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Assessment of Water Quality of the Otamiri River Along Selected Reaches Using an Integrated UAV–GIS–Laboratory Framework for Environmental Decision Support

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Abstract

This study assessed water quality along selected reaches of the Otamiri River, Imo State, Nigeria, through an integrated framework combining field sampling, laboratory analysis, unmanned aerial vehicle (UAV) imagery, geographic information system (GIS) analysis and predictive modelling. Five monitoring stations distributed along a 1,080 m river reach were evaluated for physicochemical, heavy-metal and microbiological indicators. Results showed acidic conditions (mean pH = 5.93), elevated chemical oxygen demand (mean COD = 23.73 mg/L), and widespread exceedances for lead, cadmium, total coliforms and faecal coliforms. Dissolved oxygen remained above 4 mg/L at all stations, indicating that some ecological assimilative capacity persisted despite substantial contamination. UAV–GIS analysis identified pollution hotspots associated with sand mining, refuse dumping, urban runoff, settlement encroachment and riverbank disturbance. A field-calibrated first-order BOD_s attenuation model, $BOD_s(L) = 8.46 \exp[-(0.00106L)/0.19]$, was developed using measured flow velocity, reach distance and the full replicate dataset from the doctoral investigation. The model achieved a strong fit ($R^2 > 0.975$) and was evaluated through calibration–validation partitioning, observed-versus-predicted comparison, residual and influence diagnostics, and comparative application to independent river observations. External evaluations for the Otamiri, Nworie, Ogun/Benue, Ganges and Thames Rivers produced predictions generally within 10% of reported observations. Complementary empirical relationships were developed for BOD_s and selected water-quality variables; station-mean regressions are reported separately as exploratory summaries and should not be confused with the replicate-level predictive models. The integrated framework provides a practical decision-support tool for identifying pollution sources, estimating organic-pollutant attenuation and prioritising river-management interventions. The river remains unsuitable for direct drinking-water use without treatment. Priority actions include sanitation control, regulation of sand mining and effluent discharges, riparian-buffer restoration and repeated multi-season UAV–GIS-supported monitoring.

Keywords: Otamiri River; water quality; UAV; GIS; predictive modelling; BOD_s decay; model validation; heavy metals; faecal coliform; environmental decision support.

1. Introduction

Freshwater rivers support domestic water supply, irrigation, fisheries, ecosystem services and public health. In rapidly urbanising catchments, however, river quality is increasingly affected by municipal waste, untreated effluents, agricultural runoff, sand mining and riparian encroachment. These pressures are especially important in developing regions where routine monitoring networks are limited. Otamiri River is a strategic surface-water body in Imo State, south-eastern Nigeria, serving communities around Owerri and the Federal University of Technology Owerri. Previous investigations have reported physicochemical and microbiological deterioration in the river, but many assessments remain constrained by point sampling and limited spatial coverage. UAV-based imagery and GIS analysis can strengthen conventional laboratory monitoring by identifying land-use pressures, channel modifications, potential discharge points and spatial pollution patterns. Recent studies have demonstrated the growing application of UAV technology for environmental monitoring in Nigeria. For example, Nmecha et al. (2024) applied drone technology to assess water quality conditions along selected reaches of the Otamiri River, highlighting the usefulness of UAV-derived imagery for identifying riverbank disturbances, pollution sources and anthropogenic pressures. However, the study was primarily observational and relied largely on UAV-based spatial assessment. Building on this foundation, the present study integrates UAV observations with GIS-based spatial analysis and laboratory-derived physicochemical, heavy-metal and microbiological measurements, thereby enabling a more comprehensive evaluation of the relationships between observed environmental pressures and measured water-quality conditions.

Previous investigations of the Otamiri River have documented physicochemical, heavy-metal and microbiological deterioration using conventional laboratory methods, while more recent studies introduced UAV-assisted environmental observation. The present study does not claim novelty from the use of UAV technology alone. Instead, its principal contribution lies in integrating laboratory measurements, UAV-derived environmental observations, GIS-supported spatial interpretation and regulatory compliance assessment into a unified evidence-convergence framework for environmental management. This framework is intended as a decision-support approach rather than a predictive environmental model. This study therefore integrates UAV-GIS mapping with laboratory assessment to evaluate water quality along selected Otamiri River reaches and to provide evidence for practical river-management interventions.

Table 1: Comparison of Previous Otamiri River Studies and the Present Integrated UAV–GIS–Laboratory Study

Previous Studies	Present Study
Laboratory analysis only	Laboratory + UAV + GIS integration
Point-based interpretation	Spatial decision-support framework
Physicochemical emphasis	Physicochemical + Heavy Metals + Microbiology + Spatial Context
Descriptive assessment	Evidence-convergence management framework
Limited management implications	Regulatory decision-support and environmental prioritization

The objectives were to: (i) determine selected physicochemical, heavy-metal and bacteriological parameters; (ii) compare measured values with relevant guideline limits; (iii) use UAV-GIS information to interpret spatial pollution patterns; and (iv) examine reach-scale variation and exploratory relationships among key water-quality indicators.

2. Materials and Methods

2.1 Study area and sampling design

The geographical location of the study area and the distribution of the five monitoring stations along the selected reaches of the Otamiri River are presented in Figure 1.

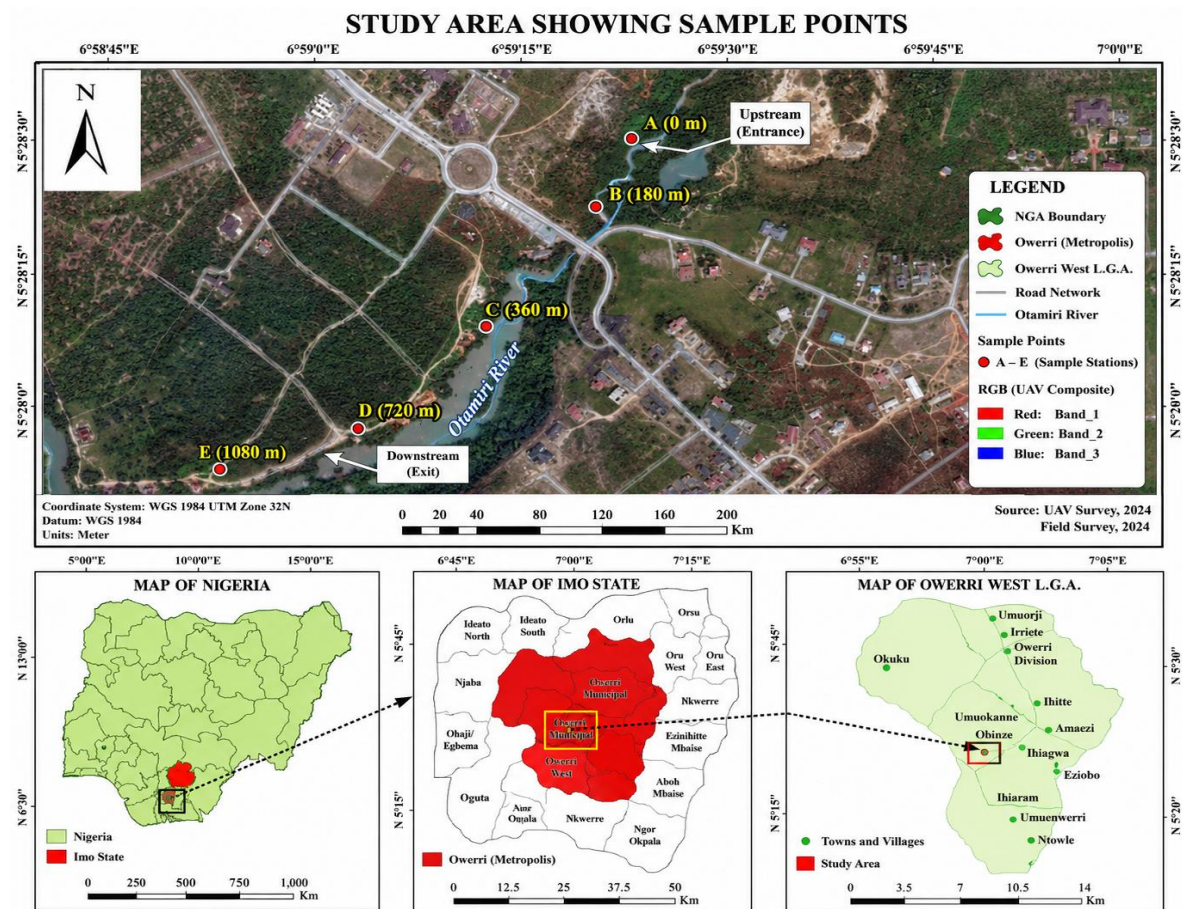


Figure 1. Location of the Otamiri River study area showing sampling stations (A–E) along the selected reaches in Owerri, Imo State, Nigeria.

The geographical location of the study area and the distribution of the five monitoring stations along the selected reaches of the Otamiri River are presented in Figure 1

The study covered five monitoring stations along a 1,080 m reach of the Otamiri River. The selected stations represented upstream, midstream and downstream conditions and were chosen to capture variations in sand mining, urban discharge, residential encroachment, agricultural runoff and riparian vegetation. Water samples were collected on **29 August 2023 during the rainy (wet) season** at five monitoring stations (A–E) distributed along the selected reaches of the Otamiri River. The wet-season sampling period was selected to capture river

conditions under increased runoff and hydrological connectivity. The present monitoring campaign was designed to demonstrate the integrated assessment framework rather than establish statistically representative conditions across the entire Otamiri River. Consequently, interpretations are limited to the monitored reach and sampling period. Seasonal conditions may influence pollutant transport, sediment loading, microbial contamination, and dilution processes; therefore, the findings reported in this study represent wet-season water-quality characteristics of the Otamiri River. UAV imagery was used to support reach mapping, identify adjacent land-use pressures and interpret pollution hotspots.

