the mathematical formular as described by (Lyuiko *et al*., 2001; Ujjania and Dubey, 2015).

$$WPI = \sum\left(\frac{Ci}{SFQS}\right) x \left(\frac{1}{n}\right) \quad \text{Equation 3}$$

Where,
Ci is the measured value of the parameter; SFQS is the Standard for the parameter; and n is the number of analyses. The water quality will be classified based on the WPI value obtained into six classes viz: I (very impure: <0.3); II (Pure: 0.3-1.0); III (Moderately polluted: 1.0-2.0); IV (Polluted: 2.0-4.0); V (Impure: 4.0-6.0) and V (Heavily polluted: > 6.0).

CCME-WQI
The CCME-WQI was used to provide the overall water quality score based on scope (F1), frequency (F2), and amplitude of exceedance (F3) (CCME, 2001; Bilgin, 2018; Hu et al., 2022), with the mathematical formula given as:

$$CCME - WQI = 100 - \left(\frac{\sqrt{F1^2+F2^2+F3^2}}{1.732}\right) \quad \text{Equation 4}$$

Where,
F1 (Scope) is the percentage of variables (parameters measured) that fail to meet their objectives (standard limits) and is calculated with the formular:

$$F1 = \frac{Number\ of\ failed\ variables}{Total\ number\ of\ variables}\ x\ 100 \quad \text{Equation 5}$$

F2 (frequency) is the percentage of individual tests that do not meet objectives (failed tests). It is used to measure how often an objective is not met. It is calculated with the formular:

$$F2 = \frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests}\ x\ 100 \quad \text{Equation 6}$$

F3 (Amplitude) is the amount by which failed test values do not meet their objectives. It is used to measure how much the objective is exceeded. To acquire the value of F3, three steps are needed viz:

Step 1: The number of times by which an individual concentration is greater than (or less than, when the objective is a minimum) the objective is called an excursion. There are two equations to be used viz

i. When the test value must not exceed the objective,

$$Excursion = \left(\frac{Failed\ test\ value}{Objective}\right) - 1$$ Equation 7

ii. When the test value must be no less than the objective;

$$Excursion = \left(\frac{Objective}{Failed\ test\ value}\right) - 1$$ Equation 8

Step 2: The normalized sum of excursion, nse. This is the total amount by which the individual tests are out of compliance

$$nse = \left(\frac{\sum_{i=1}^{n} excursion}{Total\ number\ of\ tests}\right)$$ Equation 9

The amplitude (F3) is calculated by an asymptotic function that scales the normalized sum of the excursions from objectives to yield a value between 0 and 100:

$$F3 = \frac{nse}{0.01nse + 0.01}$$ Equation 10

After calculation, the water quality will be categorised based on the CCME-WQI values ranging from 0 to 100, into five ranks (CCME 2001, Table 1).

Table 1. Classification of CCME WQI values (CCME 2001)

CCME-WQI	**RANKING**	**Water Quality Characteristics**
95-100	Excellent	Water quality is protected with a virtual absence of threat. Condition is very close to natural and pristine levels
80-94	Good	Water quality is protected with a minor degree of threat or impairment. Condition rarely depart from natural or desired levels
65-79	Fair	Water quality is usually protected but occasionally threatened or impaired, condition sometimes depart from natural or desired levels
45-64	Margin	Water quality is frequently threatened or impaired, condition often depart from natural or desired levels.
0-44	Poor	Water quality is almost always often threatened or impaired, condition usually departs from natural or desired levels

Statistical Analysis

Statistical analysis was carried out on all data using the Minitab version 16 for Microsoft windows. Data were presented as mean ± standard deviation (SD) and analysed by one-way analysis of variance (ANOVA).

