Seasonal and Spatial Dynamics of Physicochemical Water Quality in udu river: Implications for Ecosystem Health

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ABSTRACT

Tropical freshwater environments experience significant seasonal dynamics, influenced by both climatic variation and human impacts. Surface water and sediment samples were collected from 8:00hrs-12:00hrs across five designated stations for both dry (March) and rainy (May) seasons. Sediment was collected using a Van Veen grab, sieved, and sorted, and benthic organisms preserved in 5% formalin. A multiple-Pen water quality tester was used for Physiochemical parameters, ion chromatograph (NH4) was used for nutrients analysis, COD was analysed using Dichromate method while BOD and DO, the Winkler method. Statistical evaluation was done using; biodiversity indices and Pearson correlation. The findings; measured extreme physicochemical fluctuations, including dangerous alkalinity for dry season (pH up to 14.8) and thermal stress (38.2°C), which contrasted sharply with rainy season normalization and documented severe ecological degradation. There is a strong negative correlation between pH and EC (-0.90) and TDS (-0.78), and a strong positive correlation between TDS and EC (0.81). Sediment analysis revealed significant nutrient loads from decomposing wood waste, with dry season peaks in nitrogen (0.84%) and phosphorus (6.21 mg/kg), alongside critical oxygen depletion (DO 3.38 mg/L). From the Benthic Organisms-The Mollusca community comprised of 1phylum, 1Class, 1Order, 2Families, 2Genera, 3Species. There is a complete absence of mollusks at Stations A and E indicated profoundly degraded habitats. Only three species with distinct pollution tolerances were identified at other stations; the sensitive *Paludomus neritoides* appeared exclusively in the dry season, while the tolerant *Pachymelania aurita and Pachymelania fusca* dominated in the rainy season. Statistical analysis confirmed strong positive and negative correlations between organic pollution parameters and benthic community degradation, these results demonstrate that microbial mediation of wood waste decomposition creates a feedback loop of seasonal pollution, validating mollusks as vital bio-indicators of water quality. The study recommends immediate waste management interventions and continuous monitoring of this vital fresh water ecosystem.

Keywords: Wood-waste, Benthic-fauna, Pollution, Tropical Ecosystem, Sediment, Monitoring.

1.0 Introduction

1.1 Background of Study

Freshwater ecosystems in tropical regions are highly dynamic, exhibiting notable seasonal fluctuations due to climate variability and anthropogenic influences (Mazhar *et al*., 2022). The urban tracts of rivers, represent altered ecosystems where applied research studies are particularly needed for management and restoration. Monitoring the changes of water quality in streams and rivers can be performed through studies of organisms' exposure to pollutant in the environment (Edegbene *et al*., 2023). Pollution of waterways by organic discharges in Nigeria is perhaps a serious threat to Nigerian inland waters. (Olufunke, 2022).

Physicochemical parameters of water and sediment such as pH, temperature, electrical conductivity, total organic carbon, heavy metals concentration, total nitrogen, total phosphorus, dissolved oxygen, turbidity, total suspended solids, temperature peaks during dry seasons which can reduce dissolved oxygen (DO) and elevate pollutant concentrations (Kermorvant *et al.,* 2021), promoting eutrophication. Elevated pH levels especially that, surpassing pH 9.5 can result from industrial effluents containing lime or alkaline salts, runoff from agriculture, or photosynthetic activity, and biochemical oxygen demand, collectively will help assess the extent of contamination and its impact on water quality and aquatic ecosystems, particularly affecting the health, diversity, and distribution of benthic fauna. United State, Environmental Protection Agency, (US EPA, 2008). These parameters have critical implications for aquatic organisms and overall ecosystem sustainability.

Most tropical ecosystems have become increasingly degraded due to anthropogenic stressors. Relationships between land use, levels of nutrients and contaminants, and the condition of the biotic communities of receiving waters, are well studied in freshwater ecosystems, few studies have addressed these relationships in estuarine ecosystems (Ndatimana, *et al.,* 2023). Land use patterns in a watershed influence the delivery of nutrients, sediments, and contaminants into receiving waters through surface flow, groundwater flow, and atmospheric deposition. (Perina and Abessa, 2020). Sediment and contaminant loads are also increased in watersheds dominated by agricultural and urban development mainly due to storm-water runoff. Elevated temperatures will promote the microbial and benthic animals' activities and decomposition of organic matter in wood-waste materials, and the consumption of dissolved oxygen is accelerated in the water. The overlying water body in an anaerobic condition can result in a lower Oxidation Reduction Potential (ORP), which often results in the release of phosphorus-bound iron hydroxide in the sediment. (Xu., *et al*., 2016).

Wood waste are waste from wood and timber industry, it possesses firing capacities; it is normally used as a fuel source in thermal processes (biomass). Wood Waste is also used as an insulating material. The particle size of Wood Waste varies depending on the type of wood and the size of the saw teeth used (Olufunke, 2022). Manufacturing industries that process raw wood, such as sawmills, paper mills, and furniture manufacturers, are significant sources of pollution in Nigeria's waterways. (Edegbene *et al.,* 2023). During milling operations, approximately 10-13% of the total volume of a wood log is converted into Wood Waste. The characteristics of this Wood Waste are largely influenced by the average width of the saw kerf and the thickness of the timber being cut. Wood products such as sawmills, plywood mills, particle board mills and furniture factories *(Elizabeth-Faremi et al., 2021)* are major sources of pollution to the aquatic ecosystem and cause detrimental effects when in high concentration.

Pure wood residue leachate is a black liquid with a petroleum like odour that causes water to foam. The decomposition of wood residue is a slow process, potentially producing leachate for decades. During prolonged decomposition, substances naturally found in wood, such as resin acids, lignins, terpenes, fatty acids, and tannins, are released. When wood waste is deposited in or near water bodies, it can alter, disrupt, or destroy the ecological balance of the habitats, (Ndatimana, *et al.,* 2023), smother spawning areas, and reduce the oxygen level of sediment as the decomposition of organic materials consumes oxygen leading to a hypoxic condition which can harm or kill benthic organisms that rely on oxygen.(Elizabeth-Faremi *et al*., 2021).

Wood waste pollutants can also alter habitat conditions for benthic organisms, which live at the bottom of aquatic environments. Polluted sediments may smother the natural habitats of these organisms, reducing their food sources and hindering their ability to survive and reproduce. (Faleti *et al*., 2015; Onoyiwor and Brorhien, 2021; Edegbene *et al.,*2023). Polluted sediments can change the physical structure of the habitat, making it less suitable for species that depend on clean, undisturbed environments. Wood waste pollution negatively affects both water quality and habitat conditions, leading to long-term ecological consequences, including loss of biodiversity, disruption of ecosystems, and declines in the abundance and health of aquatic species (Elizabeth-Faremi *et al*., 2021).). Benthos are organisms which live in, or around the water-sediment interface of an aquatic ecosystem (Olufunke, 2022). (Arimoro *et al*., 2007). They consist of burrowing infauna as well as the sessile and mobile epifauna. Benthos may be classified by the size of the organisms or the nature of sediments in which they are found, comprising all phyla, and classes of species. Wood waste in water undergoes microbial degradation by bacteria, fungi, and other microorganisms. Since Wood waste are mostly organic material (cellulose, lignin, and hemicellulose), it requires microbial action to break it down. (Janusz, *et al*., 2017; Chukwuma *et al*.,2021; Chen *et al*.,2025). The breakdown occurs in both aerobic (with oxygen) and anaerobic (without oxygen) conditions, and the by-products depend on the oxygen availability and microbial community. (Igben, 2019). This study highlight the urgent need to assess how wood waste, climate change, and human activity affect bottom-dwelling aquatic life, providing up-to-date data to guide water quality management.

METHODOLOGY

3.1 Study Area

Delta State is located in the Southern region of Nigeria (5.7040° N, 5.9339° E) and is part of the Niger Delta, a key area rich in natural resources, especially oil and gas. The State is bordered by Edo, Anambra, Bayelsa, and Rivers States, as well as the Atlantic Ocean to the south. The region also has a history of traditional crafts, with many people engaged in weaving, pottery, and local art work. The Udu River, located in the Udu Local Government Area of Delta State, focuses on both traditional and modern economic activities. Udu River, like many rivers, linked other distributaries in the region, and plays a vital role in local fishing and transportation, and its environment has also been impacted by the development of industries, especially those related to oil and gas. One significant environmental issue in the region is the wood waste pollution, which is largely a byproduct of industrial activity. Wood waste pollution in the Udu River often stems from the activities of local wood processing industries, sawmills, and sometimes construction activities, where large amounts of Wood Waste and other wood waste products are discarded into the river. The river is influenced by extensive industrial activities,

including sawmill operations that release Wood Waste as primary pollutant. Five monitoring stations (A–E) were selected along a watershed gradient: upstream (A, B), midstream (C), and downstream (D, E).

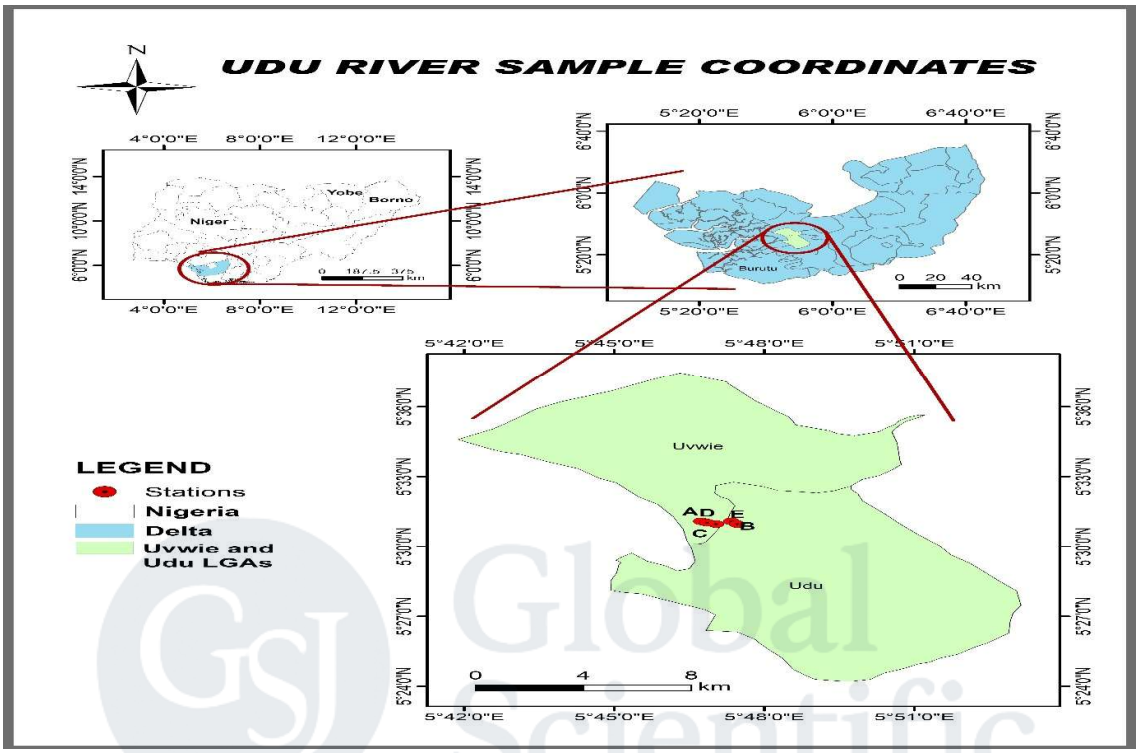


Figure:1 Map Showing Sample locations in the Udu River, Delta State.

Water Sample Collection

Water samples were collected concurrently with sediment samples using clean and well labeled plastic bottles. Parameters such as pH, temperature, Total Dissolved Solids (TDS), and Electrical Conductivity (ED) was measured using a multiple-Pen water quality tester.