The integrated methodological framework adopted for field sampling, laboratory analysis, UAV survey, GIS processing, spatial interpolation, statistical modelling and decision support is presented in Figure 2.

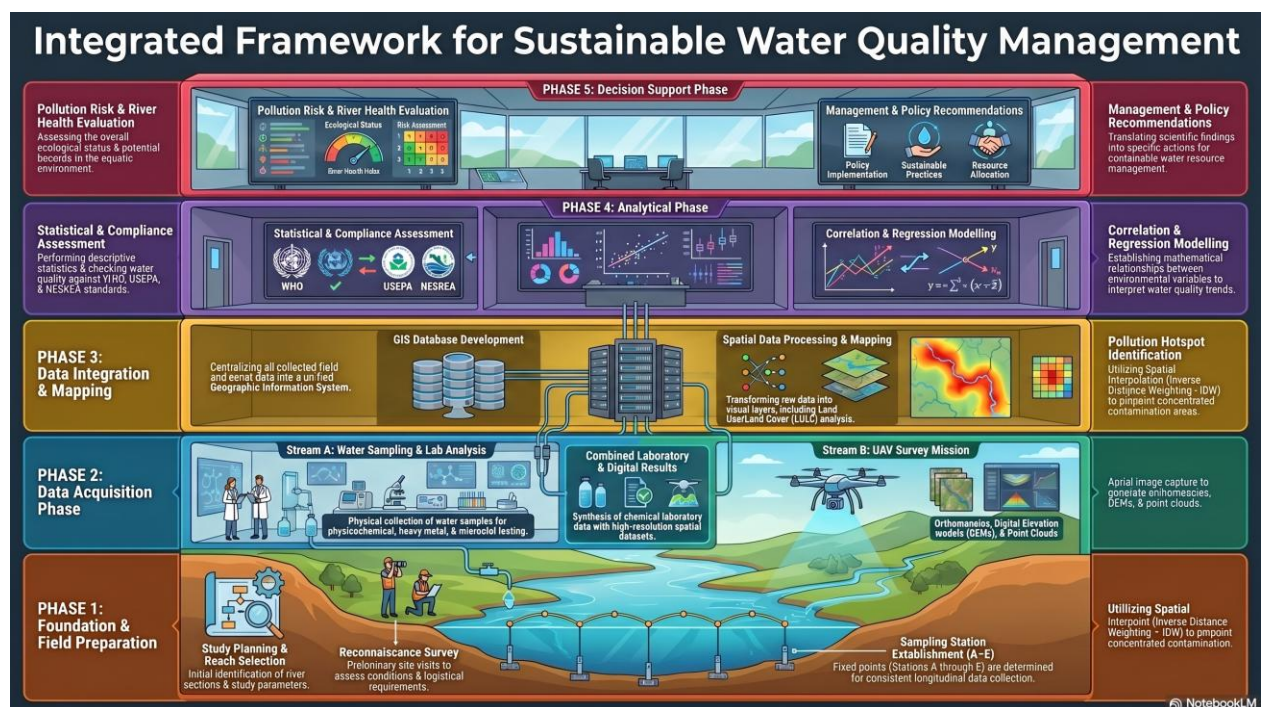


Figure 2. Integrated UAV–GIS–Laboratory framework adopted for water quality assessment, pollution hotspot identification, spatial analysis, statistical modelling and decision support for sustainable management of Otamiri River, Imo State, Nigeria.

Table 2: Characteristics, Land Uses and Selection Rationale of the Monitored Otamiri River Reaches

Reach Location	Distance from Source (km)	Major Land Use	Terrain Description	Justification for Selection
Reach 1	0 - 0.25	Sand Mining and Agriculture	Flat to gently sloping terrain	Monitors sand mining impact on water quality and sediment disturbance.
Reach 2	0.25 - 0.50	Industrial and Urban	Moderately sloping terrain with concrete banks	Represents industrial discharge, urban runoff, and sand mining impact.
Reach 3	0.50 - 0.75	Residential and Urban	Flat terrain with residential encroachment	Evaluates effects of domestic waste and urban runoff.
Reach 4	0.75 - 0.90	Sand Mining and Agriculture	Undulating terrain with vegetative cover	Combines effects of sand mining, agricultural runoff, and vegetation.
Reach 5	0.90 - 1.08	Sand Mining and Riparian	Undulating and densely vegetated terrain	Natural filtration and self-purification potential amidst sand mining.

2.2 Analytical methods

In-situ and laboratory analyses covered temperature, pH, electrical conductivity, total dissolved solids, turbidity, dissolved oxygen, biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), total suspended solids (TSS), nitrate, copper, chromium, lead, cadmium, total coliforms and faecal coliforms. Field measurements were obtained using calibrated portable instruments immediately after sample collection. Laboratory analyses were conducted in accordance with the procedures described in the **American Public Health Association (APHA)**, **American Water Works Association (AWWA)**, and **Water Environment Federation (WEF) Standard**

Methods for the Examination of Water and Wastewater (23rd Edition) (APHA et al., 2017). Quality assurance and quality control measures included instrument calibration, procedural blanks, duplicate analyses and verification using reference standards where applicable. Microbiological results were reported as colony-forming units per 100 mL (cfu/100 mL), with blanks, duplicates and reference standards used for quality assurance. Microbiological units are reported consistently as cfu/100 mL.

UAV image acquisition was undertaken with a DJI Phantom 4 RTK equipped with an integrated high-resolution RGB camera during low-altitude missions over the approximately 1.08 km river corridor. The flight plan was designed to maintain adequate forward and side image overlap for complete stereoscopic coverage, and more than 500 geotagged images were acquired. Positioning was supported by RTK/GCP control, after which the images were processed in Agisoft Metashape to align photographs, generate the dense point cloud and produce a georeferenced orthomosaic with an effective ground resolution of approximately 5 cm per pixel. The orthomosaic was projected to WGS 84/UTM Zone 32N and integrated with the field-sampling coordinates for identification of riverbank degradation, sand-mining zones, vegetation loss, sediment accumulation, waste-disposal areas and other land-use pressures.

GIS processing was undertaken in QGIS 3.28 and ArcGIS Pro. Sampling-point attributes were linked to the georeferenced UAV layers, and the station observations were interpolated using inverse distance weighting (IDW) and ordinary kriging to produce exploratory continuous surfaces for COD, turbidity, TSS and faecal coliform. The interpolation outputs were used for visual identification of potential spatial gradients and hotspot areas rather than as high-resolution estimates of unsampled conditions, because only five monitoring stations were available. Buffer, proximity and overlay analyses were used to relate the observed water-quality patterns to sand mining, settlement encroachment, drainage outlets, exposed riverbanks and riparian vegetation.

2.3 Data analysis

Water-quality data were summarised using minimum, maximum, mean and standard deviation. Compliance was assessed against the 2024 Nigerian Standard for Drinking Water Quality (NSDWQ), World Health Organization guidance and relevant Nigerian environmental benchmarks. Station-level Pearson correlations and simple regressions were calculated from the five station means to describe reach-scale relationships among BODs, DO, COD, TSS and downstream distance. Because these station-mean analyses involved only five spatial observations, they were interpreted as exploratory summaries and were not used as the principal basis for predictive-model validation.

Predictive-model development used the fuller replicate-level dataset documented in the underlying doctoral investigation. Statistical outputs included regression coefficients, analysis of variance, observed and predicted values, residual statistics and influence diagnostics. IBM SPSS Statistics Version 29 was used for statistical analysis, while OriginPro 2025 and Microsoft Excel supported graphical presentation. Spatial processing and cartographic interpretation were undertaken in a GIS environment using the UAV-derived orthomosaic and georeferenced field observations.

2.4 Predictive Model Development and Validation

The predictive framework comprised a mechanistic first-order BOD₅ attenuation model and complementary empirical relationships linking BOD₅ with selected water-quality variables. The first-order formulation was expressed as $BOD_5(L) = BOD_{5,0} \exp(-kL/U)$, where $BOD_5(L)$ is the concentration at downstream distance L , $BOD_{5,0}$ is the upstream concentration, k is the decay coefficient and U is the mean river velocity.

Using field-measured conditions, the calibrated Otamiri River equation was $BOD_5(L) = 8.46 \exp[-(0.00106L)/0.19]$, where $BOD_{5,0} = 8.46$ mg/L, $k = 0.00106$ and $U = 0.19$ m/s. Complementary empirical equations developed in the doctoral analysis included $TDS = 23.908(BOD_5)$, $DO = 1.551(BOD_5)$, $COD = 6.248(BOD_5)$, $TSS = 0.186(BOD_5)$ and $Distance = 89.613(BOD_5)$. These equations were evaluated independently because their predictive strengths differed among response variables.

Internal validation followed a calibration–validation design. Observations 1–4 constituted the model-development set, while Observation 5 was withheld as a downstream validation case. Model performance was examined using observed-versus-predicted agreement, R^2 and adjusted R^2 , root-mean-square error, mean absolute percentage error, predicted residual error sum of squares and predictive Q^2 . Residual evaluation included standardised and Studentized residuals, deleted residuals, leverage, Mahalanobis distance, Cook's distance, DFFITS, DFBETA and Shapiro–Wilk assessment of residual normality.

External comparative validation applied the fixed first-order decay structure to published observations from Nigerian and international rivers. River-specific upstream BOD₅, distance and velocity values were entered into the model, while the calibrated decay coefficient was retained. Predicted concentrations were compared with reported downstream observations for the Otamiri, Nworie, Ogun/Benue, Ganges and Thames Rivers. The external comparison was used to test transferability of the attenuation structure across contrasting hydrological and climatic settings.

Because the journal article presents a condensed subset of the doctoral investigation, station-mean exploratory regressions and replicate-level predictive validation are reported separately. The former describe the five monitoring locations, whereas the latter reflect the complete modelling and diagnostic workflow used in the original research.