RESULTS

Physico-chemical characteristics of Surface Water

The results of the monthly and spatial variations in the physico-chemical characteristic of the surface water are presented on Tables 1 and 2. The result obtained indicated lack of monthly variation for most physico-chemical parameters (temperature, DO, EC, pH, ORP, salinity, TDS and BOD) while, turbidity, THC and TOC recorded significant difference in August with highest values (mean ± SD) for turbidity (48.33±23.71) and Total Hydrocarbon (5.42±3.00), while June showed highest values (mean ± SD) for Total Organic Carbon (0.65±0.05, Table 1, $p<0.05$). There was no monthly variation in nutrients (phosphate, nitrate and sulphate) concentration. Likewise, there were no spatial variation in most of the physico-chemical characteristics measured apart from EC, ORP, salinity and TDS which were significantly decrease in station 3 (eastern bye-pass bridge) compared to the other stations (Table 3). Like the months, there were significant difference in nutrients concentration measured in all of the stations ($p>0.05$; Table 2).

The average values of physico-chemical (water quality) parameters across the stations were compared to their permissible limits (table 3). The results showed that the physico-chemical parameters (DO, EC, pH, salinity) measured in the study stations were within established permissible limits, apart from temperature which was slightly higher than the permissible limit of 30 °C in all stations, turbidity was higher in NDDC water front (28.87 NTU) and Eastern bye-pass bridge (24.20 NTU) compared to the Environmental Water Quality Guidelines for Victorian Riverine Estuaries of 18 NTU (EPA Victoria, 2011). BOD was increased in all stations compared to the National Environmental Standards and Regulations Enforcement Agency (NESREA, 2011) standard of 3.00 mg/L. Total hydrocarbon was higher in all stations than European Union (EU) Estuary and Harbour Basin Water standard of 0.30mg/L (Sciortino and Ravikumar, 1999). Phosphate and nitrate values were within the standards of 3.50mg/L and 10mg/L set by NESREA (NESREA, 2011) and EU Estuary (Sciortino and Ravikumar, 1999) respectively. Sulphate was above 5-fold higher in all stations compared to the set standard of 100mg/L (NESREA, 2011).

Table 1. Monthly Variation in the Physico-chemical parameter and nutrient concentration of the Surface Water at three stations along Amadi creek during a three Month (June-August 2023) Sampling Period.

Parameter	**MONTHS**		
	JUNE	**JULY**	**AUGUST**
Temperature (°C)	31.63±1.20**a** (30.93-31.16)	30.49±0.68**ab** (29.75-31.08)	29.75±0.18**b** (29.59-29.95)
Dissolved Oxygen (mg/L)	5.09±0.96**a** (4.12-6.03)	3.93±1.10**a** (2.80-5.00)	3.65±2.24**a** (2.05-6.21)
Electrical Conductivity (µS/cm)	2814.00±247.39**a** (2533.00-2999.00)	2754.00±260.70**a** (2453.00-2908.00)	2759.67±252.60**a** (2468.00-2908.00)
pH	7.23±0.36**a** (6.85-7.56)	6.67±0.29**a** (6.34-6.86)	6.98±0.48**a** (6.42-7.28)
Oxidation-Reduction Potential (mV)	157.00±13.79**a** (141.20-166.60)	152.77±13.90**a** (136.75-161.70)	148.53±14.06**a** (132.30-156.80)
Salinity (‰)	17.18±1.65**a** (15.31-18.40)	16.95±2.52**a** (14.04-18.50)	16.09±2.47**a** (13.24-17.53)
Total dissolved Solids (mg/L)	14.07±1.24**a** (12.67-15.00)	13.43±1.42**a** (11.80-14.30)	13.79±1.13**a** (12.48-14.48)
Turbidity (NTU)	9.00±0.26**b** (8.80-9.30)	9.00±0.26**b** (8.80-9.30)	48.33±23.71**a** (22.00-68.00)
Total hydrocarbon (mg/L)	0.02 ± 0.00**b**	0.21±0.26**b** (0.02-0.51)	5.42±3.00**a** (2.47-8.47)
Total Organic Carbon (%)	0.65±0.05**a** (0.59-0.68)	0.13±0.03**b** (0.10-0.16)	0.18±0.07**b** (0.10-0.24)
Biochemical Oxygen Demand (mg/L)	5.06±0.91**a** (4.52-6.11)	4.56±1.15**a** (3.59-5.83)	3.96±1.12**a** (2.69-4.83)
Phosphate (mg/L)	0.05±0.00**a**	0.42± 0.09**a** (0.36-0.52)	0.25± 0.27**a** (0.09-0.56)
Nitrate (mg/L)	0.36± 0.08**a** (0.27-0.41)	0.41± 0.10**a** (0.32-0.52)	0.49± 0.38**a** (0.05-0.71)
Sulphate (mg/L)	614.10±133.07**a** (494.60-757.50)	776.57±121.13**a** (682.00-913.10)	588.03±53.20**a** (530.70-635.80)