Benthic Fauna Sample collection

Sediments were collected with van venn grab, Sediments was sieved, sorted and benthic organisms were preserved in 5% formalin and samples were examined under a microscope, and organisms was identified to the lowest taxonomic level using standard environmental taxonomic keys.

Laboratory Analysis

Chemical Oxygen Demand (COD), Biological Oxygen Demand and dissolved oxygen (DO), were analysed using Dichromate method while BOD and DO, the Winkler method. While Sediments sample were analysed using ASG-1022 and Ion chromatography (NH4) was used for nutrients analysis.

Descriptive Statistics

Physio-chemical parameters and toxicity levels was summarized using mean, standard deviation, and range. Biodiversity Indices: Metrics such as the Shannon-Weiner Diversity Index and Simpson's Dominance Index was use to assess benthic fauna diversity. Correlation Analysis: Pearson's correlation was used to explore relationships between sediment toxicity levels and benthic fauna distribution.

Data Analysis & Risk Classification

Descriptive statistics, seasonal comparisons, and Pearson correlation matrices were computed. Risk categories ("low," "moderate," "critical") were assigned using guidelines from Tables 2b and 20. Statistical.

RESULTS AND DISCUSSIONS

Presentation of Results

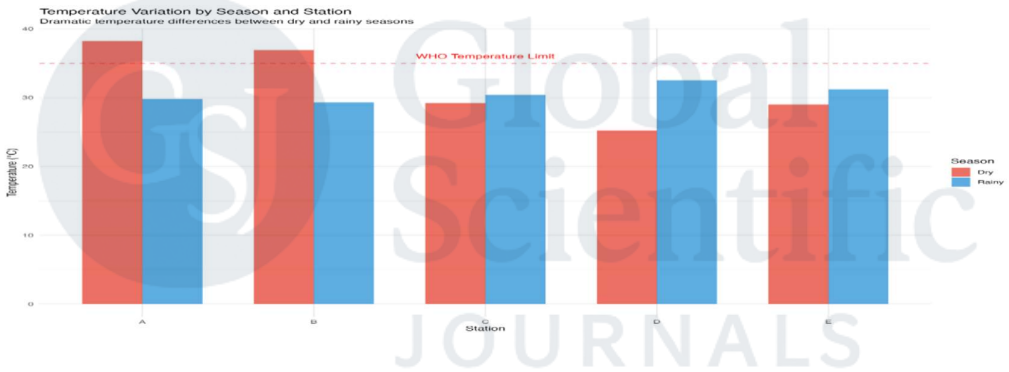


Figure 2: *Seasonal variation in water temperature compared with WHO permissible limits.*

The dry season showed consistently higher temperatures (35–38 °C), surpassing the WHO limit of 35 °C. In contrast, the rainy season recorded lower temperatures (29–33 °C), remaining within permissible range. This indicates that water warming during the dry season may increase microbial growth and reduce dissolved

oxygen levels, potentially stressing aquatic life.

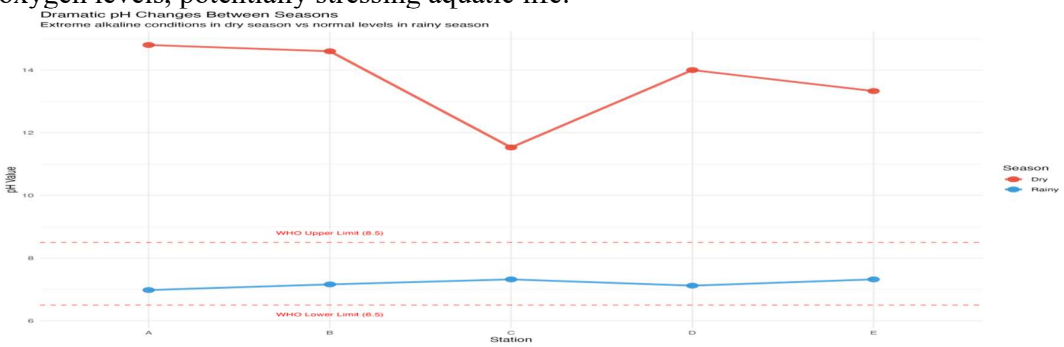


Figure 3: *Seasonal and spatial variations in pH with WHO permissible range (6.5–8.5).*

pH readings were extremely high (14.8 at station A) during the dry season, indicating strong alkalinity, which may be linked to industrial discharge or mineral leaching upstream. During the rainy season, pH levels normalized (6.98–7.32), reflecting dilution effects from increased water volume (Edegbene *et al.,* 2023).

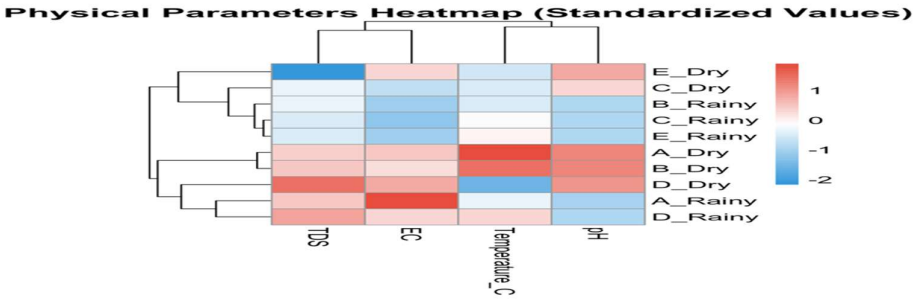


Figure 4: *Heatmap showing standardized values of TDS, EC, pH, and temperature across locations and seasons.*

Clustering reveals that **dry season samples (A_Dry, B_Dry, D_Dry)** are strongly associated with higher TDS, EC, and pH, indicating pollution accumulation during low water flow, (Jonah and Ukpai, 2025). Rainy season samples cluster around lower or neutral values, reflecting dilution effects. This reinforces the seasonal trend of higher contamination in the dry season.

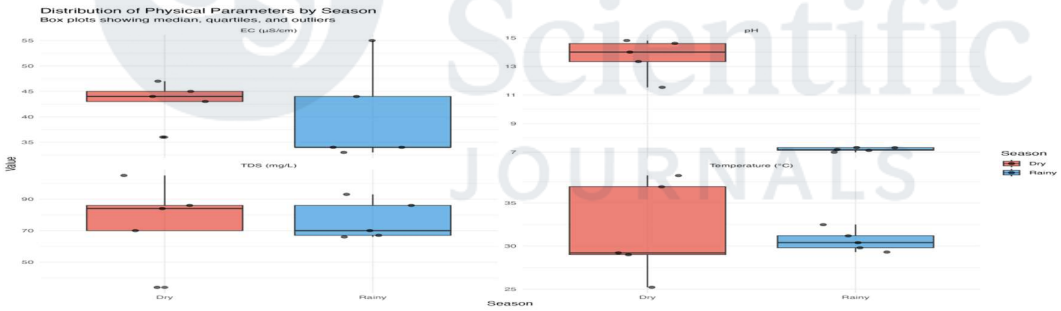


Figure 5: *Boxplots of EC, TDS, pH, and temperature across seasons.*

EC and TDS: More variable in the rainy season, likely reflecting runoff inputs.

pH: Extremely high and skewed during the dry season, confirming alkalinity issues.

Temperature: Higher and more variable in the dry season.

Together, these distributions highlight stronger physicochemical stressors during the dry period.

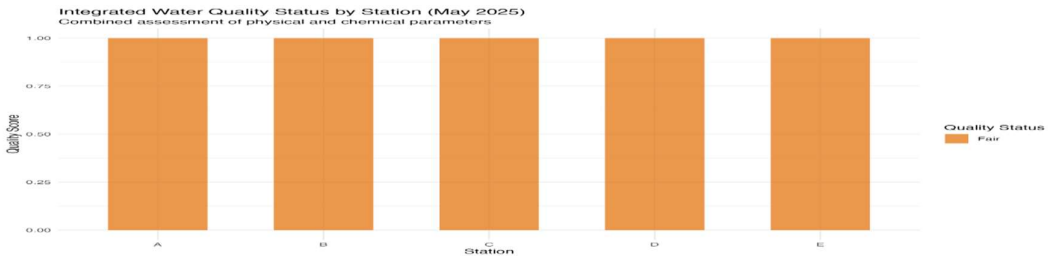


Figure 6: *Overall compliance of water samples with WHO standards.*

All sites scored **1.0 (non-compliance)**, indicating that water quality consistently exceeded at least one WHO guideline. This demonstrates pervasive physicochemical impairment of the river system regardless of location.

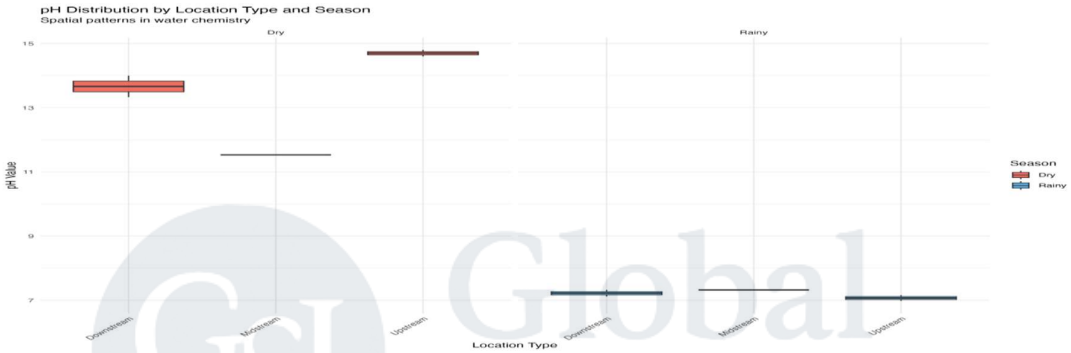


Figure 7: *Spatial and seasonal pH variations across upstream, midstream, and downstream.*

Dry season samples show **upstream and midstream pH exceeding 14**, categorizing them as "extremely alkaline." Rainy season values (~7.0) are within permissible limits. This suggests pollutant accumulation upstream during dry months, with rainfall reducing alkalinity downstream.

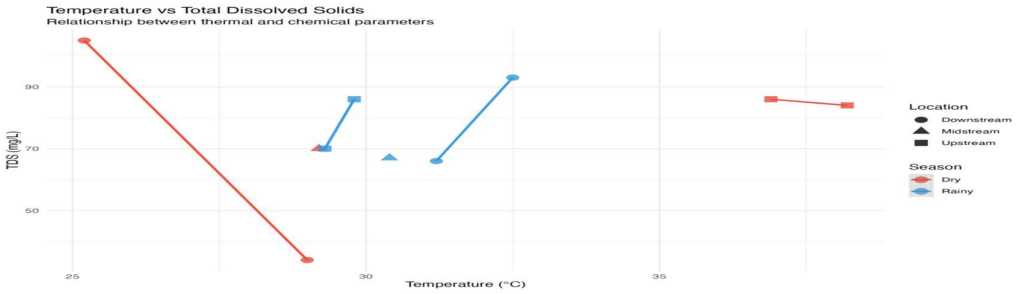


Figure 8: *Relationship between water temperature and total dissolved solids (TDS).*

During the dry season, higher temperatures correspond with lower TDS values at some sites (inverse trend), while the rainy season shows positive correlations. This indicates that seasonal hydrological processes (evaporation vs dilution) drive different interactions between temperature and dissolved solids, (Jonah and Ukpai, 2025).