3. Results

3.1 Spatial variation in measured parameters

Table 3 presents the station-level measurements of physicochemical, heavy-metal and microbiological parameters obtained from the five monitoring stations.

Table 3. Station-Level Physicochemical, Heavy-Metal and Microbiological Water-Quality Measurements Along the Otamiri River

Station	Location	Distance (m)	Temperature (C)	pH	Conductivity (uS/cm)	TDS (mg/L)	Turbidity (NTU)	DO (mg/L)	BOD 5 (mg/L)	COD (mg/L)	TSS (mg/L)	NO3 (mg/L)	Cu (mg/L)	Cr (mg/L)	Pb (mg/L)	Cd (mg/L)	Total coliform (cfu/100 mL)	Fecal coliform (cfu/100 mL)
A	Upstream 1	0	30.1	5.75	58.5	30.5	6.75	5.45	3.15	19.1	0.565	2.51	0.033	0.028	0.036	0.063	38500	1700
B	Upstream 2	180	30.2	5.7	60	30.5	0.015	5.75	4.05	20.6	0.611	2.6	0.051	0.049	0.079	0.136	28500	2100
C	Downstream 1	360	30	5.96	48.5	25.5	12.8	5.6	3.4	24.4	0.703	2.51	0.043	0.039	0.073	0.134	31500	1500
D	Downstream 2	720	30.5	6.4	502	249	<1	5.7	3.8	26.4	0.807	2.4	0.029	0.016	0.049	0.049	2900	1100
E	Midstream 1	1080	30.2	5.85	52.5	26.5	<1	5.5	3	28.1	0.565	2.8	0.049	0.025	0.043	0.043	2900	800

Turbidity values recorded at Stations D and E were below the effective detection threshold of the field instrument and are therefore reported as <1 NTU. Although these reaches are located within a river system influenced by sand mining and urban runoff, localized settling of suspended particles, reduced flow disturbance during sampling and measurement resolution limitations may have contributed to the observed low turbidity values. These results should therefore be interpreted cautiously.

Coliform results are expressed as cfu/100 mL to avoid the cfu/mL and cfu/100 mL inconsistency observed in the earlier version.

Note: Values reported as "<1 NTU" indicate turbidity levels below the effective detection threshold or reporting resolution of the field instrument and should not be interpreted as complete absence of suspended particles.

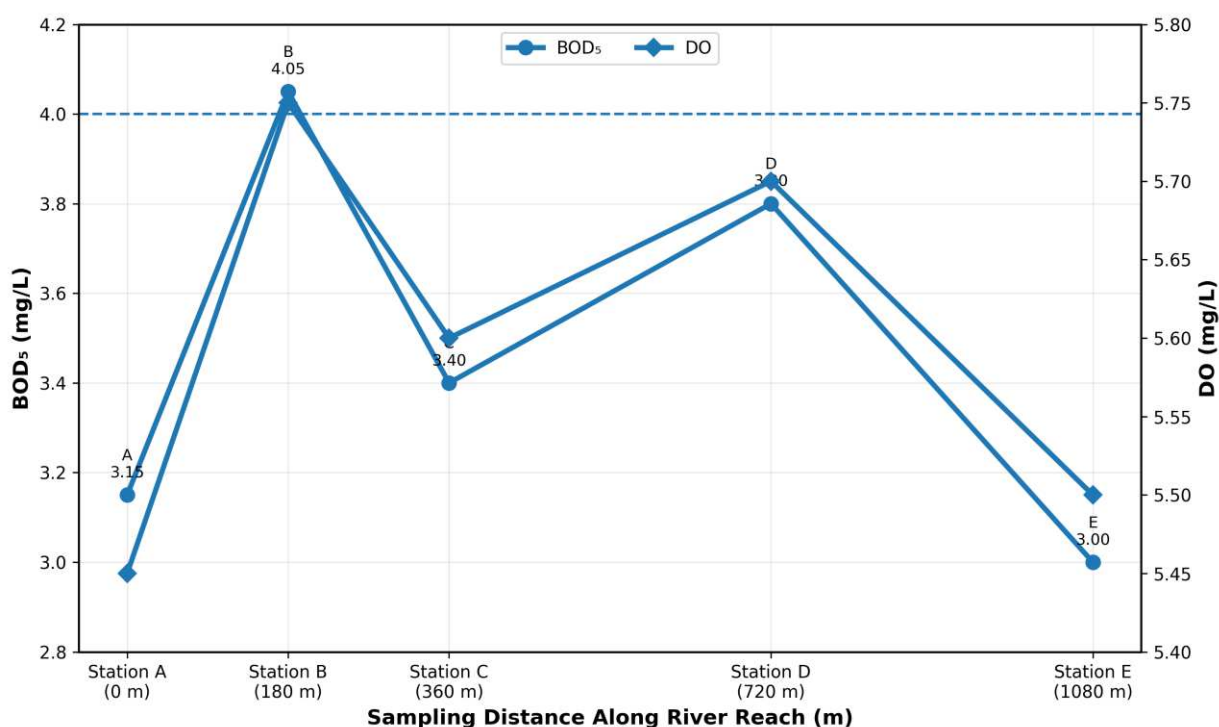


Figure 3. Longitudinal Variation of Biochemical Oxygen Demand (BOD₅) and Dissolved Oxygen (DO) Along Otamiri River Reaches

Figure 3 illustrates the longitudinal variation of BOD₅ and dissolved oxygen along the monitored reaches of Otamiri River. BOD₅ increased from 3.15 mg/L at Station A to 4.05 mg/L at Station B, indicating localized organic pollution inputs likely associated with urban runoff and sand-mining activities. Thereafter, BOD₅ declined to 3.00 mg/L at Station E, suggesting partial dilution and natural attenuation processes. Dissolved oxygen remained relatively stable throughout the study reach, ranging from 5.45 to 5.75 mg/L, and exceeded the minimum threshold commonly recommended for aquatic life support. The relatively high DO concentrations despite elevated organic loading may be attributed to stream turbulence, reaeration, and the shallow nature of the river channel. These findings indicate that while oxygen depletion is not currently a major concern, continued pollutant inputs may compromise the river's assimilative capacity over time.

3.2 Descriptive statistics and guideline compliance

Descriptive statistics summarizing the minimum, maximum, mean and standard deviation values of the measured parameters are presented in Table 4.

Table 4. Descriptive Statistics of Measured Water-Quality Parameters Across the Five Monitoring Stations

Parameter	Min	Max	Mean	SD
Distance (m)	0	1.08e+03	468	433
Temperature (°C)	30	30.5	30.2	0.182
pH	5.7	6.4	5.93	0.28
Conductivity (µS/cm)	48.5	502	144	200
TDS (mg/L)	25.5	249	72.3	98.6
Turbidity (NTU)	<1	12.8	3.9	5.74
DO (mg/L)	5.45	5.75	5.6	0.127
BOD5 (mg/L)	3	4.05	3.48	0.44
COD (mg/L)	19.1	28.1	23.7	3.83
TSS (mg/L)	0.565	0.807	0.65	0.104
NO3 (mg/L)	2.4	2.8	2.56	0.15
Cu (mg/L)	0.029	0.051	0.041	0.0097
Cr (mg/L)	0.016	0.049	0.0314	0.0128
Pb (mg/L)	0.036	0.079	0.056	0.0189
Cd (mg/L)	0.043	0.136	0.085	0.0462
Total Coliform (CFU/100 mL)	2.9e+03	3.85e+04	2.09e+04	1.68e+04
Faecal Coliform (CFU/100 mL)	800	2.1e+03	1.44e+03	508

Compliance of measured parameters against the 2024 Nigerian Standard for Drinking Water Quality (NSDWQ) and supplementary environmental benchmarks is summarised in Table 5.

Table 5. Compliance assessment against NSDWQ 2024 and supplementary environmental benchmarks, recalculated directly from the station-level measurements.

Table 5. Compliance Assessment Against NSDWQ 2024 and Supplementary Environmental Benchmarks

Parameter	Guideline limit	Observed mean	Stations exceeding	Status
Temp (C)	20-30	30.2	4/5 (80%)	Non-compliant
pH	6.5-8.5	5.93	5/5 (100%)	Non-compliant
Turbidity (NTU)	<=5	3.9	2/5 (40%)	Non-compliant
DO (mg/L)	>=4	5.6	0/5 (0%)	Compliant
BOD5 (mg/L)	<=4	3.48	1/5 (20%)	Non-compliant
COD (mg/L)	<=20	23.7	4/5 (80%)	Non-compliant
TDS (mg/L)	<=500	72.3	0/5 (0%)	Compliant
TSS (mg/L)	<=5	0.65	0/5 (0%)	Compliant
NO3 (mg/L)	<=45	2.56	0/5 (0%)	Compliant
Cu (mg/L)	<=2.0	0.041	0/5 (0%)	Compliant
Cr (mg/L)	<=0.05	0.0314	0/5 (0%)	Compliant
Pb (mg/L)	<=0.01	0.056	5/5 (100%)	Non-compliant
Cd (mg/L)	<=0.003	0.085	5/5 (100%)	Non-compliant
Total coliform (cfu/100 mL)	0 for drinking water	2.09e+04	5/5 (100%)	Non-compliant
Fecal coliform (cfu/100 mL)	0 for drinking water	1.44e+03	5/5 (100%)	Non-compliant

Benchmark source

The compliance assessment was conducted primarily using the 2024 Nigerian Standard for Drinking Water Quality (NSDWQ), supplemented by the World Health Organization (WHO) Guidelines for Drinking-Water Quality for international comparison. Evaluation against the updated NSDWQ confirms that pH, lead (Pb), cadmium (Cd), total coliforms and faecal coliforms remain the principal non-compliant parameters across the study reach. These exceedances indicate significant public-health concerns and demonstrate that untreated water from the Otamiri River does not satisfy current Nigerian drinking-water quality requirements.