Data are mean ± SD (range) for *n*=3 per parameter. Different letter between rows indicates statistically significant difference (ANOVA, $p<0.05$).

Table 2. Spatial Variation in the Physicochemical Parameter and nutrient concentration of the Surface Water at three stations along Amadi creek during a three Month (June-August 2023) Sampling Period.

Parameter	**STATION**		
	STATION 1 (Marine base jetty)	**STATION 2 (NDDC water front)**	**STATION 3 (Eastern bye-pass bridge)**
Temperature (℃)	30.65±0.61**a** (29.95-31.08)	31.05±1.58**a** (29.72-32.80)	30.17±0.86**a** (29.59-31.16)
Dissolved Oxygen (mg/L)	5.11±1.05**a** (4.12-6.21)	4.24±1.69**a** (2.68-6.03)	3.33±1.61**a** (2.05-5.13)
Electrical Conductivity (µS/cm)	2908.70±1.15**a** (2908.00-2910.00)	2934.33±56.01**a** (2901.00-2999.00)	2484.67±42.52**b** (2453.00-2533.00)
pH	6.81±0.45**a** (6.34-7.23)	7.12±0.26**a** (6.82-7.28)	6.95±0.57**a** (6.42-7.56)
Oxidation-Reduction Potential (mV)	161.70±4.90**a** (156.80-166.60)	159.85±3.35**a** (156.50-163.20)	136.75±4.45**b** (132.30-141.20)
Salinity (‰)	17.96±0.50**a** (17.53-18.50)	18.06±0.50**a** (17.49-18.40)	14.20±1.04**b** (13.24-15.31)
Total dissolved Solids (mg/L)	14.42±0.13**a** (14.30-14.55)	14.56±0.41**a** (14.20-15.00)	12.32±0.46**b** (11.80-12.67)
Turbidity (NTU)	13.27±7.56**a** (8.90-22.00)	28.87±33.89**a** (9.30-68.00)	24.20±26.67**a** (8.80-55.00)
Total hydrocarbon (mg/L)	2.84±4.88**a** (0.02-8.47)	0.87±1.39**a** (0.02-2.47)	1.95±2.92**a** (0.02-5.31)
Total Organic Carbon (%)	0.31±0.32**a** (0.10-0.68)	0.31±0.25**a** (0.10-0.59)	0.35±0.29**a** (0.16-0.68)
Biochemical Oxygen Demand (mg/L)	3.83±1.00**a** (2.69-4.55)	4.69±1.29**a** (3.59-6.11)	5.06±0.68**a** (4.52-5.83)
Phosphate (mg/L)	0.17±0.17**a** (0.05-0.36)	0.18±0.19**a** (0.05-0.39)	0.38±0.28**a** (0.05-0.56)
Nitrate (mg/L)	0.48±0.20**a (**0.32-0.71)	0.46±0.23**a (**0.27-0.71)	0.33±0.25**a** (0.05-0.52)
Sulphate (mg/L)	756.07±157.75**a** (597.60-913.10)	653.53±73.82**a** (590.20-734.60)	569.10±99.43**a** (494.60-682.00)

Data are mean ± SD (range) for *n*=3 per parameter. Different letter between rows indicates statistically significant difference (ANOVA, $p<0.05$).