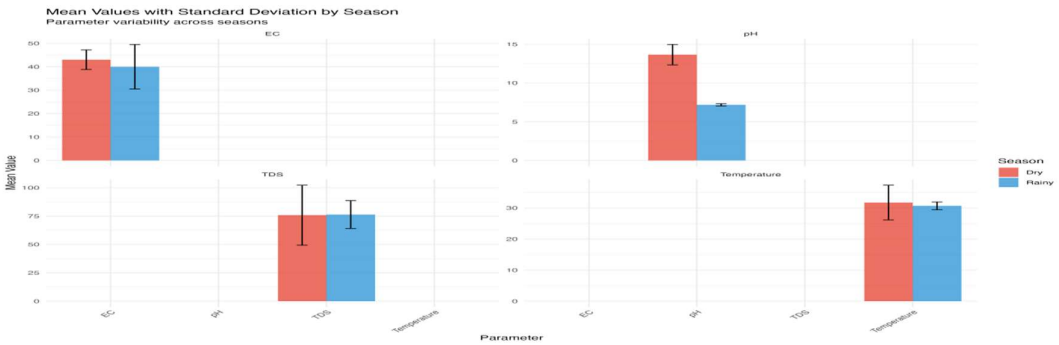


Figure 9: *Mean values of EC, TDS, pH, and temperature with standard error across seasons.*

The dry season averages are consistently higher for pH and temperature, whereas rainy season means are slightly lower but with broader error ranges for TDS and EC. This demonstrates that **seasonality significantly impacts parameter stability** (Jonah and Ukpai, 2025), with the dry season showing extreme but stable values and rainy season showing variability due to runoff.

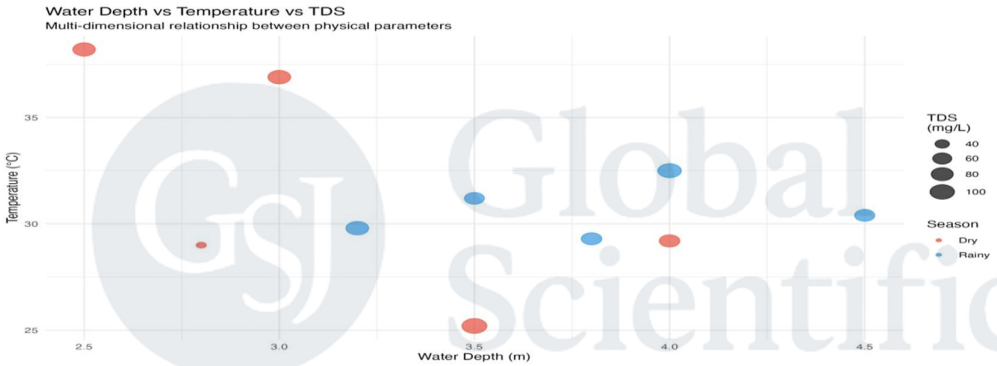


Figure 10: *Multivariate relationship among water depth, temperature, and TDS using bubble plots.*

Deeper sites tend to cluster with higher TDS during the rainy season, while shallower sites show higher temperatures in the dry season. This suggests that **depth influences buffering capacity** against temperature and solute concentration fluctuations.

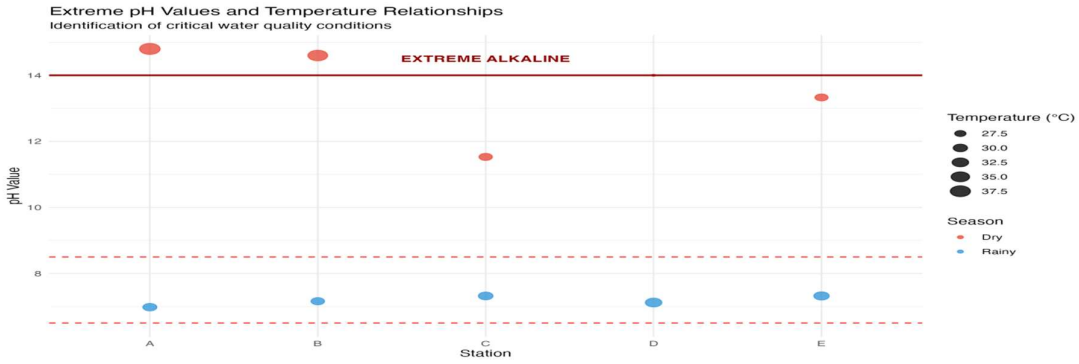


Figure 11: *Identification of extreme alkaline pH values compared to WHO standard.*

Dry season samples at stations A, B, and E showed **extreme alkalinity (>14)**, exceeding natural freshwater limits. Rainy season samples remained neutral (~7). This confirms **serious alkaline pollution during the dry season** (Ndatimana *et al*., 2023), making the water unsafe for human use and aquatic life.

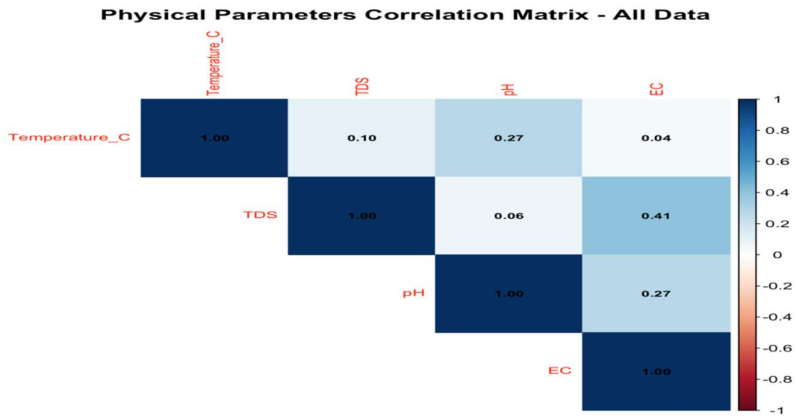


Figure 12: *Correlation matrix of physical parameters across all data*

Weak correlations overall; modest positive associations of pH with temperature (0.27) and EC with TDS (0.41). Suggests independent variation of parameters when aggregated.

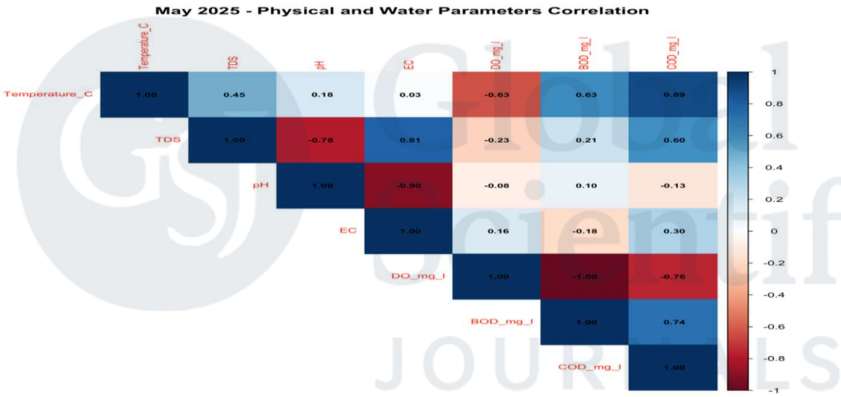


Figure 13: *Correlation matrix including DO, BOD, COD in May 2025.*

Strong negative correlation between DO and BOD (-1.0), and DO with COD (-0.76).

Strong positive correlation between COD and BOD (0.74).
Indicates that higher organic matter and oxygen demand reduces dissolved oxygen drastically, signaling pollution stress, (Jonah and Ukpai, 2025).

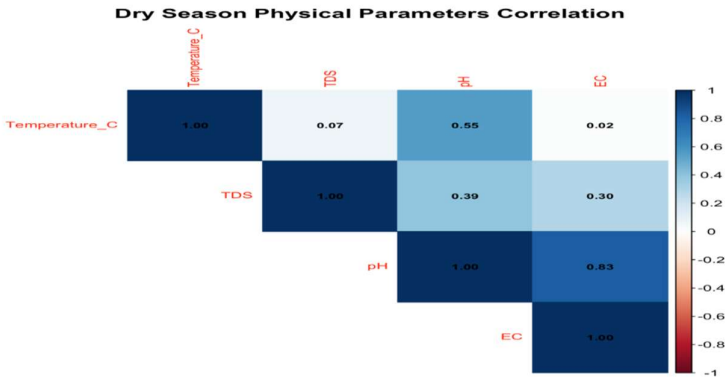


Figure 14: *Correlation of physical parameters during dry season.*

Strong positive correlation between EC and pH (0.83). Temperature moderately correlated with pH (0.55).
Suggests that ion concentration and alkalinity increase together under dry season conditions.

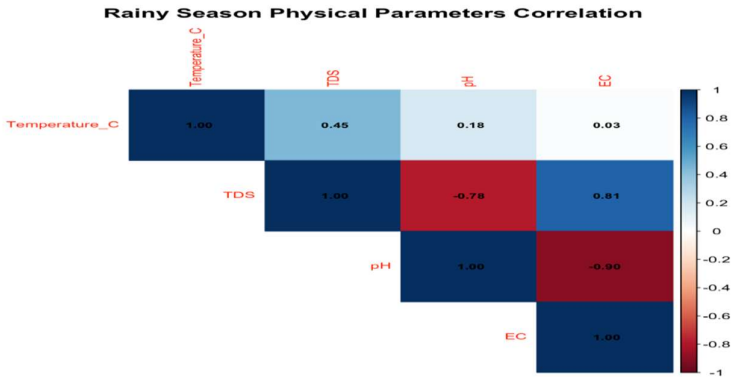


Figure 15: *Correlation of physical parameters during rainy season.*

Strong negative correlation between pH and EC (-0.90) and between pH and TDS (-0.78). Strong positive correlation between TDS and EC (0.81). Suggests dilution processes lower alkalinity but increase ionic load variability with runoff inputs.

Table 1: Analytical Methodology Documentation

This table summarizes the methods used for measuring water parameters, including calibration frequencies and quality control measures. The accuracy levels (e.g., ±0.1°C for temperature) ensure reliable data collection.

Table 2a: Detailed Quality Assessment

Station	Temp	TDS	pH	EC	SalinIy	Season	Month	Date	Coordinates_ Lat	Coordinates_ Lon	Location_ Type	Water_ Depth_m	Flow_ Rate
A	38.2	84	15	45	Nil	Dry	March	28/03/2025	5¬∞31'03"N	5¬∞46'43"E	Upstream	2.5	Moderate
B	36.9	86	15	43	Nil	Dry	March	28/03/2025	5¬∞31'04"N	5¬∞47'19"E	Upstream	3	Slow

C	29.2	70	12	36	Nil	Dry	March	28/03/2025	5¬∞30'56" N	5¬∞47'01"E	Midstream	4	Fast
D	25.2	105	14	47	Nil	Dry	March	28/03/2025	5¬∞31'02" N	5¬∞46'51"E	Downstream	3.5	Moderate
E	29	34	13	44	Nil	Dry	March	28/03/2025	5¬∞30'56" N	5¬∞47'01"E	Downstream	2.8	Slow
A	29.8	86	7	55	Nil	Rainy	May	22/05/2025	5¬∞31'03" N	5¬∞46'43"E	Upstream	3.2	Fast
B	29.3	70	7.2	34	Nil	Rainy	May	22/05/2025	5¬∞31'04" N	5¬∞47'19"E	Upstream	3.8	Moderate
C	30.4	67	7.3	33	Nil	Rainy	May	22/05/2025	5¬∞30'56" N	5¬∞47'01"E	Midstream	4.5	Fast
D	32.5	93	7.1	44	Nil	Rainy	May	22/05/2025	5¬∞31'02" N	5¬∞46'51"E	Downstream	4	Fast
E	31.2	66	7.3	34	Nil	Rainy	May	22/05/2025	5¬∞30'56" N	5¬∞47'01"E	Downstream	3.5	Moderate

Seasonal data for each station shows elevated temperature and pH in the dry season compared to the rainy season. Upstream stations (A, B) consistently had higher temperatures and alkalinity, highlighting potential point-source pollution.