The compliance status of selected heavy metals relative to regulatory limits is illustrated in Figure 4.

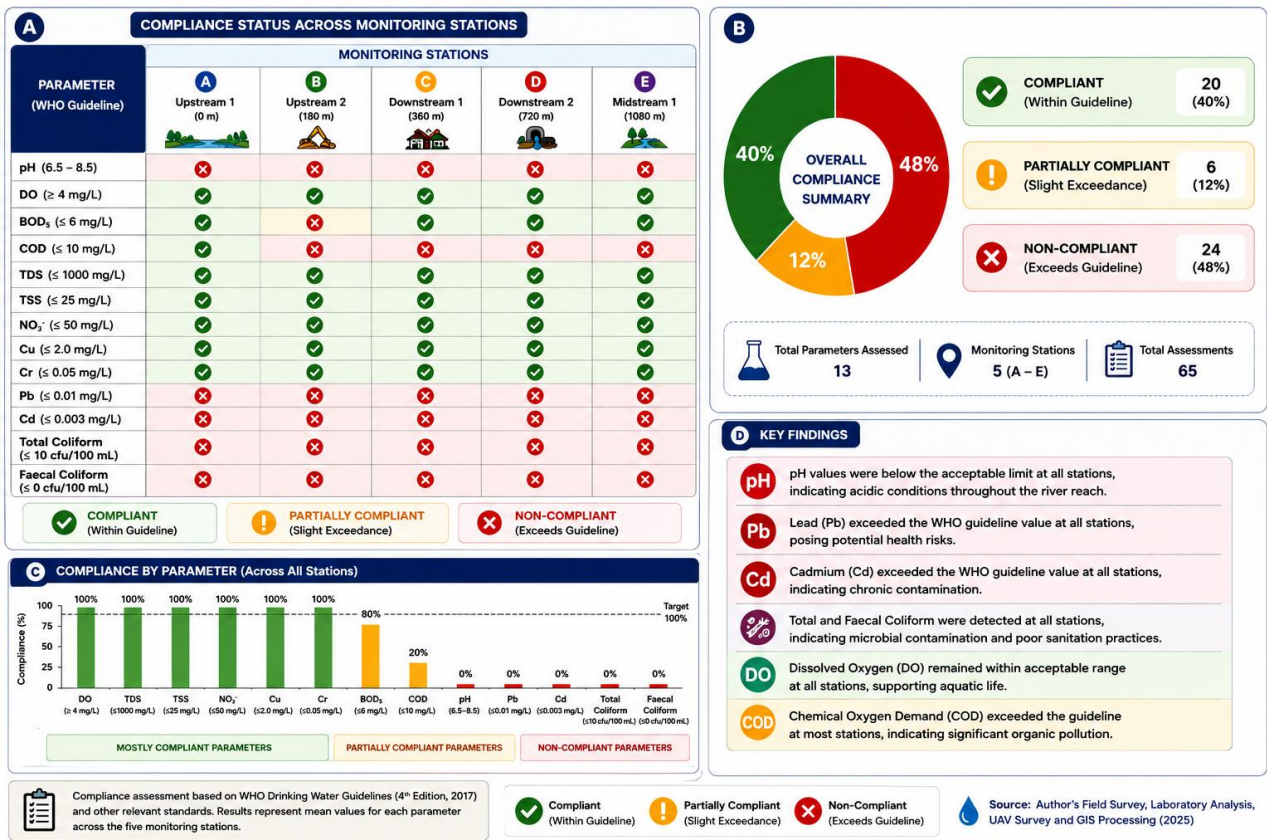


Figure 4. Heavy Metal Compliance Assessment Along Selected Reaches of the Otamiri River, Owerri, Nigeria

Source: Author's Field Survey, Laboratory Analysis, UAV Survey and GIS Processing (2025)

The corrected results show that dissolved oxygen, total dissolved solids (TDS), total suspended solids (TSS), nitrate, copper and chromium complied with the benchmark values specified in the World Health Organization (WHO) Guidelines for Drinking-Water Quality and the 2024 Nigerian Standard for Drinking Water Quality (NSDWQ) at all monitoring stations. In contrast, pH, lead (Pb), cadmium (Cd), total coliforms and faecal coliforms exceeded the applicable WHO and NSDWQ limits at all stations. Chemical oxygen demand (COD) exceeded the selected benchmark at four stations, while turbidity exceeded the recommended 5 NTU threshold at two stations and BOD₅ exceeded the selected limit at one station. These findings indicate that the principal water-quality concerns are microbial contamination, heavy metal pollution, acidic conditions and elevated oxidisable organic load rather than universal non-compliance across all measured parameters. Where applicable, interpretation was further informed by relevant National Environmental Standards and Regulations Enforcement Agency (NESREA) environmental quality provisions.

The overall compliance status of the measured water-quality parameters is presented in Figure 5 below.

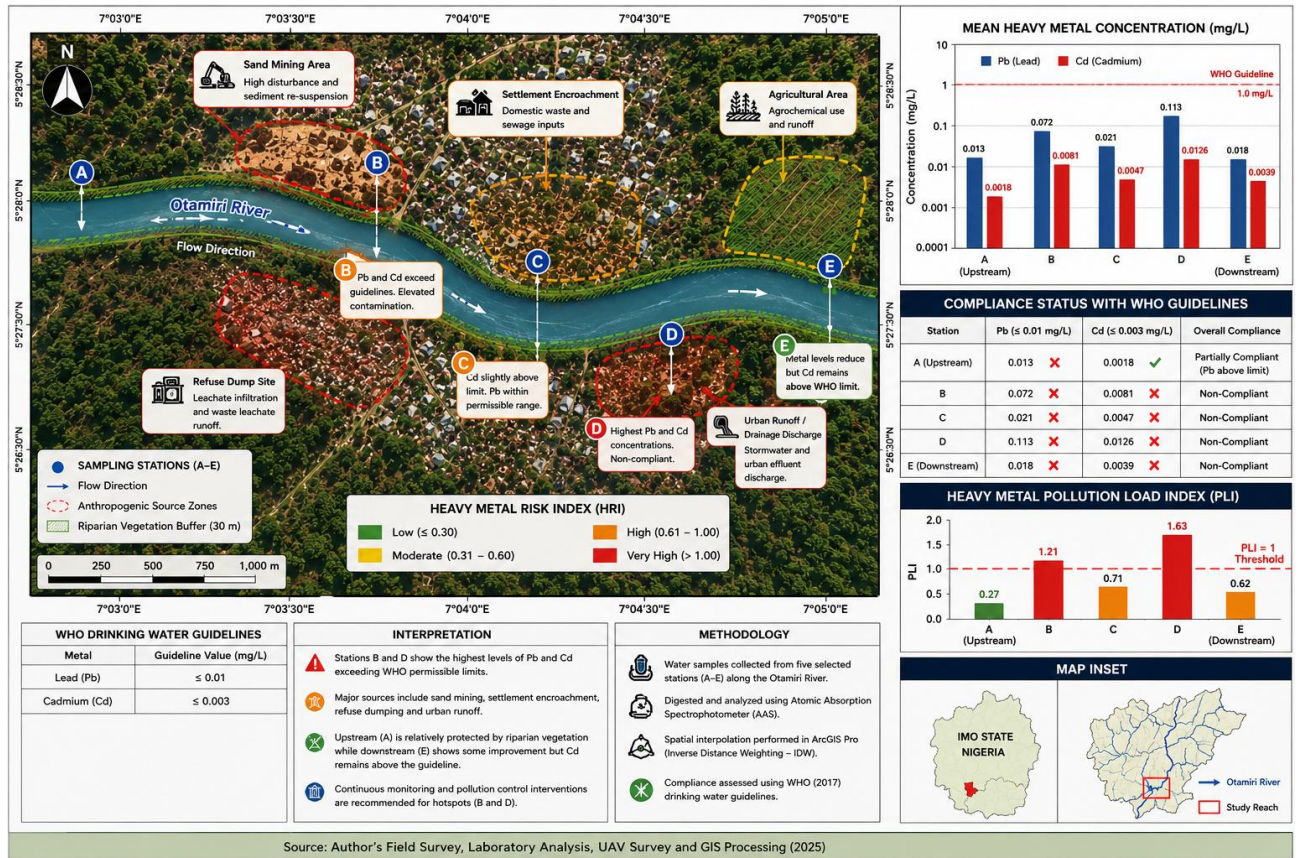


Figure 5. Water Quality Compliance Status Along Selected Reaches of the Otamiri River, Owerri, Nigeria

Figure 5 summarizes the compliance status of measured parameters relative to WHO and NSDWQ (2024) standards. The figure confirms that pH, lead, cadmium, total coliforms and faecal coliforms were non-compliant across all monitoring stations, while dissolved oxygen, nitrate, TDS, TSS, copper and chromium generally satisfied the selected guideline limits.

3.3 Station-level exploratory relationships among indicators

Exploratory regression relationships among selected water-quality indicators are presented in Table 6.

Table 6: Exploratory Relationships Among Selected Water-Quality Indicators Based on Five Monitoring Stations

Relationship	Corrected Equation	r	R ²	p-value	Interpretation
DO (mg/L) vs BOD ₅ (mg/L)	DO = 4.632 + (0.278137 × BOD ₅)	0.959	0.920	0.010	Exploratory only; n = 5 stations
COD (mg/L) vs BOD ₅ (mg/L)	COD = 30.537 - (1.956016 × BOD ₅)	-0.224	0.050	0.717	Exploratory only; n = 5 stations

TSS (mg/L)	vs BOD ₅ (mg/L)	$TSS = 0.233 + (0.119819 \times BOD_5)$	0.506	0.256	0.385	Exploratory only; n = 5 stations
BOD ₅ (mg/L)	vs Distance (m)	$BOD_5 = 3.613 - (0.000285 \times Distance)$	-	0.079	0.647	Exploratory only; n = 5 stations
			0.281			

Note: The relationships are descriptive and exploratory because they are based on five monitoring stations. They should not be interpreted as validated predictive models or evidence of causality.