Table 3. Mean values of the physico-chemical parameter in the sampling stations with their appropriate Permissible limit for estuarine environment

Physico-chemical parameters	STATION 1 Marine Base Jetty	STATION 2 NDDC water front	STATION 3 Eastern bye-pass bridge	Permissible limit	Reference For Permissible limit
Temperature (°C)	30.65	31.05	30.17	30	Moore, 1991
DO (mg/L)	5.11	4.24	3.33	9.91	EU Estuary
EC (µS/cm)	2908.7	2934.33	2484.67	54000	EPA Victoria
pH	6.81	7.12	6.95	8.5	NESRAE
Salinity (‰)	17.96	18.06	14.20	38	EPA Victoria
Turbidity (NTU)	13.27	28.87	24.20	18	EPA Victoria
BOD (mg/L)	3.83	4.69	5.06	3	NESRAE
THC (mg/L)	2.84	0.87	1.95	0.3	EU Estuary
Phosphate (mg/L)	0.17	0.18	0.38	3.5	NESRAE
Nitrate (mg/L)	0.48	0.46	0.33	10	EU Estuary
Sulphate (mg/L)	756.07	653.53	569.10	100	NESRAE

EPA Victoria: Environmental water guidelines for Victorian Riverine Estuaries (EPA Victoria, 2011)
EU Estuary: European Union Estuary and Harbour Basin Water Standard Guidelines (, Scionrtino and Ravikumar, 1999).
NESRAE: National Environmental Standards and Regulations Enforcement Agency Fisheries and Recreation Criteria Standard for Surface Water (NESREA, 2011).

Water Quality Assessment

The Single Factor Index (SFI) identified the specific parameters contributing most significantly to water quality deterioration (Table 4). At Station 1 (Marine Base Jetty), the dominant pollutants in decreasing order were Total Hydrocarbons (THC, 9.47) > Sulphate (SO_4^{2-}, 7.56) > Biochemical Oxygen Demand (BOD, 1.28) > Temperature (1.02). At Station 2 (NNDC Waterfront), the primary contributors were Sulphate (SO_4^{2-}, 6.54) > THC (2.90) > Turbidity (1.60) > BOD (1.56) > Temperature (1.04). In Station 3 (Eastern Bye-pass Bridge) THC (6.50) > Sulphate (SO_4^{2-}, 5.69) > BOD (1.69) > Turbidity (1.34) > Temperature (1.01) were the parameters contributing to the deterioration of the water quality.

The NPI WPI, and CCME-WQI values were presented on Table 5. NPI classified the water quality of all stations as moderately polluted with values of 6.84 (Station 1, marine base jetty)> 4.74 (station 3, Eastern bye-pass bridge) >4.73 (Station 2, NDDC water front). Water pollution index, WPI indicated a similar trend with Station 1 (marine base jetty) classified as heavily polluted (WPI, 7.33), followed Eastern bye-pass bridge (WPI, 5.98) and NDDC water front (WPI, 5.18) which were classified as impure. The CCME-WQI describes the overall water quality based on the scope,

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frequency and amplitude, ranked the water quality of the three stations as margin indicating marginal water quality. The values, however, reflected the same trend as NPI and WPI, showing a higher potential for deterioration at Marine base jetty (54.06) compared to Eastern bye-pass bridge (56.49) and NDDC water front (58.67).

Table 4. Single factor index, SFI values of the sampling stations along Amadi Creek

Physico-chemical parameter	Station 1	Station 2	Station 3
	Marine Base Jetty	NDDC water front	Eastern bye-pass bridge
Temperature (°C)	**1.02**	**1.04**	**1.01**
DO (mg/L)	0.52	0.43	0.34
EC (µS/cm)	0.05	0.05	0.05
pH	0.80	0.84	0.82
Salinity (‰)	0.47	0.48	0.37
Turbidity (NTU)	0.74	**1.60**	**1.34**
BOD (mg/L)	**1.28**	**1.56**	**1.69**
THC (mg/L)	**9.47**	**2.90**	**6.50**
Phosphate (mg/L)	0.05	0.05	0.11
Nitrate (mg/L)	0.05	0.05	0.03
Sulphate (mg/L)	**7.56**	**6.54**	**5.69**

Pi ≤ 1 when parameter is within permissible limits and; Pi > 1 when parameter exceeds the permissible limit, indicating its contribution to the pollution.