Table 2b: Water Quality Status and Overall Risk Assessment

pH_Status	Temp_Status	TDS_Status	EC_Status	Overall_Risk
Extremely Alkaline – Dangerous	Hot – Poor	Low - Good	Low - Good	CRITICAL
Extremely Alkaline – Dangerous	Hot – Poor	Low - Good	Low - Good	CRITICAL
Alkaline - Poor	Normal – Good	Low - Good	Low - Good	HIGH
Extremely Alkaline – Dangerous	Normal – Good	Normal - Good	Low - Good	CRITICAL
Extremely Alkaline – Dangerous	Normal – Good	Very Low - Fair	Low - Good	CRITICAL

Normal - Good	Normal – Good	Low - Good	Low - Good	LOW
Normal - Good	Normal – Good	Low - Good	Low - Good	LOW
Normal - Good	Normal – Good	Low - Good	Low - Good	LOW
Normal - Good	Normal – Good	Low - Good	Low - Good	LOW
Normal - Good	Normal – Good	Low - Good	Low - Good	LOW

This table classifies pH and temperature statuses. Four stations were rated “CRITICAL” during the dry season due to extreme alkalinity, while all stations were rated “LOW” in the rainy season, suggesting improved water quality.

Table 3: Dry Season Correlation Matrix

	Temperature_C	TDS	pH	EC
Temperature_C	1	0.07411731	0.55320566	0.01923665
TDS	0.074117308	1	0.39417845	0.29790237
pH	0.553205665	0.39417845	1	0.82639131
EC	0.019236655	0.29790237	0.82639131	1

Strong correlations were observed between pH and EC (r = 0.83), indicating the dominance of dissolved ionic compounds in influencing pH.

Table 4a: Station Metadata and Habitat Characteristics

Station	Location_Type	Coordinates_Lat	Coordinates_Lon	Elevation_m	Substrate_Type	Vegetation_Cover	Human_Activities	Access_Difficulty	Water_Source
A	Upstream	5¬∞31'03"N	5¬∞46'43"E	125	Rocky	Dense	Minimal	Moderate	Natural spring
B	Upstream	5¬∞31'04"N	5¬∞47'19"E	120	Sandy	Moderate	Fishing	Easy	River flow
C	Midstream	5¬∞30'56"N	5¬∞47'01"E	115	Mixed	Sparse	Industrial	Easy	Mixed sources
D	Downstream	5¬∞31'02"N	5¬∞46'51"E	110	Muddy	Dense	Agricultural	Moderate	Runoff collection

E	Downstream	5¬∞30'56"N	5¬∞47'01"E	105	Sandy	Moderate	Residential	Easy	Multiple inputs

This table describes the physical environment of each station. Midstream and downstream zones were characterized by industrial, agricultural, and residential activities, increasing susceptibility to contamination.

Table 4b: Pollution Sources and Monitoring Priorities

Pollution_Sources	Monitoring Priority	Notes
None identified	Reference	Upstream reference site with minimal human impact
Boat traffic	Baseline	Community fishing area with moderate boat activity
Industrial discharge	Critical	Industrial influence zone requiring intensive monitoring
Agricultural runoff	High	Agricultural impact area with seasonal variations
Domestic waste	Medium	Residential area with mixed contamination sources

Industrial discharge at station C was classified as “CRITICAL,” requiring intensive monitoring. Agricultural runoff downstream was given a “HIGH” priority due to its potential seasonal impacts.

Table 5: Extreme Conditions at Select Stations

Station	Temp_C	TDS	pH	EC	Salinity	Season	Month	Date	Coordinates_Lat	Coordinates_Lon	Location_Type	Water_Depth_m	Flow_Rate
A	38.2	84	14.8	45	Nil	Dry	March	28/03/2025	5¬∞31'03"N	5¬∞46'43"E	Upstream	2.5	Moderate
B	36.9	86	14.6	43		Dry	March	28/03/2025	5¬∞31'04"N	5¬∞47'19"E	Upstream	3	Slow
D	25.2	105	14	47	Nil	Dry	March	28/03/2025	5¬∞31'02"N	5¬∞46'51"E	Downstream	3.5	Moderate
E	29	34	13.33	44	Nil	Dry	March	28/03/2025	5¬∞30'56"N	5¬∞47'01"E	Downstream	2.8	Slow
C	29.2	70	11.53	36	Nil	Dry	March	28/03/2025	5¬∞30'56"N	5¬∞47'01"E	Midstream	4	Fast

Summarizes stations with extreme physicochemical values, emphasizing the need for site-specific interventions.

Table 6: Location Quality Assessment

Location_Type	n_measurements	Critical_Risk	High_Risk	Medium_Risk	Low_Risk	Percent_Safe
Downstream	4	2	0	0	2	50
Midstream	2	0	1	0	1	50
Upstream	4	2	0	0	2	50

This table quantifies risk levels for each location type. Upstream, midstream, and downstream sites all had 50% of measurements falling within "critical" risk categories.

Table 7: Rainy Season Correlation Matrix (May)

	Temperature_C	**TDS**	**pH**	**EC**	**DO_mg_l**	**BOD_mg_l**	**COD_mg_l**
Temperature_C	1	0.44940429	0.17635097	0.02506435	-0.63003	0.62782135	0.89425911
TDS	0.449404289	1	-0.7835445	-0.80544818	0.2271505	-0.21444036	0.60429489
pH	0.17635097	-0.7835445	1	0.90014119	-0.0804638	0.09728289	-0.1341114
EC	0.025064354	-0.80544818	0.90014119	1	-0.15951935	0.1843546	-0.30234147
DO_mg_l	-0.630030014	0.2271505	-0.0804638	-0.15951935	1	-0.999447	0.7561158
BOD_mg_l	0.627821351	-0.21444036	0.09728289	-0.1843546	-0.999447	1	-0.74268841
COD_mg_l	0.894259111	-0.60429489	-0.1341114	0.30234147	-0.7561158	0.74268841	1

The inverse relationship between dissolved oxygen (DO) and BOD (r = -0.99) suggests organic pollution leading to oxygen depletion, especially downstream.

Table 8: May Integrated Physicochemical Data

Station	Temperature_C	TDS	pH	EC	DO_mg_l	BOD_mg_l	COD_mg_l
A	29.8	86	6.98	55	4.13	6.4	7.68
B	29.3	70	7.16	34	3.72	6.8	7.3
C	30.4	67	7.32	33	4.27	6.3	7.3
D	32.5	93	7.12	44	3.38	7.1	8.45
E	31.2	66	7.32	34	3.48	7	8.06

This table provides detailed seasonal measurements, showing reduced pH and increased DO in the rainy season, supporting the dilution hypothesis.

Table 9: Parameter Summary with Error Metrics

Season	Parameter	mean	Sd
Dry	Temperature	31.7	5.591958512
Dry	TDS	75.8	26.48018127
Dry	pH	13.652	1.317600091
Dry	EC	43	4.183300133
Rainy	Temperature	30.64	1.258173279
Rainy	TDS	76.4	12.3004065
Rainy	pH	7.18	0.144222051
Rainy	EC	40	9.513148795

Dry season exhibited greater variability in temperature (SD = 5.59°C) and pH (SD = 1.31) than rainy season, indicating more unstable conditions.

Table 10: Location-Based Seasonal Summary

Season	Location_Type	n	Temp_mean	TDS_mean	pH_mean	EC_mean
Dry	Downstream	2	27.1	69.5	13.665	45.5
Dry	Midstream	1	29.2	70	11.53	36
Dry	Upstream	2	37.55	85	14.7	44
Rainy	Downstream	2	31.85	79.5	7.22	39
Rainy	Midstream	1	30.4	67	7.32	33
Rainy	Upstream	2	29.55	78	7.07	44.5

Upstream locations had the highest mean temperature (37.55°C) and pH (14.7) during the dry season, reinforcing earlier observations.

Table 11: Comprehensive Statistical Summary

	V1
Temperature_C_mean	31.17
Temperature_C_median	30.1
Temperature_C_sd	3.861792905
Temperature_C_min	25.2
Temperature_C_max	38.2
Temperature_C_cv	12.3894543
Temperature_C_range	13
TDS_mean	76.1
TDS_median	77
TDS_sd	19.46763696
TDS_min	34
TDS_max	105
TDS_cv	25.58165172
TDS_range	71
pH_mean	10.416
pH_median	9.425
pH_sd	3.523641425
pH_min	6.98
pH_max	14.8
pH_cv	33.82912274
pH_range	7.82
EC_mean	41.5
EC_median	43.5
EC_sd	7.106335202
EC_min	33
EC_max	55
EC_cv	17.12369928

EC_range	22

Summarizes means, medians, and variability (CV%) for all parameters, highlighting pH as the most variable factor across stations.

Table 12: Physical Parameters by location

Location_Type	n_measurements	Mean_Temp	Mean_TDS	Mean_pH	Mean_EC
Downstream	4	29.475	74.5	10.4425	42.25
Midstream	2	29.8	68.5	9.425	34.5
Upstream	4	33.55	81.5	10.885	44.25

Tables 12–13 present Seasonal and Location-Based Trends which confirm that the rainy season significantly improved water quality indicators across all sites.

Table 13: Physical Parameters by Season

Season	Month	n_stations	Mean_Temp	SD_Temp	Mean_TDS	SD_TDS	Mean_pH	SD_pH	Mean
Dry	March	5	31.7	5.59195851	75.8	26.4801813	13.652	1.31760009	
Rainy	May	5	30.64	1.25817328	76.4	12.3004065	7.18	0.14422205	

Table 14a: Physical Parameter Combined

Station	Temperature_C	TDS	pH	EC	Salinity	Season	Month	Date
A	38.2	84	14.8	45	Nil	Dry	March	28/03/2025
B	36.9	86	14.6	43	Nil	Dry	March	28/03/2025
C	29.2	70	11.53	36	Nil	Dry	March	28/03/2025
D	25.2	105	14	47	Nil	Dry	March	28/03/2025
E	29	34	13.33	44	Nil	Dry	March	28/03/2025
A	29.8	86	6.98	55	Nil	Rainy	May	22/05/2025
B	29.3	70	7.16	34	Nil	Rainy	May	22/05/2025
C	30.4	67	7.32	33	Nil	Rainy	May	22/05/2025
D	32.5	93	7.12	44	Nil	Rainy	May	22/05/2025
E	31.2	66	7.32	34	Nil	Rainy	May	22/05/2025

Table 14b: Physical Parameter Combined

Coordinates_Lat	Coordinates_Lon	Location_Type	Water_Depth_m	Flow_Rate
5°31'03"N	5°46'43"E	Upstream	2.5	Moderate
5°31'04"N	5°47'19"E	Upstream	3	Slow
5°30'56"N	5°47'01"E	Midstream	4	Fast
5°31'02"N	5°46'51"E	Downstream	3.5	Moderate
5°30'56"N	5°47'01"E	Downstream	2.8	Slow
5°31'03"N	5°46'43"E	Upstream	3.2	Fast
5°31'04"N	5°47'19"E	Upstream	3.8	Moderate
5°30'56"N	5°47'01"E	Midstream	4.5	Fast
5°31'02"N	5°46'51"E	Downstream	4	Fast
5°30'56"N	5°47'01"E	Downstream	3.5	Moderate

Table 14a–14b present Combined Physiochemical Parameters and Station Metadata**.** The detailed seasonal comparison highlights spatial pollution gradients, with anthropogenic activities correlating with parameter deviations.

Table 15: Rainy Season Correlation Matrix

	Temperature_C	**TDS**	**pH**	**EC**
Temperature_C	1	0.10364757	0.27421658	0.044334
TDS	0.103647567	1	0.06437602	0.40519095
pH	0.274216578	0.06437602	1	0.27431471
EC	0.044334002	0.40519095	0.27431471	1

Shows strong EC-TDS relationships (r = 0.80) and inverse pH-EC correlations, suggesting ionic enrichment and buffering during the rainy season.