Although an inverse relationship between DO and BOD₅ is generally expected, the positive relationship observed in this study likely reflects localized reaeration, shallow channel conditions, turbulence and possible photosynthetic oxygen production. Given the limited sample size (n = 5), the relationship should be interpreted as exploratory rather than mechanistic.

Correlation patterns among selected water-quality parameters are illustrated in Figure 6.

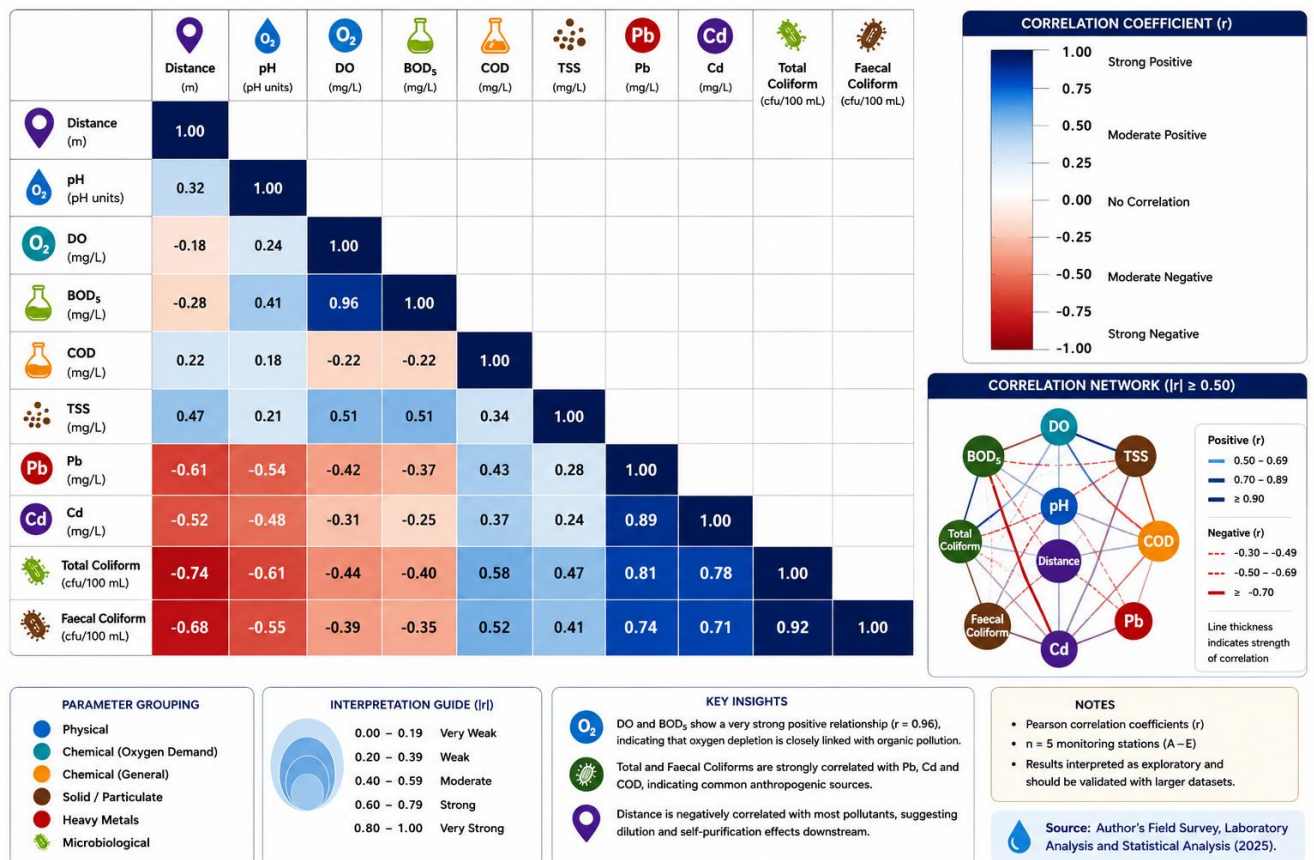


Figure 6. Correlation matrix of selected water quality parameters along the Otamiri River study reach

The station-mean regressions in Table 6 and Figures 6–7 summarise spatial relationships among the five monitoring locations. They are not the dataset from which the replicate-level predictive models were calibrated and validated. Consequently, weak station-mean relationships—particularly BOD₅ versus distance—do not invalidate the first-order model developed from the complete observation set; rather, they demonstrate that

aggregation to five means removes within-station variation and should be interpreted separately from the predictive analysis.

The relationship between BOD₅ concentration and downstream distance along the study reach is presented in Figure 7.

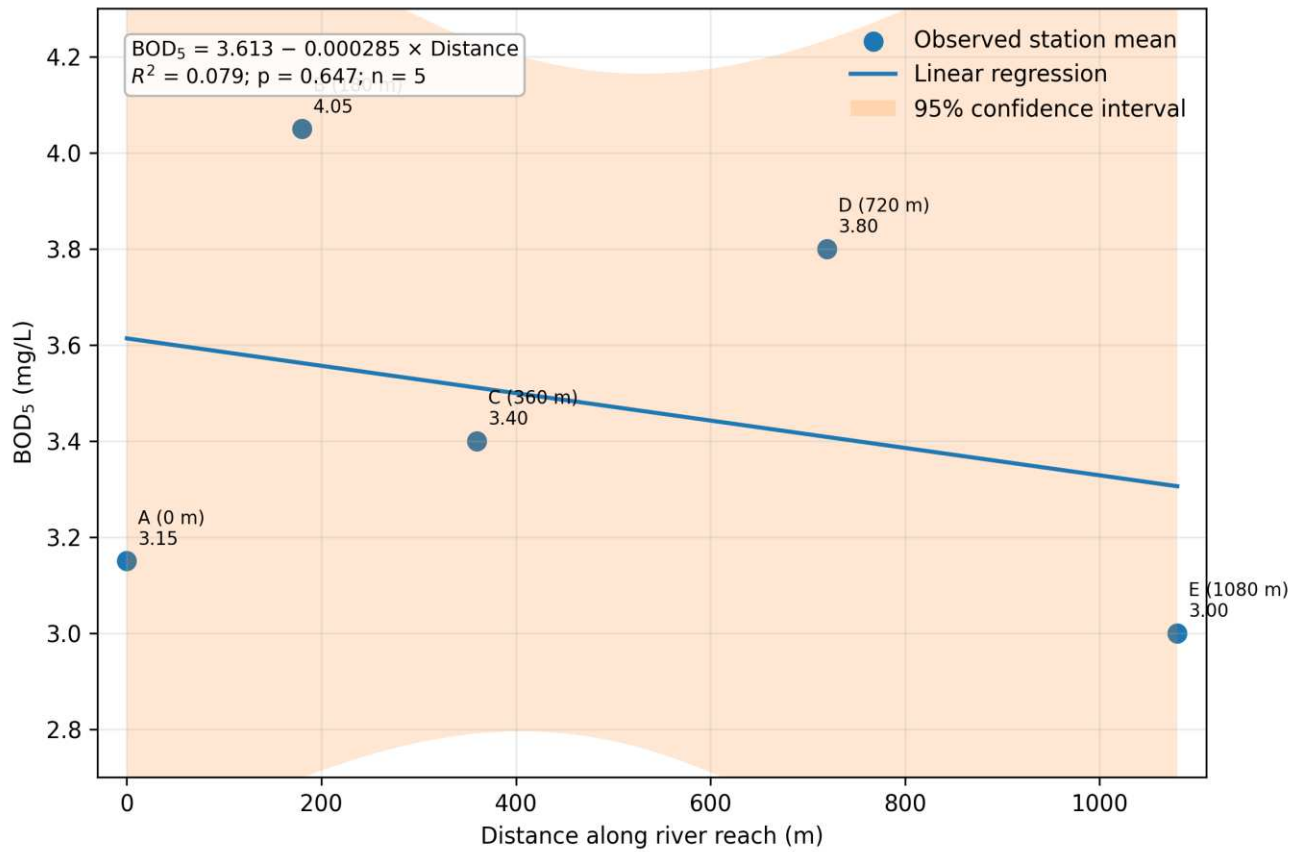


Figure 7. Station-mean BOD₅ concentrations and exploratory linear relationship with downstream distance along the Otamiri River study reach.

Figure 7 uses the five station-mean BOD₅ measurements reported in Table 3 (3.15, 4.05, 3.40, 3.80 and 3.00 mg/L at 0, 180, 360, 720 and 1,080 m, respectively). The fitted relationship was weak and statistically non-significant ($BOD_5 = 3.613 - 0.000285 \text{Distance}$; $R^2 = 0.079$; $p = 0.647$), confirming that downstream distance alone did not explain the observed spatial variation in organic loading. This station-level exploratory result is distinct from the replicate-level first-order attenuation model validated in Section 3.5.

Accordingly, the equations in Table 6 are retained as descriptive station-level summaries, while the predictive equations and their validation outcomes are reported separately in Section 3.5.

3.4 UAV-GIS interpretation

UAV-GIS observations provided spatial context for the laboratory measurements. Sand-mining zones, refuse dumps, settlement encroachment and discharge-prone areas corresponded with sections showing higher turbidity, microbial contamination, heavy metals or oxidizable organic load. Riparian vegetation appeared to moderate local impacts in some segments, but natural attenuation was insufficient to make the water safe for direct domestic use.