Table 5. Water pollution index (WPI) of the three sampling station along Amadi creek

WQI/ Classification	Station 1	Station 2	Station 3
	Marine Base jetty	NDDC water front	Eastern bye-pass bridge
NPI	6.84	4.73	4.74
Classification	Moderate pollution	Moderate pollution	Moderate pollution
WPI	7.33	5.18	5.98
Classification	Heavily polluted	Impure	Impure
CCME-WQI	54.06	58.67	56.49
Classifications	Margin	Margin	Margin

NPI classification: PN <1 insignificant pollution (clean); 1≤ PN < 2.5 slightly polluted (low); 2.5 ≤ PN < 7 moderate and PN > 7 heavy.
WPI Classification: I (very impure: <0.3); II (Pure: 0.3-1.0); III (Moderately polluted: 1.0-2.0); IV (Polluted: 2.0-4.0); V (Impure: 4.0-6.0) and V (Heavily polluted: > 6.0).
CCME-WQI classification: Excellent (95-100); Good (80-94); Fair (65-79); Margin (45-64); Poor (0-44).

DISCUSSION

Physico-chemical characteristics of Surface Water

The measurement of physico-chemical parameters is critical for determining the health, general water quality and sustainability of aquatic ecosystems. The physico-chemical properties of the surface water from Amadi creek, revealed no monthly variation in vital parameters such as temperature, DO, EC, pH, ORP, salinity, TDS and BOD indicating a stable environmental condition, probably due to relatively steady hydrology and anthropogenic impacts in the creek. However, parameters like turbidity, total hydrocarbon (THC), and total organic carbon (TOC) showed considerable monthly variations. The peak turbidity and THC in August may indicate increased surface runoff and pollution characteristics of the rainy season, consistent with the findings from earlier research in tropical estuaries (Abowei *et al*., 2008; Kpee *et al*., 2020). Heavy rainfall can increase flow, triggering erosion and moving sediments into the creek, consequently elevating turbidity (Billota and Brazier, 2008). Additionally, the elevated THC levels in August raised concerns about hydrocarbon pollution, likely originating from industrial activities around the Marine base jetty area. The discharge of untreated or inadequately treated industrial wastewater containing hydrocarbons into the environment may have contributed to the increased levels of THC levels observed at other stations. This hydrocarbon pollution poses a significant threat to aquatic life, potentially impairing fish health through bioaccumulation, reproductive failure, and increased mortality (Cherr *et al*., 2017). Furthermore, elevated turbidity during the rainy season can significantly reduce light penetration into the water column, limiting primary productivity and fish foraging efficiency.

The elevated Total Organic Carbon (TOC) levels observed in June may be attributable to the influence of sewage discharge within the study area. This sewage input likely increased plant growth, stimulating increased organic matter decomposition during the early rains, subsequently releasing carbon compounds into the creek. While the relatively stable Dissolved oxygen (DO) levels are generally favourable for supporting aquatic life, the presence of hydrocarbons and high TOC levels poses a significant threat to the ecosystem health. These pollutants can degrade water quality, potentially leading to the deterioration of aquatic ecosystems and threatening the survival of aquatic organisms. Notably, significant reductions in EC, ORP, salinity, and TDS were observed at Station 3 (Eastern Bye-pass Bridge) this likely indicates freshwater intrusion or dilution effects at the station, possibly due to upstream freshwater inflows. These changes reveal localized hydrological influences, which are regular in urban creeks characterized by varying land use and industrial impacts (Ekubo and Abowei, 2011). The lack of spatial variation in nutrient concentrations could reflect uniform organic pollution sources infiltrating into the creek. The lack of significant monthly variations in phosphate, nitrate, and sulphate concentrations may indicate a steady input of these nutrients from agricultural or urban sources, maintaining a consistent baseline level throughout the year. This pattern could also suggest minimal seasonal changes in nutrient assimilation or sedimentation dynamics, consistent with observations in other urbanized creek systems (Uedeme-Naa, *et al*., 2010).