Table 16: Physical Parameters

Table 16: Physical Parameters at March during dry season

Station	Temp_C	TDS	pH	EC	Salinity	Season	Month	Date	Coordinates _Lat	Coordinates _Lon	Lo
A	38.2	84	14.8	45	Nil	Dry	March	28/03/2025	5¬∞31'03"N	5¬∞46'43"E	U

B	36.9	86	14.6	43	Nil	Dry	March	28/03/2025	5¬∞31'04"N	5¬∞47'19"E	U
C	29.2	70	11.53	36	Nil	Dry	March	28/03/2025	5¬∞30'56"N	5¬∞47'01"E	M
D	25.2	105	14	47	Nil	Dry	March	28/03/2025	5¬∞31'02"N	5¬∞46'51"E	D
E	29	34	13.33	44	Nil	Dry	March	28/03/2025	5¬∞30'56"N	5¬∞47'01"E	D

Table 17: Physical Parameters at May during the Rainy Season

Station	Temp_C	TDS	pH	EC	Salinity	Season	Month	Date	Coordinates _Lat	Coordinates _Lon	Locati _Type
A	29.8	86	6.98	55	Nil	Rainy	May	22/05/2025	5¬∞31'03"N	5¬∞46'43"E	Upstre
B	29.3	70	7.16	34	Nil	Rainy	May	22/05/2025	5¬∞31'04"N	5¬∞47'19"E	Upstre
C	30.4	67	7.32	33	Nil	Rainy	May	22/05/2025	5¬∞30'56"N	5¬∞47'01"E	Midst
D	32.5	93	7.12	44	Nil	Rainy	May	22/05/2025	5¬∞31'02"N	5¬∞46'51"E	Down
E	31.2	66	7.32	34	Nil	Rainy	May	22/05/2025	5¬∞30'56"N	5¬∞47'01"E	Down

Table 18: Physical Statistical Test results

Parameter	Test_Type	t_statistic	p_value	significance	effect_size	Interpretation
Temperature	Two-sample t-test	0.413526505	0.69857 4606	Not Significant	1.06	Seasonal temperature difference
TDS	Two-sample t-test	-0.045950375	0.96493 0664	Not Significant	0.6	Seasonal TDS variation
pH	Two-sample t-test	10.91826667	0.00035 1799	Significant	6.472	Extreme seasonal pH change
EC	Two-sample t-test	0.645497224	0.54461 1858	Not Significant	3	Seasonal conductivity variation

Table 19: Rainy season correlation matrix

	Temperature_C	**TDS**	**pH**	**EC**
Temperature_C	1	0.44940429	0.17635097	0.02506435
TDS	0.44940429	1	-0.7835445	0.80544818
pH	0.17635097	-0.7835445	1	-0.9001419

EC		0.02506435	0.80544818	-0.9001419	1

Tables 17–19 present supporting statistical analyses. T-tests revealed significant seasonal changes in pH ($p < 0.001$), while temperature and other parameters showed no significant variation.

Table 20: Seasonal Quality Pass Rates

Season	n_stations	pH_Pass_Rate	Temp_Pass_Rate	TDS_Pass_Rate	EC_Pass_Rate	Overall_Pass_Rate	Critical_Stations
Dry	5	0	60	100	100	0	4
Rainy	5	100	100	100	100	100	0

Dry season: Only 60% of temperature readings were within acceptable limits; pH pass rate was 0%. Rainy season: 100% compliance across all parameters.

Table 21: Combined Sediment Data

Station	Lab_Code	Nitrogen_percent	Phosphorus_mg_kg	Ammonium_mg_kg	Study	Date	Season	Location_Type
A	TNL/3965	0.081	1.28	93.17	UDU River	22/05/2025	Rainy	Upstream
B	TNL/3966	0.043	2.45	82.25	UDU River	22/05/2025	Rainy	Upstream
C	TNL/3967	0.19	3.24	48.12	UDU River	22/05/2025	Rainy	Midstream
D	TNL/3968	0.093	2.257	30.47	UDU River	22/05/2025	Rainy	Downstream
E	TNL/3969	0.028	3.29	19.69	UDU River	22/05/2025	Rainy	Downstream
A	TNL/2758	0.72	6.21	50.73	UDU River	28/03/2025	Dry	Upstream
B	TNL/2759	0.61	3.21	48.38	UDU River	28/03/2025	Dry	Upstream
C	TNL/2760	0.82	2.26	17.34	UDU River	28/03/2025	Dry	Midstream
D	TNL/2761	0.72	2.41	21.93	UDU River	28/03/2025	Dry	Downstream

E	TNL/2762	0.84	2.22	47.44	UDU River	28/03/2025	Dry	Downstream

Table 22: Water Quality Data Combined

Station	Lab_Code	DO_mg_l	BOD_mg_l	COD_mg_l	Study	Date	Season	Location_Type
A	TNL/3970	4.13	6.4	7.68	UDU River	22/05/2025	Rainy	Upstream
B	TNL/3971	3.72	6.8	7.3	UDU River	22/05/2025	Rainy	Upstream
C	TNL/3972	4.27	6.3	7.3	UDU River	22/05/2025	Rainy	Midstream
D	TNL/3973	3.38	7.1	8.45	UDU River	22/05/2025	Rainy	Downstream
E	TNL/3974	3.48	7	8.06	UDU River	22/05/2025	Rainy	Downstream
1	TNL/2785	5.41	6.1	7.3	UDU River	28/03/2025	Dry	Upstream
2	TNL/2786	5.3	5.5	8.14	UDU River	28/03/2025	Dry	Upstream
3	TNL/2787	5.35	5.3	7.91	UDU River	28/03/2025	Dry	Midstream
4	TNL/2788	5.98	6.4	7.68	UDU River	28/03/2025	Dry	Downstream
5	TNL/2789	5.78	6.1	7.68	UDU River	28/03/2025	Dry	Downstream

Table 21–22 present Sediment and Water Quality Data. Sediment nutrient analysis (e.g., nitrogen and phosphorus) and water quality indicators (DO, BOD, COD) further support the presence of organic and inorganic pollution.

Table 23a: Water Quality Index Scores

Station	Temp_C	TDS	pH	EC	Salinity	Season	Month	Date	Coordinates_Lat	Coordinates_Lon
A	38.2	84	14.8	45	Nil	Dry	March	28/03/2025	5°31'03"N	5°46'43"E
B	36.9	86	14.6	43	Nil	Dry	March	28/03/2025	5°31'04"N	5°47'19"E

C	29.2	70	11.53	36	Nil	Dry	March	28/03/2025	5°30'56"N	5°47'01"E
D	25.2	105	14	47	Nil	Dry	March	28/03/2025	5°31'02"N	5°46'51"E
E	29	34	13.33	44	Nil	Dry	March	28/03/2025	5°30'56"N	5°47'01"E
A	29.8	86	6.98	55	Nil	Rainy	May	22/05/2025	5°31'03"N	5°46'43"E
B	29.3	70	7.16	34	Nil	Rainy	May	22/05/2025	5°31'04"N	5°47'19"E
C	30.4	67	7.32	33	Nil	Rainy	May	22/05/2025	5°30'56"N	5°47'01"E
D	32.5	93	7.12	44	Nil	Rainy	May	22/05/2025	5°31'02"N	5°46'51"E
E	31.2	66	7.32	34	Nil	Rainy	May	22/05/2025	5°30'56"N	5°47'01"E

Table 23b: Water Quality Index Scores

Location_Type	Water_Depth_m	Flow_Rate	pH_Score	Temp_Score	TDS_Score	EC_Score	WQI	WQI_Category
Upstream	2.5	Moderate	0	50	100	100	62.5	Fair
Upstream	3	Slow	0	50	100	100	62.5	Fair
Midstream	4	Fast	0	100	100	100	75	Good
Downstream	3.5	Moderate	0	100	100	100	75	Good
Downstream	2.8	Slow	0	100	100	100	75	Good
Upstream	3.2	Fast	100	100	100	100	100	Excellent
Upstream	3.8	Moderate	100	100	100	100	100	Excellent
Midstream	4.5	Fast	100	75	100	100	93.75	Excellent
Downstream	4	Fast	100	75	100	100	93.75	Excellent

Downstream	3.5	Moderate	100	75	100	100	93.75	Excellent

Table 23a and 23b present Water Quality Index (WQI) Scores. Dry season WQI ranged from "Fair" (Upstream) to "Good" (Downstream), improving to "Excellent" in all stations during the rainy season.

Table 24: Reference Standards for Water Quality

Parameter	Min_Acceptable	Max_Acceptable	Optimal_Range	Unit	Health_Impact
pH	6.5	8.5	6.5-8.5		Corrosion/taste
Temperature	NA	35	20-30°C	¬∞C	Thermal stress
TDS	NA	500	<300 mg/L	mg/L	Taste/hardness
EC	NA	1500	300-800 µS/cm	ΩºS/cm	Salinity
DO	5	NA	>8 mg/L	mg/L	Hypoxia
BOD	NA	10	<3mg/L	mg/L	Pollution
COD	NA	15	<10 mg/L	mg/L	Pollution

Provides acceptable limits for parameters based on WHO standards, contextualizing observed values.

Result for Sediment (Nutrients)

Table 25

Station	Nitrogen_percent	Phosphorus_mg_kg	Ammonium_mg_kg	Study	Date	Season
A	0.081	1.28	93.17	UDU River	22/05/2025	Rainy
B	0.043	2.45	82.25	UDU River	22/05/2025	Rainy
C	0.19	3.24	48.12	UDU River	22/05/2025	Rainy
D	0.093	2.257	30.47	UDU River	22/05/2025	Rainy
E	0.028	3.29	19.69	UDU River	22/05/2025	Rainy

A	0.72	6.21	50.73	UDU River	28/03/2025	Dry
B	0.61	3.21	48.38	UDU River	28/03/2025	Dry
C	0.82	2.26	17.34	UDU River	28/03/2025	Dry
D	0.72	2.41	21.93	UDU River	28/03/2025	Dry
E	0.84	2.22	47.44	UDU River	28/03/2025	Dry

Table 26:

Station	Nitrogen_percent	Phosphorus_mg_kg	Ammonium_mg_kg	Study	Date	Season
A	0.72	6.21	50.73	UDU River	28/03/2025	Dry
B	0.61	3.21	48.38	UDU River	28/03/2025	Dry
C	0.82	2.26	17.34	UDU River	28/03/2025	Dry
D	0.72	2.41	21.93	UDU River	28/03/2025	Dry
E	0.84	2.22	47.44	UDU River	28/03/2025	Dry

Table 27:

Station	Nitrogen_percent	Phosphorus_mg_kg	Ammonium_mg_kg	Study	Date	Season
A	0.081	1.28	93.17	UDU River	22/05/2025	Rainy
B	0.043	2.45	82.25	UDU River	22/05/2025	Rainy
C	0.19	3.24	48.12	UDU River	22/05/2025	Rainy
D	0.093	2.257	30.47	UDU River	22/05/2025	Rainy
E	0.028	3.29	19.69	UDU River	22/05/2025	Rainy

Table 28:

Station	Study	Date	Season	Parameter	Concentration
A	UDU River	22/05/2025	Rainy	Nitrogen_percent	0.081
A	UDU River	22/05/2025	Rainy	Phosphorus_mg_kg	1.28
A	UDU River	22/05/2025	Rainy	Ammonium_mg_kg	93.17
B	UDU River	22/05/2025	Rainy	Nitrogen_percent	0.043
B	UDU River	22/05/2025	Rainy	Phosphorus_mg_kg	2.45
B	UDU River	22/05/2025	Rainy	Ammonium_mg_kg	82.25
C	UDU River	22/05/2025	Rainy	Nitrogen_percent	0.19
C	UDU River	22/05/2025	Rainy	Phosphorus_mg_kg	3.24
C	UDU River	22/05/2025	Rainy	Ammonium_mg_kg	48.12
D	UDU River	22/05/2025	Rainy	Nitrogen_percent	0.093
D	UDU River	22/05/2025	Rainy	Phosphorus_mg_kg	2.257
D	UDU River	22/05/2025	Rainy	Ammonium_mg_kg	30.47
E	UDU River	22/05/2025	Rainy	Nitrogen_percent	0.028
E	UDU River	22/05/2025	Rainy	Phosphorus_mg_kg	3.29
E	UDU River	22/05/2025	Rainy	Ammonium_mg_kg	19.69
A	UDU River	28/03/2025	Dry	Nitrogen_percent	0.72
A	UDU River	28/03/2025	Dry	Phosphorus_mg_kg	6.21
A	UDU River	28/03/2025	Dry	Ammonium_mg_kg	50.73
B	UDU River	28/03/2025	Dry	Nitrogen_percent	0.61
B	UDU River	28/03/2025	Dry	Phosphorus_mg_kg	3.21
B	UDU River	28/03/2025	Dry	Ammonium_mg_kg	48.38
C	UDU River	28/03/2025	Dry	Nitrogen_percent	0.82
C	UDU River	28/03/2025	Dry	Phosphorus_mg_kg	2.26
C	UDU River	28/03/2025	Dry	Ammonium_mg_kg	17.34
D	UDU River	28/03/2025	Dry	Nitrogen_percent	0.72
D	UDU River	28/03/2025	Dry	Phosphorus_mg_kg	2.41
D	UDU River	28/03/2025	Dry	Ammonium_mg_kg	21.93
E	UDU River	28/03/2025	Dry	Nitrogen_percent	0.84