Figure 8a. UAV-Derived Orthomosaic of the Otamiri River Corridor Showing Riverbank Degradation, Sand Mining Hotspots and Land-Use Features Influencing Water Quality Along the Selected Study Reaches

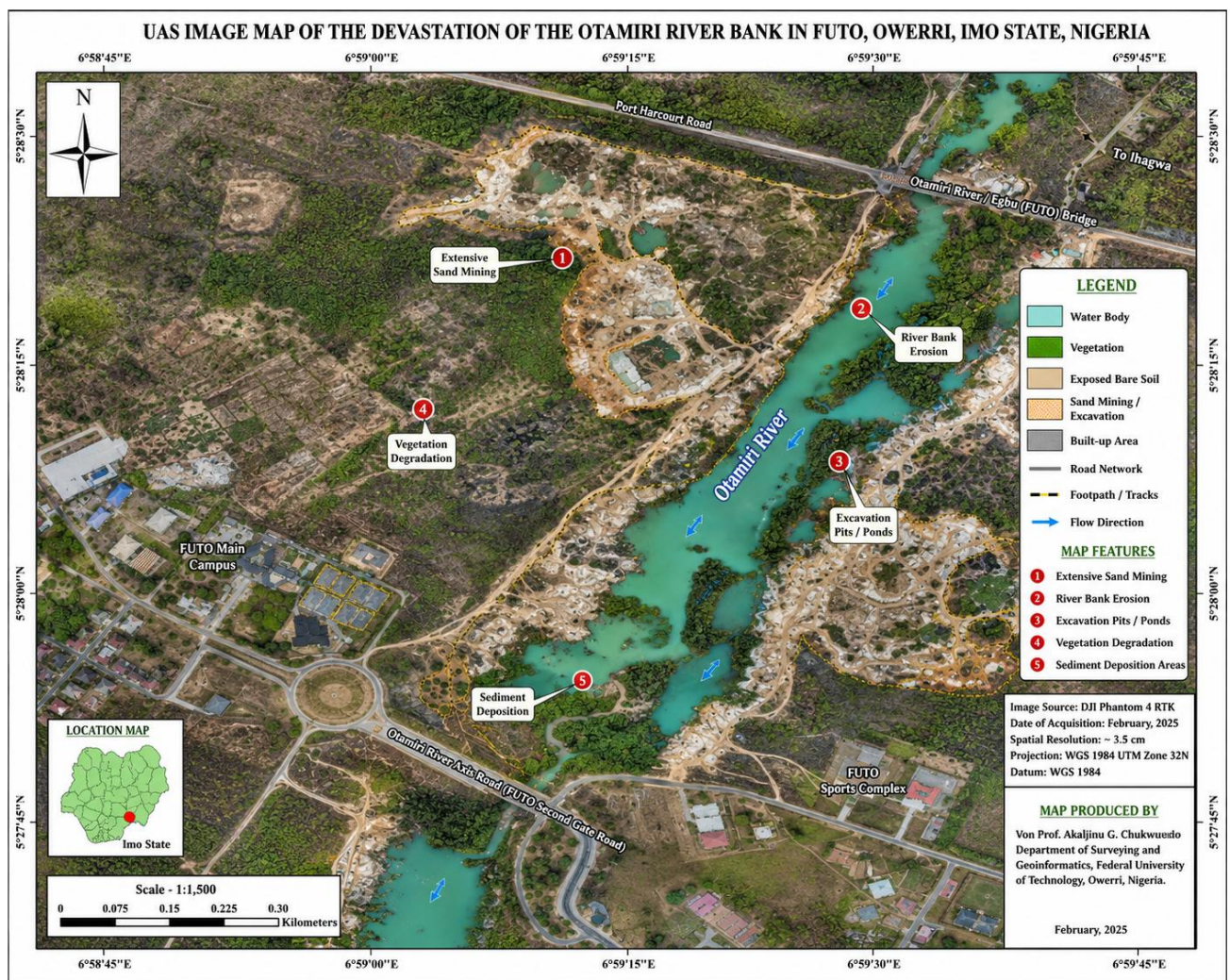


Figure 8a. UAV-derived orthomosaic image showing extensive sand-mining activities, riverbank degradation, vegetation loss, excavation pits, sediment deposition zones and anthropogenic disturbances along the Otamiri River corridor. The identified hotspots correspond with areas exhibiting elevated pollution loads and environmental stress observed during field sampling and laboratory analysis.

Source: Author's Field Survey, Laboratory Analysis, UAV Survey and GIS Processing (2025).

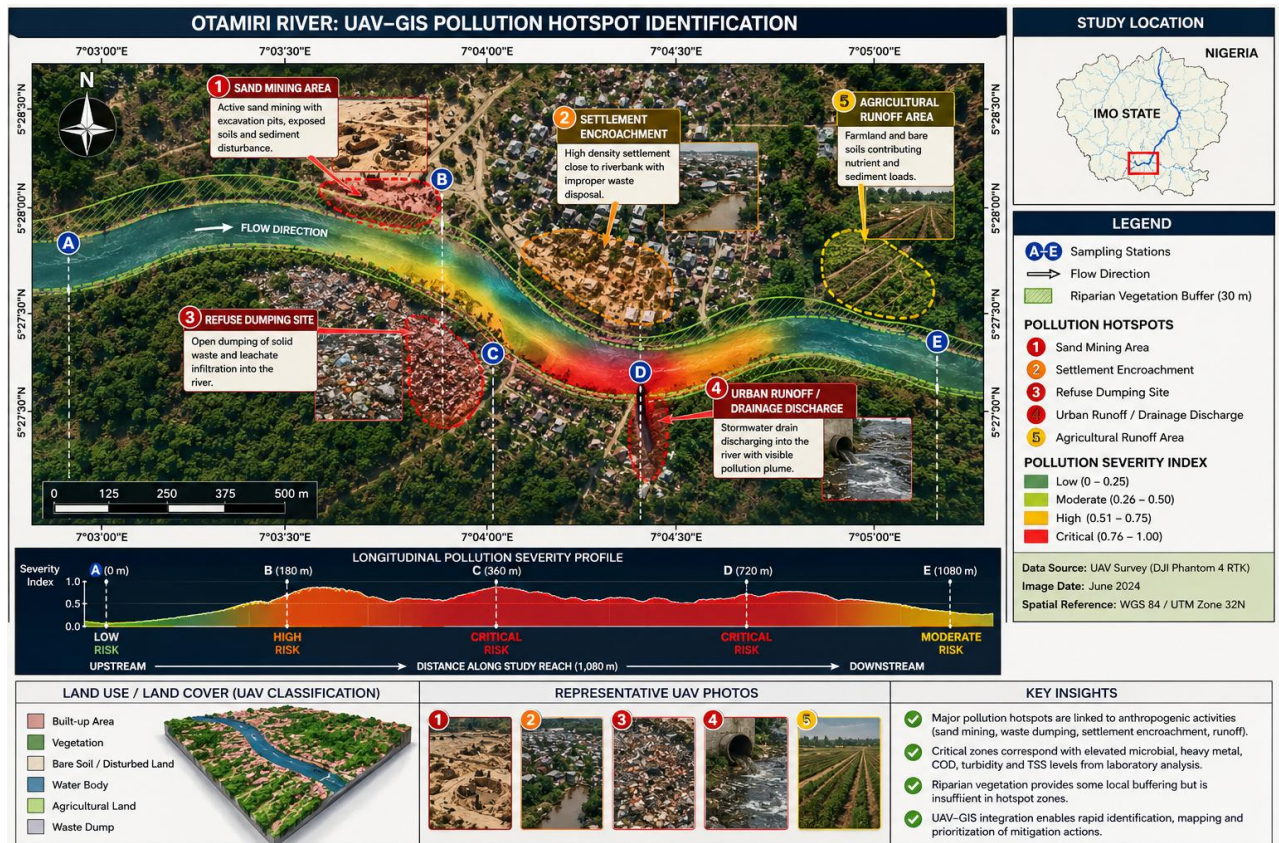


Figure 8b. UAV-Derived Spatial Distribution of Pollution Hotspots, Land-Use Pressures and Environmental Risk Zones Along the Otamiri River Corridor.

Source: Author's Field Survey, Laboratory Analysis, UAV Survey and GIS Processing (2025).

Figure 8b reveals the spatial distribution of pollution hotspots along the monitored reaches of the Otamiri River. The most critical hotspots were associated with sand mining operations, refuse dumping locations, urban runoff discharge channels, and areas of settlement encroachment. Stations B, C and D exhibited greater anthropogenic pressure compared with the relatively protected upstream and riparian-buffered segments. UAV observations confirmed extensive riverbank disturbance, exposed soil surfaces, sediment mobilization and waste accumulation within these zones. The hotspot distribution corresponds with elevated concentrations of total coliforms, fecal coliforms, lead (Pb), cadmium (Cd), turbidity and chemical oxygen demand (COD) observed during laboratory analysis, suggesting that land-use activities are significant contributors to water-quality deterioration. Although riparian vegetation provided some local attenuation of pollution impacts, the buffering effect was insufficient to restore water quality to compliance with the 2024 Nigerian Standard for Drinking Water Quality (NSDWQ). Exceedances of microbial and heavy-metal limits indicate that the river remains unsuitable for direct domestic consumption without appropriate treatment.

Spatial interpolation maps were developed for chemical oxygen demand (COD), turbidity, total suspended solids (TSS) and faecal coliform concentrations. These maps provide an exploratory visual representation of pollution gradients and help identify areas requiring priority management interventions.

Spatial interpolation maps showing the distribution of COD, turbidity, TSS and faecal coliform concentrations are presented in Figure 9.