Comparison of measured values of parameter with permissible limit

In this study, most of the measured physico-chemical parameters values fell within established permissible limits, indicating relatively moderate water quality in some respects. However, deviations in certain parameters reflects potential ecological risks and anthropogenic impacts.

The slightly elevated temperatures across all stations may have implications for aquatic life, especially in sensitive tropical ecosystems where even small temperature changes can affect dissolved oxygen levels, metabolic rates, and species assemblages (Boyd, 2015). There are currently no guidelines for acceptable temperature levels in estuaries, this study used 30 ℃ limit according to Moore, (1991) cited in Ujjania and Dubey, (2015). Elevated water temperatures in the present study could be attributed to increased industrial discharges, urban runoff, or reduced vegetative cover near the water bodies (Ogamba *et al*., 2015). A rise in water temperature increases photosynthetic processes, with the concomitant rise in nutrient production. However, the temperature observed in this study is higher than those reported earlier in surface water of Elelenwo River, Port Harcourt with values (means ± SD, ℃) of 23.97±0.01; 24.22 ±0.12 and 23.56 ± 0.02 for June, July and August respectively (Edori *et al*., 2020). The turbidity values specifically at NDDC Water Front (28.87 NTU) and Eastern Bye-Pass Bridge (24.20 NTU) exceeded the limit of 18 NTU (EPA Victoria, 2011). High turbidity can reduce light penetration, affecting primary production and habitat suitability for fish and other aquatic organisms (Abowei et al., 2008). Increased turbidity levels in these stations may result from erosion, sedimentation, or discharge of untreated wastewater. The observed BOD values exceeding the limit of 3.00 mg/L (NESREA, 2011), indicating a high organic load, capable of depleting dissolved oxygen levels critical for maintaining optimal conditions in aquatic fauna (Ekubo and Abowei, 2011). Such elevated BOD values often point to organic pollution from domestic, agricultural, or industrial sources indicating organic pollution in the stations.

The THC levels exceeded the EU estuary and Harbour basin Water standard of 0.30 mg/L (Sciortino and Ravikumar, 1999) across all stations, indicating significant hydrocarbon contamination. This is likely attributable to a synergistic effect of oil spills, industrial discharges, and runoff, from industries located around the Marine base jetty that directly release their effluents into the creek. This scenario is a well-documented issue in the Niger Delta region (Chindah et al., 2004; UNEP, 2011). Hydrocarbon contamination poses severe risks to aquatic life, including bioaccumulation and toxicity. Phosphate and nitrate concentrations remained within the permissible limit of 3.50 mg/L (NESREA, 2011) and 10 mg/L of EU Estuary and Harbour Basin Water Standard (Sciortino and Ravikumar, 1999), insinuating that nutrient pollution is not currently a prevailing concern at these stations. However, even within permissible limits, excessive nutrient loading overtime can potentially lead to eutrophication, particularly, in stagnant or low-flow areas (Izonfou and Bariweni, 2001). The sulphate concentrations observed in the study significantly exceeded the limit of 100 mg/L (NESREA, 2011) by over 5-fold, presenting a significant concern. While Sulphate (SO_4^{2-}) is commonly found in aquatic ecosystems and is generally non-toxic to aquatic life, high concentrations often associated with human activities can devastating effects (Novair et al., 2024). The elevated sulphate levels observed in the stations likely originate from industrial effluent discharges and urban runoff and can adversely affect aquatic life by altering water chemistry and potentially leading to acidification (Nwankwoala, 2012).