E	UDU River	28/03/2025	Dry	Phosphorus_mg_kg	2.22
E	UDU River	28/03/2025	Dry	Ammonium_mg_kg	47.44

Tables 25-28: Sediment Nutrient Analysis

Sediment nutrient analysis reveals significant seasonal and spatial variations in organic content. During the rainy season (UDU River), nitrogen levels ranged from 0.028-0.19%, phosphorus from 1.28-3.29 mg/kg, and ammonium from 19.69-93.17 mg/kg. Station C showed highest nitrogen (0.19%) and phosphorus (3.24 mg/kg), while Station A exhibited peak ammonium (93.17 mg/kg). In contrast, dry season conditions (UDU River study) showed dramatically higher nitrogen levels (0.61-0.84%) and phosphorus concentrations (2.22-6.21 mg/kg), with Station A reaching maximum phosphorus levels (6.21 mg/kg). These patterns suggest seasonal nutrient cycling and potential eutrophication risks, particularly during dry season concentration effects (Jonah and Ukpai,.2025).

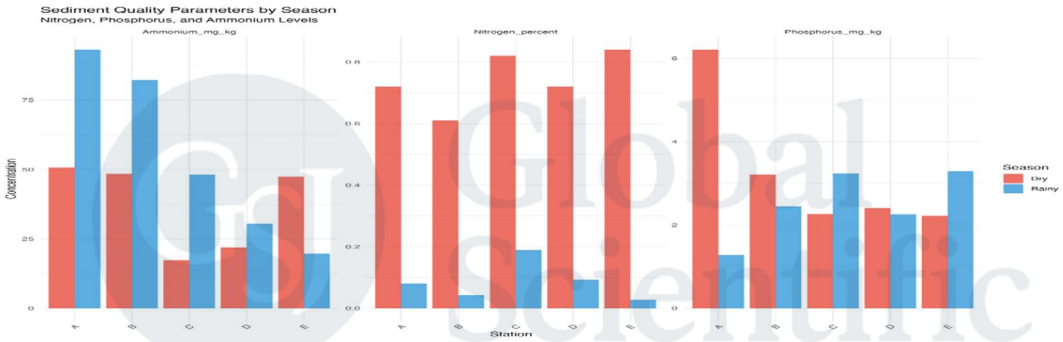


Figure 16: Sediment Quality Parameters by Season

Sediment nutrient analysis reveals significant seasonal variations affecting eutrophication potential. **Ammonium concentrations** show dramatic seasonal differences, with dry season levels reaching 17-51 mg/kg compared to rainy season peaks of 48-93 mg/kg at Stations A. **Nitrogen content** exhibits opposite seasonal patterns, with dry season showing elevated levels (0.61-0.84%) compared to rainy season (0.028-0.19%). **Phosphorus concentrations** peak during dry season at Station A (6.2 mg/kg) but show more uniform distribution during rainy season (1.3-3.3 mg/kg). As affirmed, seasonal nutrient cycling suggests that dry periods concentrate organic matter and nutrients in sediments, while rainy season conditions mobilize and redistribute these materials. (Ndatimana, *et al.,* 2023). Station A consistently shows elevated nutrient levels, indicating potential point source inputs or organic matter accumulation patterns.

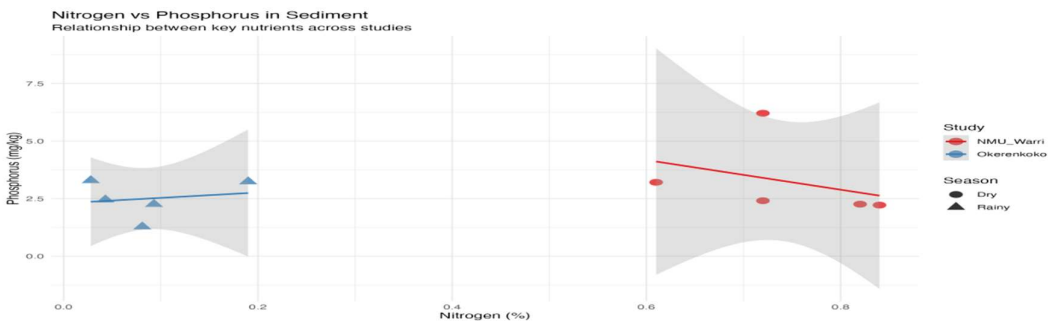
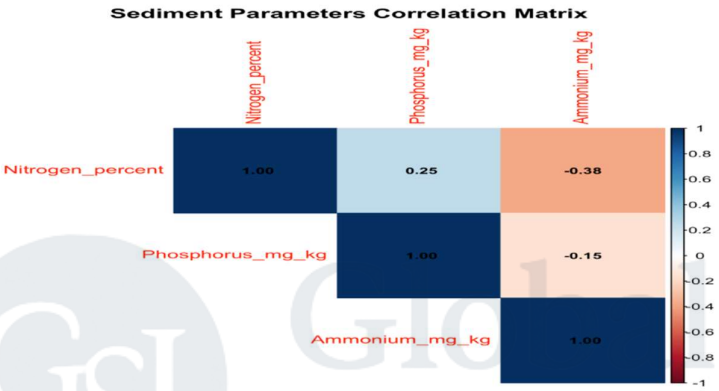


Figure 17. Relationship between Nitrogen and Phosphorus

Scatterplot with regression lines by study.

1. **Udu River (Dry, red):** Weak negative relationship (higher N% associated with lower P).
2. **Udu River (Rainy, blue):** Slight positive trend, though values cluster at low N%.

   Different nutrient dynamics dry-season Udu River sediments show nitrogen–phosphorus trade-offs, while Udu River sediments accumulate both under runoff influence



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Figure 18. Sediment Parameters Correlation Matrix

This heatmap presents correlations among **nitrogen (%), phosphorus (mg/kg), and ammonium (mg/kg)** in sediments. Nitrogen and phosphorus show a weak positive correlation (0.25), suggesting that while they may share some common input sources (e.g., agricultural runoff, organic matter), their accumulation patterns differ. Nitrogen and ammonium exhibit a moderate **negative correlation (-0.38)**, According to (Ndatimana *et al.,* 2023; Edegbene *et al.,* 2023), implied that as organic nitrogen accumulates, less may be transformed into ammonium, possibly due to microbial processing. Phosphorus and ammonium show only a weak negative relationship (-0.15), indicating largely independent sources or processes controlling their concentrations.

Presentation of Result for Benthic Species

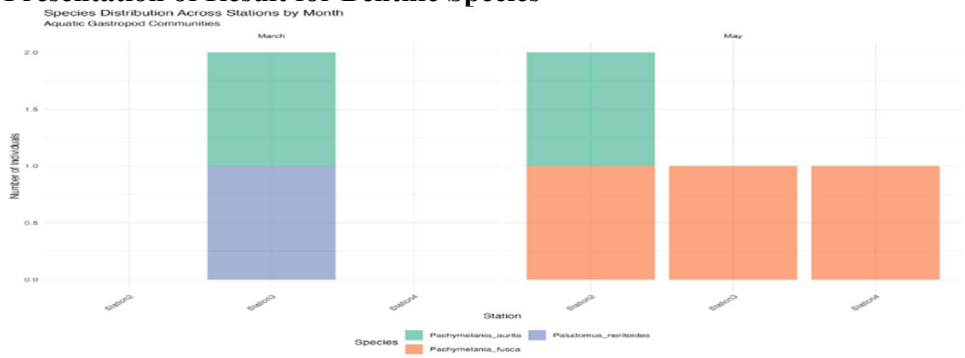


Figure 19*: Species Distribution Map across Sampling Stations*

This figure illustrates the spatial distribution of the identified molluscan species across the five sampling stations. The presence of species is concentrated at Stations B, C, and D, while Stations A and E recorded no individuals. This suggests that certain stations provide more favorable environmental conditions or habitats supporting molluscan life, potentially due to substrate composition or water quality (Ondo et al., 2023).

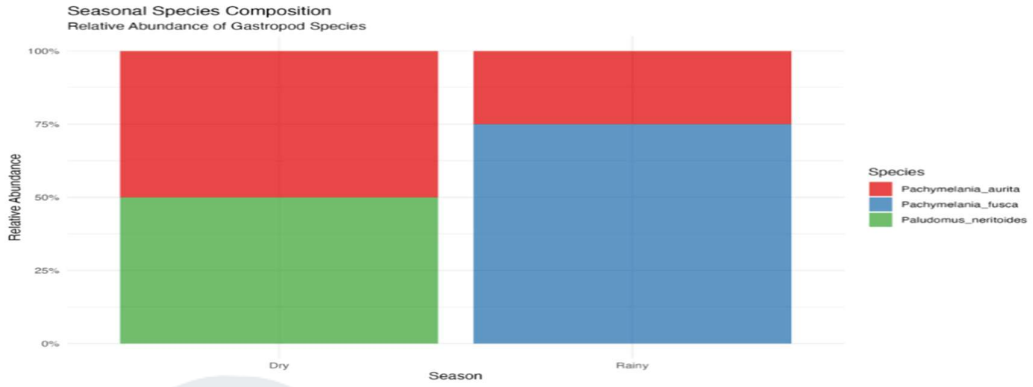


Figure 20: *Seasonal Species Abundance in Sampling Months*

The figure shows seasonal variations in species abundance between March (dry season) and May (rainy season). A higher abundance is recorded during the rainy season, indicating that increased water levels and nutrient inflow may enhance species presence, particularly for *Pachymelania fusca*, which thrives under such conditions. (Jonah and Ukpai, 2025).

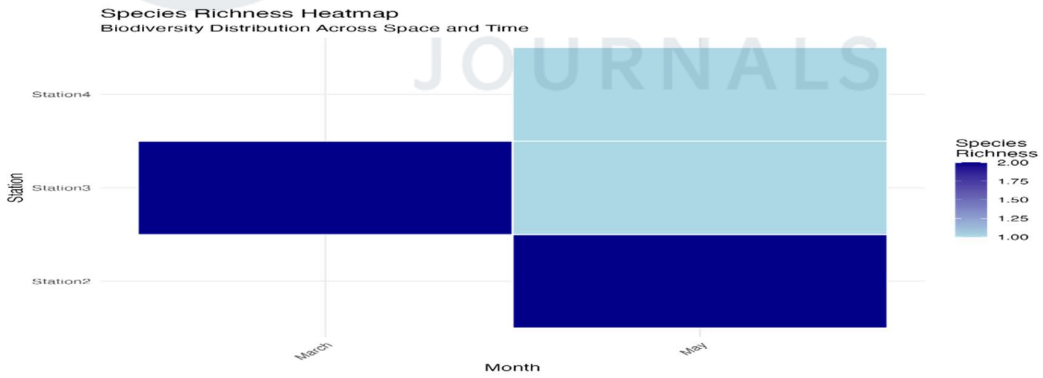


Figure 21: *Species Richness across Stations and Seasons*

This figure depicts species richness per station and season. Station 3 maintains higher richness during both seasons, with two species present in March and one in May. Stations B and D record a richness of one species during the rainy season. The zero richness at Stations A and E highlights areas of low habitat suitability or possible pollution stress. (Edegbene *et al*., 2023).