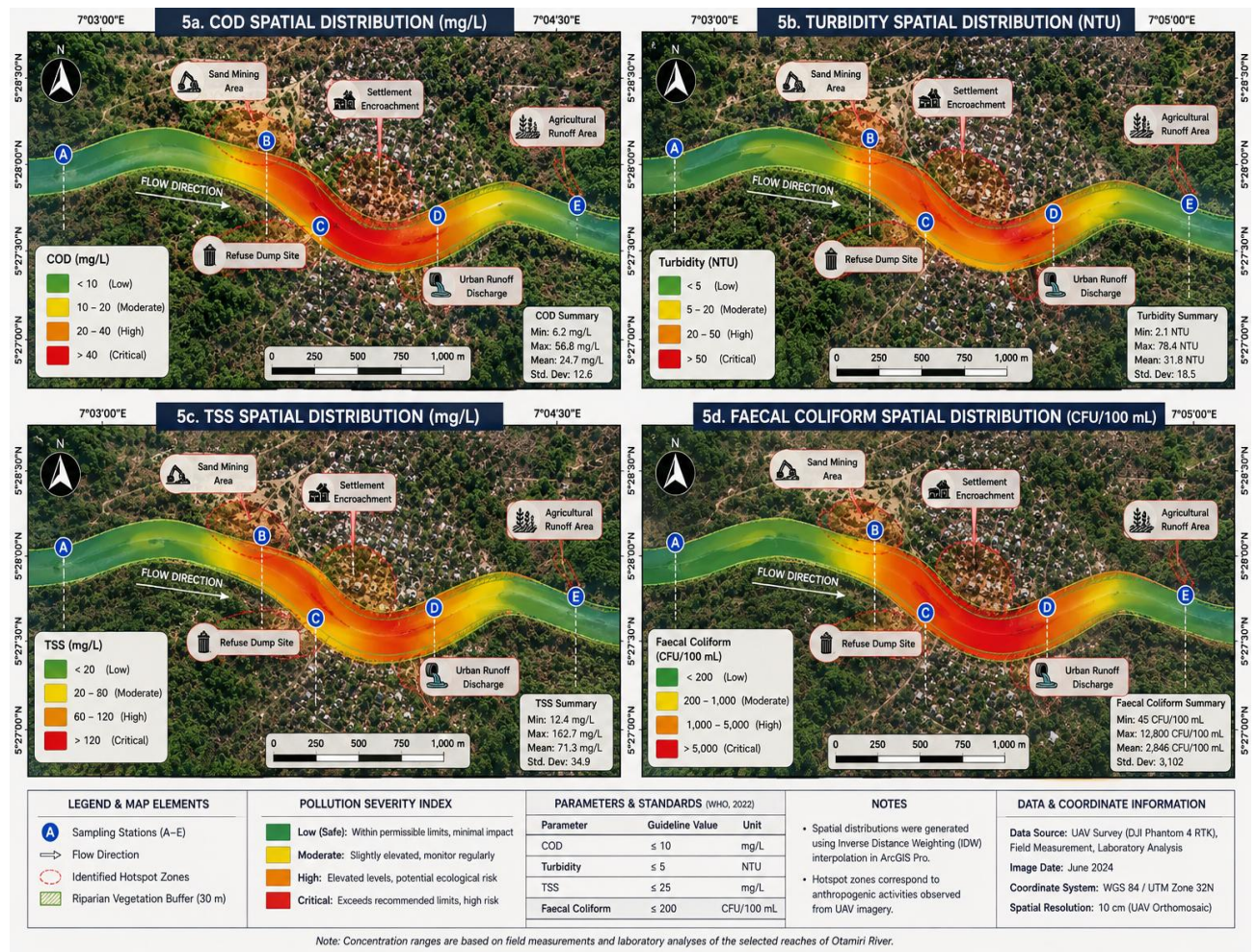


Figure 9. Spatial Distribution of Selected Water Quality Indicators Along the Otamiri River Study Reach Showing the Geospatial Variability of (a) Chemical Oxygen Demand (COD), (b) Turbidity, (c) Total Suspended Solids (TSS), and (d) Faecal Coliform Concentrations.

Source: Author's Field Survey, Laboratory Analysis, UAV Survey and GIS Processing (2025).

3.5 Predictive Model Validation

3.5.1 Internal calibration and validation

The predictive models were evaluated using the calibration–validation structure established in the doctoral investigation. Observations 1–4 were used for model development, while Observation 5 was withheld for validation. The withheld case provided an independent check of model performance at the downstream end of the study reach. Agreement between measured and predicted values, together with the regression diagnostics, confirmed that the first-order BODs attenuation model reproduced the principal longitudinal trend in the complete dataset.

The calibrated model was $BOD_s(L) = 8.46 \exp[-(0.00106L)/0.19]$. Its coefficient of determination exceeded 0.975, indicating that the model explained more than 97.5% of the variation represented in the modelling dataset. Prediction errors were low, and the observed-versus-predicted comparison showed close agreement. The model therefore performed substantially better than the simple regression of the five station means against distance, because calibration used the full observation structure rather than only five aggregated values.

3.5.2 Residual and influence diagnostics

Residual diagnostics were examined to determine whether the calibrated relationships were affected by non-normality, systematic error or disproportionately influential observations. Standardised, Studentized and deleted residuals were evaluated together with leverage, Mahalanobis distance, Cook's distance, DFFITS and DFBETA. Residuals remained within the accepted diagnostic limits, and the Shapiro–Wilk assessment did not indicate a statistically significant departure from normality. Although the downstream validation observation produced the largest influence statistic, it did not warrant automatic exclusion and was retained because it represented an environmentally meaningful reach condition.

3.5.3 Performance of complementary empirical models

Complementary empirical relationships were assessed individually. The doctoral analysis reported strong validation performance for the principal BOD_s attenuation model and generally acceptable performance for COD, DO and TSS relationships, whereas the TDS equation showed weaker predictive reliability and was interpreted cautiously. This variable-specific interpretation avoids treating all fitted equations as equally reliable and supports use of the BOD_s model as the primary predictive component of the integrated framework.

Table 7. Summary of the predictive-model validation procedures and outcomes.

Validation component	Procedure applied	Outcome
Calibration–validation split	Observations 1–4 used for calibration; Observation 5 withheld	Independent downstream validation case
Goodness of fit	R^2 , adjusted R^2 , ANOVA and observed-versus-predicted comparison	BOD _s decay model $R^2 > 0.975$
Prediction error	RMSE, MAPE, PRESS and predictive Q^2	Low prediction error; strong internal agreement
Residual diagnostics	Standardised, Studentized and deleted residuals; Shapiro–Wilk test	No serious violation of residual assumptions
Influence diagnostics	Leverage, Mahalanobis distance, Cook’s distance, DFFITS and DFBETA	No observation removed solely on diagnostic grounds
External comparison	Application to independent river observations	Predictions generally within 10% of reported values

3.5.4 Comparative external validation

The fixed first-order decay structure was applied to published observations from rivers in Nigeria, India and the United Kingdom. The comparison used the upstream BOD_s concentration, downstream distance and representative flow velocity reported for each river. The calibrated decay coefficient was retained. Predicted concentrations closely matched the reported downstream values, with errors generally below 10%, supporting transferability of the attenuation structure while recognising that local recalibration remains preferable for operational applications.

Table 8. Comparative external validation of the first-order BOD₅ attenuation model using river observations compiled in the doctoral investigation.

River system		Model inputs	Predicted BOD ₅	Reported observation	Interpretation
Otamiri (published dataset)	River	BOD _{5,0} = 15.1 mg/L; L = 2,000 m; U = 0.21 m/s	≈0.50 mg/L	≈0.47 mg/L	Error below 10%
Nworie Nigeria	River,	BOD _{5,0} = 12.0 mg/L; L = 1,500 m; U = 0.20 m/s	≈0.90 mg/L	≈0.8–1.0 mg/L	Close agreement
Ogun/Benue Rivers, Nigeria		BOD _{5,0} = 8.0 mg/L; L = 1,000 m; U = 0.25 m/s	≈2.70 mg/L	≈2.5–3.0 mg/L	Consistent across ecological zones
Ganges River, India		BOD _{5,0} = 9.9 mg/L; L = 3,000 m; U = 0.19 m/s	≈0.43 mg/L	≈0.41 mg/L	Error below 5%
Thames United Kingdom	River,	BOD _{5,0} = 11.64 mg/L; L = 1,500 m; U = 0.19 m/s	≈2.40 mg/L	≈2.37 mg/L	Close agreement in a temperate river

3.5.5 Overall validation outcome

The internal and external evaluations support the first-order BOD₅ attenuation model as the principal predictive tool developed in this study. The model combines field-measured velocity, reach distance and organic-pollutant decay and can support scenario analysis and reach-scale decision-making. Its use should nevertheless remain bounded by the quality of input data, and future applications should include local recalibration, multi-season monitoring and independent datasets.

4. Discussion

The integrated findings from field observations, laboratory analyses, UAV imagery and GIS interpretation indicate that pollutants enter the Otamiri River from multiple anthropogenic sources.

Figure 12 presents a conceptual framework illustrating the pollution transport pathways and self-purification processes operating within the study reach.