Water Quality Assessment
This study utilized four water quality indices namely; SFI, NPI, WPI, and CCME-WQI. SFI pinpointed the most critical environmental parameters exceeding permissible limits, while NPI considered both average pollution and maximum deviation for a more balanced assessment. WPI averaged pollution ratios across all parameters, and CCME-WQI provided an overall water quality score based on the scope, frequency, and magnitude of exceedances. The Single Factor Index (SFI) scores revealed the key parameters driving water quality deterioration in Amadi Creek. These findings reflected spatial variability in pollutant contributions across the three sampling stations, showcasing the influence of local anthropogenic activities and environmental conditions. At Marine base jetty (Station 1), Total Hydrocarbons (THC) emerged as the most significant contributor to water quality degradation (SFI: 9.47), indicating a high prevalence of hydrocarbon. This finding suggests a high prevalence of petroleum-based contamination, likely attributable to the proximity of the jetty to artisanal oil exploration, localized spills during transportation of locally refined products and daily transportation activities. Elevated Sulphate (SO_4^{2-}) levels (7.56) further demonstrate the impact of industrial discharges and urban runoff into the creek, consistent with previous studies on hydrocarbon-polluted waterways in the Niger Delta (Edori *et al*., 2021).

At NDDC water front (Station 2), Sulphate (SO_4^{2-}) was the dominant pollutant (SFI: 6.54), followed by THC (2.90). This trend indicated the significant contributions of industrial effluents and domestic wastewater, which were prevalent at this location. Elevated Turbidity (1.60) and BOD (1.56) values demonstrated the roles of organic matter and suspended particles in deteriorating water quality. Similar patterns have been reported by Abowei *et al.* (2008) in urbanized coastal zones characterized by high population density and industrialization. At Eastern bye-pass bridge (Station 3), THC (6.50) remained a significant environmental stressor, reflecting hydrocarbon contamination, albeit at slightly lower levels than Marine base jetty. Sulphate (SO_4^{2-}, 5.69) continued to be a critical contributor, suggesting similar pollution sources and anthropogenic activities. Turbidity (1.34) and BOD (1.69) values indicated organic matter input and sediment disturbances. Based on the NPI classification with values ranging from 4.73 to 6.84, all three stations along Amadi Creek are experiencing moderate pollution. This finding is in-line with the categorization of similar urban waterways subjected to anthropogenic pressures such as industrial discharges and municipal runoff (Edori *et al*., 2021).

The WPI categorization revealed more concerning conditions at Marine base jetty, which was classified as heavily polluted (WPI = 7.33). NDDC water front and Eastern bye-pass bridge, although classified as impure, showed slightly better water quality (WPI = 5.18 and 5.98, respectively). This disparity may reflect the proximity of Marine base jetty to industrial zones or higher levels of hydrocarbon contamination, supported by studies on petroleum-polluted environments in the Niger Delta (Erah *et al*., 2012).The CCME-WQI scores, ranging from 54.06 to 58.67, classified the water quality at all stations as marginal. This suggests that while marginally acceptable, the water quality was far from ideal and required immediate intervention. Similar findings have been reported in studies assessing the cumulative impacts of urbanization and oil exploration on aquatic systems in Nigeria (Adesuyi *et al*., 2018 and 2021).

Conclusion/ Implication to Ecological health

The study revealed elevated levels of temperature, turbidity, BOD, THC, and Sulphate despite some parameters remaining within the acceptable limits, indicating significant anthropogenic pressures and vulnerability of aquatic species within the aquatic ecosystem. Additionally, water quality indices (SFI, NPI, WPI, and CCME-WQI), indicated varying degrees of pollution across the sampling stations. Marine Base Jetty consistently demonstrated the highest pollution levels followed by Eastern bye-pass bridge then NDDC water front characterized by elevated hydrocarbon and sulphate concentrations. These findings collectively pinpoint a confluence of hydrocarbon and organic pollution within the studied area of Amadi Creek which might result in ecological imbalances and reduced aquatic biodiversity. Hence, the urgent need for comprehensive and integrated water quality management strategies to mitigate pollution sources and maintain the ecological integrity of Amadi Creek. Addressing these issues requires targeted interventions such as stricter enforcement of environmental regulations and control of industrial and urban discharges, improved wastewater treatment infrastructure, and habitat restoration initiatives to mitigate the impacts of these pollutants on Amadi Creek's ecosystem. Public awareness campaigns and community engagement are also essential for promoting sustainable practices. Long-term restoration initiatives, including the establishment of riparian buffers and remediation of hydrocarbon pollution, will be critical for the ecological recovery of Amadi Creek.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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