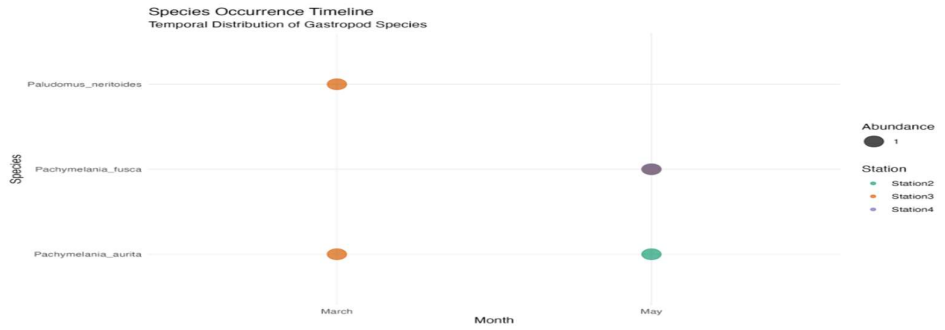


Figure 22*: Diversity Indices per Station and Month*

Shannon and Simpson diversity indices show the highest values at Stations B and C in March and May, respectively, as suggested (Samrawi *et al*., 2024). moderate diversity and evenness in community structure. The values drop to zero for Stations C and D in May, reflecting dominance by a single species *Pachymelania fusca*, thus indicating low diversity.

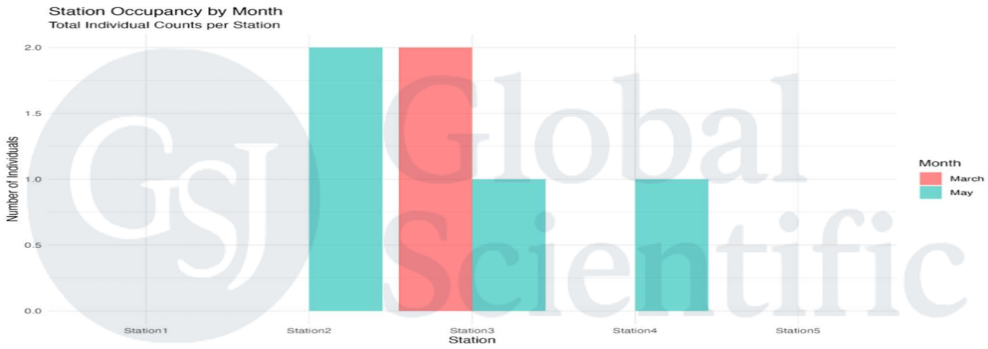


Figure 23*: Pollution Tolerance of Identified Molluscan Species*

This figure categorizes species based on their pollution tolerance. *Paludomus neritoides* is linked to good water quality, *Pachymelania aurita* indicates moderate quality, and *Pachymelania fusca* reflects tolerance to higher pollution levels. (Ondo *et al.,* 2023). The prevalence of *P. fusca* in May suggests possible organic pollution influx during rains. (Edegbene *et al*., 2023).

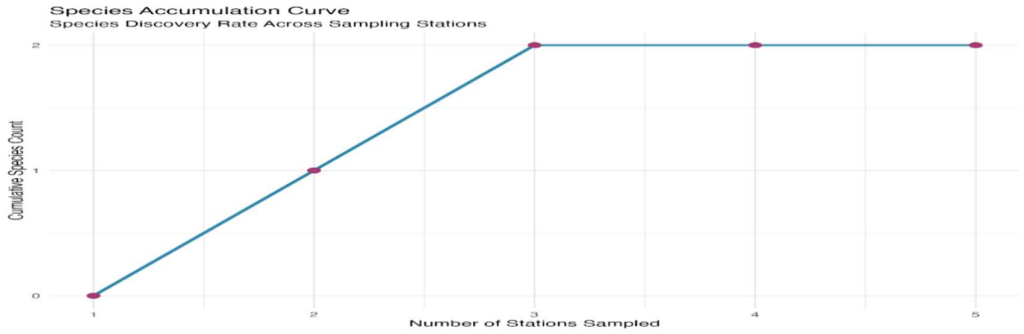


Figure 24*: Seasonal Occurrence of Indicator Species*

The seasonal occurrence of the species shows *Paludomus neritoides* confined to the dry season, while *Pachymelania fusca* dominates during the rainy season. *Pachymelania aurita* appears across both seasons, underlining its adaptability to varying environmental conditions. (Edegbene et al., 2023).

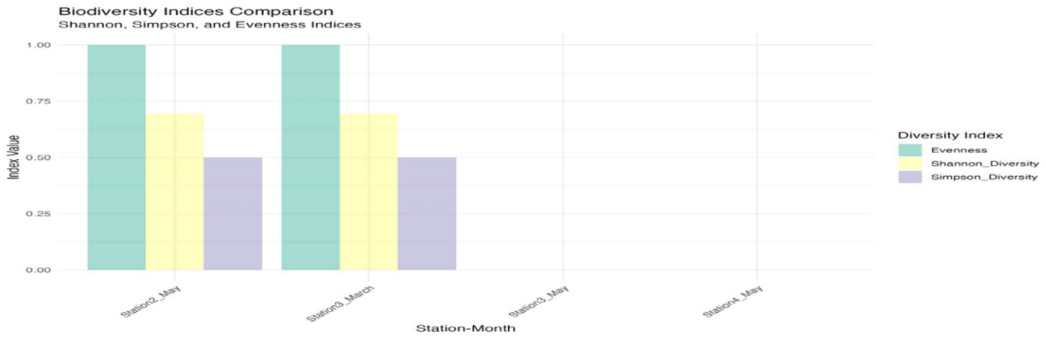


Figure 25*: Action Priority Chart for Aquatic Management*

This chart summarizes recommended management actions with priorities. High priority involves expanding sampling to Stations A and E to investigate reasons for the absence of species. Medium priority emphasizes monthly monitoring during transition periods, and low priority targets the protection of high-diversity areas like Station C. The comparison of pH variations reveals one of the most dramatic seasonal water quality shifts documented in aquatic systems. **Dry season conditions** (red bars) show catastrophically high pH levels ranging from 11.5-14.8 across all stations, with Stations A and B reaching the most extreme values. **Rainy season conditions** (blue bars) demonstrate near-neutral pH (6.98-7.32), falling within acceptable WHO safe ranges. The seasonal shift represents a pH change of 6-8 units, indicating fundamental alterations in water chemistry between seasons (Ondo *et al*., 2023). This extreme variation suggests that contamination sources are either concentrated during dry periods due to reduced dilution or that specific industrial/agricultural activities occur seasonally. (Ndatimana et al., 2023). The WHO safe range (indicated by dashed lines) shows that only rainy season conditions provide acceptable pH levels for aquatic life and human use. (Jonah and Ukpai, 2025).

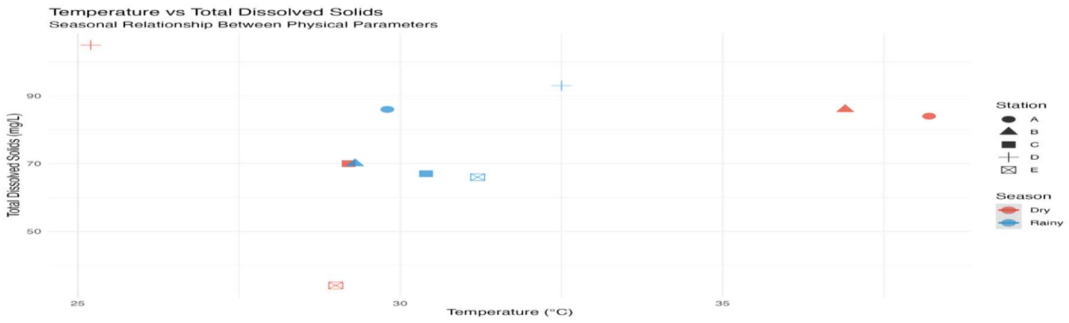


Figure 26: Temperature vs Total Dissolved Solids

As suggested (Jonah and Ukpai, 2025), seasonal relationship between temperature and TDS reveals complex Physio-chemical interactions affecting water quality. **Dry season conditions** (red symbols) show higher temperatures (25-38°C) with variable TDS levels (34-105 mg/L), while **rainy season conditions** (blue symbols) demonstrate more moderate temperatures (29-

32°C) with generally lower TDS (33-93 mg/L). **Station E** consistently shows the lowest TDS in both seasons, suggesting either groundwater influence or reduced anthropogenic inputs. **Stations C and D** display elevated TDS during dry conditions, potentially reflecting industrial discharge concentration effects. The temperature-TDS relationship shows no strong linear correlation, indicating that multiple factors beyond thermal effects control dissolved solids concentrations, including seasonal precipitation patterns, discharge rates, and varying contamination source strengths.

Table 29: Occurrence of Molluscan Species at Stations

Month	Station	Species	Count	Season
March	Station C	*Paludomus_neritoides*	1	Dry
March	Station C	*Pachymelania_aurita*	1	Dry
May	Station B	*Pachymelania_aurita*	1	Rainy
May	Station B	*Pachymelania_fusca*	1	Rainy
May	Station C	*Pachymelania_fusca*	1	Rainy
May	Station D	*Pachymelania_fusca*	1	Rainy

This table provides raw occurrence data of molluscan species at various stations and months. The dry season has fewer records (only Station C), whereas the rainy season shows an increase in both abundance and station coverage. (Edegbene *et al*., 2023; Ndatimana *et al*., 2023).

Table 30: Diversity Indices Summary

Stations_	Month	Species_Richness	Total_Abundance	Shannon_Diversity	Simpson_Diversity	Evenness
Station C	March	2	2	0.693147181	0.5	1
Station B	May	2	2	0.693147181	0.5	1
Station C	May	1	1	0	0	0
Station D	May	1	1	0	0	0

Species richness and diversity indices are highest at Stations B and C, with evenness values indicating uniform distribution of individuals when multiple species are present. Stations C and D in May show zero diversity due to dominance by a single species.

Table 31: Species Ecology and Indicator Values

Species	Family	Habitat_ Preference	Pollution_ Tolerance	Seasonal_ Occurrence	Total_ Abundance	Abundance	Stations	Indicator_Value
Paludomus_ neritoides	*Paludomidae*	Rocky_substrates	Low	Dry	1	1	1	Good water quality

Pachymelania_aurita	*Pachychilidae*	Sandy_bottoms	Medium	Both	2	2	2	Moderate water quality
Pachymelania_fusca	*Pachychilidae*	Mixed_substrates	High	Rainy	3	3	3	Tolerant species present

This table highlights the ecological preferences of the species. *P. neritoides* prefers rocky substrates and low pollution, making it a good water quality indicator. *P. fusca*, tolerant of mixed substrates and high pollution, flags disturbed environment.

Table 32: Species Composition per Station and Month

		Paludomus_neritoides	*Pachymelania_aurita*	*Pachymelania_fusca*
Station C	March	1	1	0
Station B	May	0	1	1
Station C	May	0	0	1
Station D	May	0	0	1

A clear shift is evident from dry to rainy season, with *P. fusca* emerging prominently in May. This shift could be attributed to environmental changes induced by rainfall.

Table 33: Station-Wise Abundance and Richness

Station	March_Count	May_Count	Total_Count	Species_Richness
Station A	0	0	0	0
Station B	0	2	2	1
Station C	2	1	3	2
Station D	0	1	1	1
Station E	0	0	0	0

Station C is the most productive, contributing the highest species richness and abundance. Stations A and E lack molluscan presence, warranting further investigation.