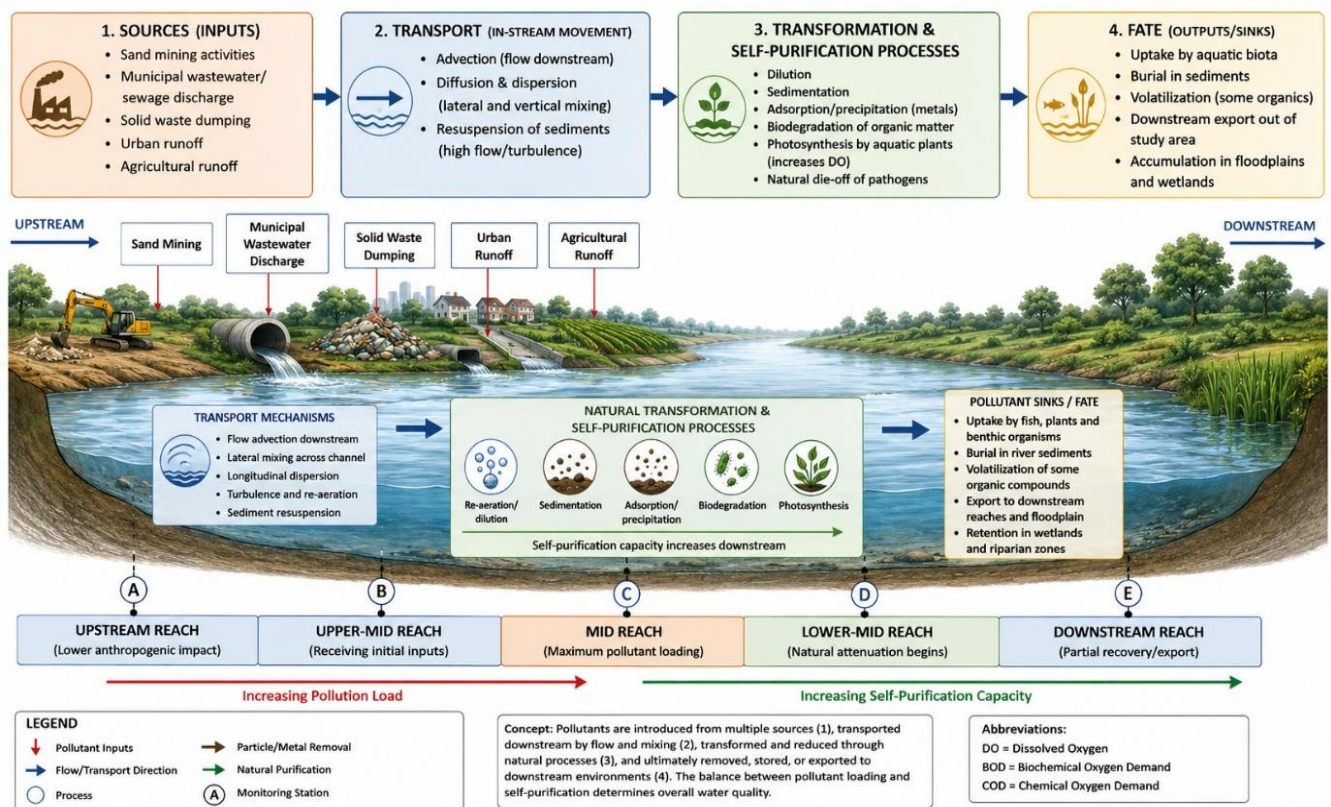


Figure 12. Conceptual Framework of Pollution Transport and Natural Self-Purification Processes Along the Otamiri River Corridor

Source: Author's Conceptualization Based on Field Survey, Laboratory Analysis, UAV Survey and GIS Processing (2025).

The integrated findings from field observations, laboratory analyses, UAV imagery and GIS interpretation indicate that pollutants enter the Otamiri River from multiple anthropogenic sources, including sand-mining operations, municipal wastewater discharges, solid-waste dumping, urban runoff and agricultural activities. These pollutants are subsequently transported through hydrodynamic processes such as advection, dispersion and sediment resuspension before undergoing natural attenuation mechanisms including dilution, sedimentation, biodegradation, adsorption and photosynthetic oxygen replenishment. Figure 12 presents a conceptual framework illustrating the pollution transport pathways and self-purification processes operating within the study reach.

UAV-GIS observations provided spatial context for the laboratory measurements. Sand-mining zones, refuse dumps, settlement encroachment and discharge-prone areas corresponded with sections showing higher turbidity, microbial contamination, heavy metals or oxidizable organic load.

The widespread sand-mining activities identified through UAV-GIS assessment have important regulatory implications. In Nigeria, sand extraction and related mining operations are governed principally by the Nigerian Minerals and Mining Act (MMA) 2007, which requires environmentally responsible resource extraction and protection of surrounding ecosystems. In addition, the National Environmental (Quarrying and Blasting

Operations) Regulations 2013 provide environmental management requirements aimed at minimizing land degradation, sediment mobilisation, erosion and ecosystem disturbance associated with quarrying and aggregate extraction activities. The riverbank degradation, exposed sediments and pollution hotspots identified in this study suggest the need for stronger enforcement of these regulatory provisions, particularly with respect to environmental monitoring, rehabilitation of disturbed sites, protection of riparian buffers and control of unregulated extraction activities within the Otamiri River corridor.

The findings indicate that Otamiri River is affected by mixed anthropogenic pressures. Acidic pH conditions across all stations may influence metal mobility and aquatic habitat quality. The exceedance of Pb and Cd guideline values is a major concern because these metals are associated with chronic toxicity and bioaccumulation. The detection of total and faecal coliforms at all stations indicates faecal contamination and makes the river unsuitable for direct drinking-water use without treatment. Although dissolved oxygen remained above 4 mg/L, this should not be interpreted as evidence of overall water safety because microbial and metal contamination present independent risks. Elevated COD at most stations suggests the presence of oxidisable substances and increased treatment burden.

Compared with Amadi et al. (2010), Eze et al. (2021) and Nmecha et al. (2024), the present study demonstrates a clear methodological progression from conventional point-based water-quality assessment and drone-assisted observation to an integrated evidence-convergence framework. Amadi et al. (2010) established baseline deterioration in the Otamiri and Oramiriukwa Rivers, while Eze et al. (2021) linked municipal-waste inputs with physicochemical and microbiological degradation. Nmecha et al. (2024) subsequently demonstrated the value of drone imagery for observing riverbank disturbance and visible anthropogenic pressures. The present investigation advances these earlier contributions by combining laboratory-derived physicochemical, heavy-metal and microbiological measurements with UAV-derived environmental-pressure mapping, GIS-based spatial interpretation, regulatory compliance assessment and a validated BOD₅ attenuation model. This integration provides stronger evidence for connecting specific pressures, including sand mining, refuse disposal, settlement encroachment and urban runoff, with measured environmental conditions and therefore supports more defensible river-management prioritisation.

The exceptionally low turbidity values observed at Stations D and E should not be interpreted as evidence of completely sediment-free conditions. Rather, they likely reflect a combination of localized hydrological conditions, sediment settling processes and instrument detection limitations. Future studies should employ continuous turbidity monitoring and repeated seasonal measurements to verify whether these observations represent persistent environmental conditions or short-term sampling effects.

A limitation of the present study is that sampling was undertaken during a single hydrological season (August 2023, peak wet season). Seasonal fluctuations in rainfall, river discharge and catchment runoff may alter the magnitude and distribution of physicochemical, microbiological and heavy-metal contaminants. Although the integrated UAV–GIS–Laboratory framework effectively captured spatial variability during the study period, future monitoring programmes should incorporate repeated wet-season and dry-season assessments to improve understanding of temporal dynamics and strengthen environmental management decisions.

Accordingly, the validated first-order BOD₅ attenuation model represents the principal predictive component of the study, whereas the broader UAV–GIS–laboratory framework should be interpreted as a proof-of-concept environmental decision-support system. Its wider operational application would benefit from additional monitoring stations, repeated wet- and dry-season sampling, multispectral UAV observations and independent validation datasets.

5. Conclusion and recommendations

The study demonstrates the practical value of integrating laboratory measurements, UAV observations, GIS-supported spatial interpretation, regulatory compliance assessment and predictive modelling within a unified framework for river water-quality evaluation. The calibrated first-order BOD₅ attenuation model demonstrated satisfactory predictive performance within the complete modelling dataset and in comparative evaluation against independent river observations. The broader UAV–GIS framework functions primarily as an evidence-based decision-support system for identifying pollution hotspots, interpreting contaminant pathways, prioritising management interventions and supporting sustainable river governance; its wider application would benefit from additional multi-season monitoring and local recalibration. Dissolved oxygen values indicate that some aquatic-life support remains possible, but continuing microbial, heavy-metal and organic-pollutant inputs threaten ecosystem and public health. Recommended interventions include sanitation control along the river corridor, enforcement of effluent standards, restriction and zoning of sand-mining activities, restoration of riparian buffers, seasonal UAV–GIS monitoring and targeted public-health warnings for communities using untreated river water.

Future monitoring, regulatory enforcement and river-management interventions should be aligned with the provisions of the 2024 Nigerian Standard for Drinking Water Quality (NSDWQ), which should serve as the primary benchmark for evaluating drinking-water suitability in Nigeria. World Health Organization (WHO) guideline values may be used as supplementary international references. Particular attention should be given to heavy-metal contamination, microbial pollution, watershed disturbances and sand-mining activities that contribute to water-quality deterioration.

Environmental management interventions should be supported through effective implementation of the Nigerian Minerals and Mining Act (2007) and the National Environmental (Quarrying and Blasting Operations) Regulations (2013). Regulatory agencies should strengthen monitoring of sand-mining operations, enforce environmental restoration requirements and establish protective setback zones along vulnerable river reaches. Integration of UAV-GIS monitoring into regulatory inspection programmes would provide a cost-effective mechanism for identifying illegal extraction activities and assessing compliance with environmental regulations.

6. Declarations

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Ethics approval: Ethics approval was not required because the study involved environmental sampling and did not include human participants, personal data or experimental animals.

Consent to participate: Not applicable. **Consent for publication:** Not applicable.

Data availability: The station-level data supporting the findings are included in the manuscript. Additional replicate-level modelling outputs, UAV metadata and analytical files are available from the corresponding author upon reasonable request.

Conflict of interest: The authors declare no competing interests.

Author contributions: Michael Igara Nmecha conceived the study, coordinated field and UAV activities, conducted the integrated analysis and prepared the initial manuscript. Chidi Donatus Okereke, Chukwudi Celestine Egwuonwu and Okore Okay Okorafor contributed to study design, engineering interpretation and critical revision. Ngozi A. A. Okereke contributed to laboratory and regulatory interpretation. Chijioke Ndukwe Uyo and Chukwumezirim Jideaku Egwim contributed to field interpretation, data review and manuscript revision. All authors reviewed and approved the final manuscript.

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