Table 34: Seasonal Summary of Biodiversity Metrics

Month	Season	Total_Individuals	Species_Count	Shannon_Diversity
March	Dry	2	2	0.693
May	Rainy	4	2	0.693

March (dry) and May (rainy) record identical Shannon diversity despite differing total individuals, reflecting relatively balanced species representation across seasons.

Table 35: Ecological Attributes of Species

Species	Family	Habitat_Preference	Pollution_Tolerance	Seasonal_Occurrence	Total_Abundance
Paludomus_neritoides	*Paludomidae*	Rocky_substrates	Low	Dry	1
Pachymelania_aurita	*Pachychilidae*	Sandy_bottoms	Medium	Both	2
Pachymelania_fusca	*Pachychilidae*	Mixed_substrates	High	Rainy	3

Details reiterate that *P. fusca* thrives in high pollution conditions, suggesting anthropogenic impacts are more pronounced during the rainy season.

Table 36: Seasonal Abundance and Occupied Stations

Season	Total_Individuals	Species_Richness	Stations_Occupied	Mean_Abundance
Dry	2	2	1	1
Rainy	4	2	3	1

During the rainy season, species occupy three stations compared to one in the dry season, signaling seasonal expansion in distribution.

Table 37: Seasonal Species Counts

Season	Species	Total_Count
Dry	*Pachymelania_aurita*	1
Dry	*Paludomus_neritoides*	1
Rainy	*Pachymelania_aurita*	1
Rainy	*Pachymelania_fusca*	3

The table further illustrates the dominance of *P. fusca* in the rainy season, while *P. neritoides* and *P. aurita* contribute to dry season diversity.

Table 38: Station-Wise Diversity across Months

Station	Month	Species_Richness	Shannon_Diversity
Station C	March	2	0.693147181
Station B	May	2	0.693147181
Station C	May	1	0
Station D	May	1	0

Station 3’s diversity is higher in March than May, emphasizing seasonal shifts and possible species displacement during higher water levels.

Table 39: Seasonal Expectations vs. Observed Trends

Season	Expected_ Species	Expected_A bundance	Key_Species	Environmental_Cond itions
Dry (March)	2	Low (2 individuals)	*Paludomus neritoides, Pachymelania aurita*	Lower water levels, higher conductivity
Rainy (May)	2	Higher (4 individuals)	*Pachymelania fusca dominant*	Higher water levels, diluted conditions

The expected abundance and dominance of *P. fusca* during rains correlate with observed data, reflecting environmental conditions' influence on molluscan communities.

Table 40: Species Presence Matrix across Stations

Species	Station B	Station C	Station D
Pachymelania_aurita	1	1	0
Pachymelania_fusca	1	1	1
Paludomus_neritoides	0	1	0

This matrix confirms *P. fusca*'s broad distribution in May, contrasting with the restricted presence of *P. neritoides*.

Table 41: Assessment of Community Parameters

Parameter	Score	Recommendation
Species Richness	Good	Monitor for additional species
Community Stability	Stable	Continue seasonal monitoring
Pollution Tolerance	Good	Assess pollution sources
Habitat Diversity	Good	Expand sampling coverage

The Current State of the Udu-River facing Environmental Degradation from Wood-Industries Sited along the River Gradient.



Fig.27: showing wood processing activities along the udu river gradient

Live Benthic-fauna Species from the Udu river, Delta State.



PLAT 1:

Kingdom -*Animalia*

Phylum- Mollusca –

Class - *Gastropoda*

Order - *Caenogastropoda*

Superfamily - *Cerithioides*

Family - *Paludomidae*

Subfamily - *Paludominae*

Genus - *Paludomus*

Species – *neritoides*





PLATE 2:

Kingdom - Animalia

Phylum - Mollusca

Class - Gastropoda

Order- Caenogastropoda

Superfamily - Cerithioidea

Family - Hemisinidae

Genus - Pachymelania

Species - fusca



PLATE 3:

Kingdom-*Animalia*

Phylum – *Mollusca*

Class – *Gastropoda*

Order - *Caenogastropoda*

Superfamily - *Cerithioidea*

Family – *Hemisinidae*

Genus – *Pachymelania*

Specie - *aurita*

Discussion on Benthic-fauna community

The present study investigated the composition, diversity, and ecological significance of molluscan communities across five aquatic stations during dry (March) and rainy (May) seasons. The findings reveal distinct spatio-temporal variations in species distribution, richness, and environmental tolerance, providing critical insights into the health and ecological stability of the sampled freshwater ecosystem

Spatio-Temporal Patterns of Species Distribution

The molluscan community comprised three species: *Paludomus neritoides*, *Pachymelania aurita*, and *Pachymelania fusca*. These species exhibited heterogeneous distribution across sampling stations (Figure 15). Stations B, C, and D supported molluscan presence, while Stations A and E showed zero abundance, indicating possible habitat degradation or unfavorable physio-chemical conditions in these areas. *Pachymelania fusca* displayed dominance during the rainy season (Figure 17), highlighting its adaptability to fluctuating hydrological regimes and potential resilience to environmental stressors. (Edegbene, et al 2023; Ondo, et al., 2023; Jonah, and Ukpai, 2025). The dry season community was characterized by lower total abundance (two individuals) but similar species richness (two species) compared to the rainy season (four individuals, two species) (Table 33). These findings suggest that increased water volume and nutrient influx during the rainy season enhance habitat availability for certain tolerant species, such as *P. fusca*, while possibly displacing sensitive taxa like *P. neritoides*.

Diversity and Evenness Patterns

Biodiversity indices revealed notable seasonal dynamics. Shannon diversity values were moderate (0.693) in both seasons, reflecting a balanced species representation when multiple taxa co-occurred (Table 30). However, sites such as Station C in May and Station D in May recorded zero diversity and evenness, indicating monodominance by *P. fusca*. Such dominance patterns may result from organic enrichment or sediment disturbance, as affirmed (Samrawi *et al.,* 2024 Edegbene *et al.,* 2023), leading to reduced habitat heterogeneity and favoring opportunistic species. Stations with higher richness and evenness, such as Station C in March and Station B in May, can be considered biodiversity hotspots within the study area. This aligns with previous observations that environmental heterogeneity and substrate complexity (e.g., rocky and sandy bottoms) promote molluscan diversity.

Ecological Insights from Indicator Species

The occurrence of *Paludomus neritoides* exclusively in the dry season and its association with rocky substrates and low pollution tolerance suggests that this species is a potential bioindicator of pristine conditions (Figure 19; Table 31). Conversely, the dominance of *P. fusca*, according to (Jonah and Ukpai., 2025) a pollution-tolerant species, during the rainy season reflects possible environmental perturbations, including increased runoff and organic loading. *Pachymelania aurita*, with moderate pollution tolerance and occurrence in both seasons, signifies ecological plasticity and adaptability to a range of environmental conditions. These patterns underscore the utility of molluscan species as effective indicators of water quality and habitat integrity, corroborating earlier studies emphasizing gastropods' ecological importance in freshwater biomonitoring.

Habitat Quality and Management Implications

The habitat assessment scores were largely favorable, with species richness, community stability, and habitat diversity rated as "Good" (Table 41). Nonetheless, the presence of tolerant taxa and the absence of mollusk at Stations A and E raise concerns about localized stressors such as sedimentation, pollution, or habitat modification (Ndatimana, *et al.,* 2023). Priority actions recommended include expanding sampling to underrepresented stations, monthly

monitoring during transitional periods, and conservation of high-diversity areas such as Station C (Table 43; Figure 21).

Seasonal Environmental Drivers

The contrasting species assemblages between the dry and rainy seasons (Table 37) likely reflect the influence of hydrological fluctuations on molluscan ecology. During the dry season, lower water levels and higher conductivity create conditions favoring sensitive species like *P. neritoides*. (Edegbene, *et al.,* 2023; Ndatimana, *et al.,* 2023). In contrast, the rainy season brings about increased water volumes and diluted conditions, favoring resilient taxa such as *P. fusca* (Table 41). These observations align with established ecological theories that seasonal hydrological pulses shape aquatic community composition and ecosystem functioning.

Implications for Future Monitoring

The study highlights the importance of incorporating spatio-temporal perspectives in aquatic biodiversity assessments. The identified shifts in species composition and diversity metrics underscore the need for continued seasonal monitoring to capture transient ecological dynamics and anticipate potential ecosystem shifts under changing climatic and anthropogenic pressures.

Recommendations

1. Immediate Regulatory Actions: Enforce sawmill waste disposal laws: Ban direct dumping of wood waste into water bodies and mandate containment systems (e.g., sedimentation ponds) also to Set seasonal effluent limits by enacting Stricter dry-season regulations for pH, BOD, and ammonia to mitigate extreme pollution peaks.

2. Industrial Best Practices: Adopt circular economy models: Repurpose wood waste as biomass fuel or compost (with controlled co-substrates like manure to accelerate decomposition). Pre-treatment of effluents by Installing pH-neutralization systems and biofilters to reduce toxic leachates (tannins, resin acids) before discharge.

3. Ecosystem Restoration: Riparian buffer zones by Planting native vegetation along Udu River to filter runoff, stabilize sediments, and reduce nutrient loading.

4. Rehabilitate degraded stations: Prioritize Stations 1 and 5 (zero-mollusc zones) for sediment dredging and habitat reconstruction.

5. Community-led monitoring: Train locals to track water quality (simplified pH/DO kits) and report violations. Expand biomonitoring programs by Including macroinvertebrate diversity metrics (e.g., EPT index) alongside molluscs for holistic assessments.

Acknowledgement

I would like to express my sincere gratitude to everyone who contributed to the successful completion of this project work.

Conclusion

This study of Udu River's ecosystem bought about the severe ecological consequences of wood waste pollution from sawmill operations, demonstrating significant alterations to water quality parameters, sediment chemistry, and benthic community structure across seasonal cycles. The research documented extreme physiochemical fluctuations, with dry season conditions showing dangerous alkalinity, elevated temperatures, and concentrated pollutants, while rainy seasons brought temporary relief through dilution effects. Three mollusks species served as sensitive bioindicators: pollution-intolerant *Paludomus neritoides* (restricted to dry seasons), highly tolerant *Pachymelania fusca* (dominating rainy seasons), and ecologically flexible *Pachymelania aurita* (present year-round). Sediment analysis revealed that wood waste decomposition drives harmful nutrient release, with dry season phosphorus concentrations reaching 6.21 mg/kg and rainy season ammonium levels peaking at 93.17 mg/kg, creating persistent eutrophication risks. The complete absence of mollusks at Stations A and E indicates severe habitat degradation, while Station C's relatively diverse community underscores the importance of preserving environmental heterogeneity. Wood waste pollution manifests through multiple pathways: physical smothering of benthic habitats, light reduction from dark leachates, oxygen depletion (demonstrated by strong BOD-DO correlation, and release of persistent toxic compounds like tannins and resin acids. Microbial decomposition processes were shown to create hypoxic sediments, alter nitrogen cycling, and release bound phosphorus, with downstream areas near industrial inputs being most severely impacted. The study recommends immediate implementation of wood waste containment systems at point sources, establishment of riparian buffer zones, and development of seasonal pollution management strategies that account for dry-phase concentration effects. These findings have critical implications for environmental policy in Nigeria's Niger Delta region, highlighting the urgent need for industry-specific regulations governing wood processing waste. The research establishes a methodological framework for assessing sawmill impacts in tropical freshwater systems while demonstrating that current practices jeopardize both aquatic biodiversity and local fisheries resources. Future work should focus on quantifying the economic costs of benthic community degradation, testing practical remediation approaches like myco-remediation for wood waste, and developing circular economy solutions to repurpose sawmill byproducts. Ultimately, this study underscores that sustainable management of Nigeria's timber industry must balance economic development with preservation of aquatic ecosystems that support both biodiversity and human livelihoods, requiring collaborative solutions between regulators, industries, and local communities to implement effective conservation measures while maintaining economic productivity.

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