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To cite this article: Danasabe S. Abubakar, Jacob A. Meye, Adesola V. Ayanwale, Yohanna I. Auta, Azubuike C. Ukubuiwe & Francis O. Arimoro (2026) Hydraulic-oxygenation and nutrient-ionic axes structure fish assemblages in a tropical river: a pre-impoundment baseline from the Lower Gurara River, Nigeria, *Ethology Ecology & Evolution*, 38:5, 660-690, DOI: [10.1080/03949370.2026.2675995](https://doi.org/10.1080/03949370.2026.2675995)

To link to this article: <https://doi.org/10.1080/03949370.2026.2675995>



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Published online: 29 Jun 2026.



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Hydraulic–oxygenation and nutrient–ionic axes structure fish assemblages in a tropical river: a pre-impoundment baseline from the Lower Gurara River, Nigeria

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Received 18 March 2026, accepted 13 May 2026

This study establishes a comprehensive pre-impoundment ecological baseline for the Lower Gurara River, quantifying how physicochemical gradients structure fish assemblages across spatial and seasonal scales in advance of hydropower regulation. The assemblage comprised 3,831 individuals representing 15 species and 11 families, reflecting a typical West African tropical river community. Multivariate analyses identified two dominant environmental axes: a “hydraulic–oxygenation axis” associated with coarse substrates, high turbulence, and elevated dissolved oxygen in upstream reaches, and a “nutrient–ionic axis” that intensified progressively downstream with increasing conductivity, sulphate, and phosphate. These gradients corresponded closely with observed community patterns. Rheophilic and benthic foraging taxa were most abundant at well-oxygenated upstream stations (S1–S2), whereas generalist and disturbance-tolerant species dominated depositional, nutrient-enriched downstream habitats (S3–S4). Species richness remained constant across stations, but evenness declined and dominance increased downstream, indicating an altered assemblage structure rather than compositional turnover. Seasonal patterns showed strong wet-season increases in abundance driven by flood-pulse connectivity, while α -diversity metrics remained comparatively stable, consistent with hydrology-mediated dynamics in tropical rivers. Interannual increases in total abundance from 2021 to 2022 reflected regional hydroclimatic variability, particularly sensitivity of low flows and flood extent. Collectively, these results demonstrate that linked hydraulic–oxygenation and nutrient–ionic gradients offer a robust, mechanistic framework for interpreting fish assemblage responses. The baseline also identifies key sentinel stations, S2 for aeration sensitivity and S4 for enrichment, and thermal change, and supports the development of threshold-based monitoring dashboards to guide adaptive management following impoundment. This dataset provides a defensible reference condition crucial for safeguarding ecological integrity during and after hydropower development on the Lower Gurara River.

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

KEY WORDS: fish assemblages, physicochemical gradients, hydraulic–oxygenation axis, nutrient–ionic axis, tropical river ecology, pre-impoundment baseline.

INTRODUCTION

Freshwater ecosystems concentrate a disproportionate share of global biodiversity while facing escalating pressures from climate change, land-use intensification, and hydrological alteration, with tropical systems especially vulnerable to rapid ecological change and biodiversity loss (Oberdorff 2022; Dudgeon & Strayer 2025). In tropical rivers, seasonal flood pulses and flow variability structure fish communities by regulating connectivity, nutrient exchanges, reproduction, and dispersal; disruptions to these regimes therefore reverberate through assemblage composition and function (White et al. 2012; Mosepele et al. 2022; van der Sleen & Rams 2023).

Across the tropics, land-use conversion, riparian degradation, mining, and urban growth degrade water quality and reassemble communities. In African and Neotropical basins alike, local environmental filters dissolve oxygen (DO), turbidity, nutrients, channel morphology, and canopy cover consistently predict spatial and seasonal turnover in fish and plankton (Akachukwu et al. 2025a, 2025b; Hirko et al. 2025; Silva et al. 2026). In West Africa, fish assemblages reflect joint controls of water chemistry, flow regime, geomorphology, and disturbance; for example, in the Great Kwa River, lower DO, elevated hydrocarbons, and contaminated sediments coincide with reduced fish diversity and macroinvertebrate richness (Allison et al. 2025). Basin-scale topology also matters: the “hydrographic nodality” of tributary junctions predicts species richness across West African rivers, highlighting network geometry as a biodiversity determinant (King et al. 2024). Meanwhile, continental hydrological shifts heighten vulnerability to ecological instability, underscoring the need for locally resolved, process-based assessments (Adeyeri 2025).

Within the Gurara system, reservoir studies already indicate low moderate fish diversity dominated by cichlids and seasonal water-quality stress affecting benthos, emphasizing the value of a robust pre-impoundment baseline (Auta et al. 2019, 2021; Samuel et al. 2021). Ichthyofaunal surveys further report low productivity and under-exploitation in Gurara Reservoir, reinforcing the need to document present assemblage structure before regulation intensifies (Ago et al. 2020). At the system level, inter-basin transfer from Gurara to Lower Usuma and the Kaduna–Shiroro chain stabilizes storage but increases downstream flood risk and clear evidence that flow alteration in coupled reservoirs has cascading ecological and hazard implications (Jimoh & Ayodeji 2003). Diversion also imprints measurable, seasonally varying water quality linkages between reservoirs, relevant for abstraction and treatment (Oseke et al. 2020).

Nigeria’s energy transition foregrounds hydropower, particularly small hydro-power (SHP) as a local, low carbon option, yet national appraisals show that the country’s SHP potential remains vastly under-exploited and governance challenges persist (Ugwu et al. 2022). Policy and partnership analyses similarly call for stronger environmental safeguards, stakeholder processes, and monitoring around dams and water transfer projects (Arachie & Moti 2026a, 2026b). In practice, ecological consequences of impoundment are well documented across Nigeria: studies at Challawa/Tiga reveal marked divergence between reservoir and below-dam fish assemblages,

consistent with global expectations under altered connectivity and flow (Abdul-Azeez et al. 2024).

The Lower Gurara River is now slated for hydropower development, shifting the reach from free-flowing to regulated conditions. Feasibility and sector documents indicate hydropower potential near Gurara Falls and Kaplan-turbine generation at the existing multipurpose dam, pointing to imminent changes in flow periodicity, connectivity, and habitat mosaics (Okeleke 2004; Emeterie et al. 2021). Given the demonstrated roles of flood-pulse dynamics and connectivity in sustaining tropical fish diversity, altered hydroperiods can be expected to restructure trophic interactions and functional diversity (White et al. 2012; Mosepele et al. 2022).

Accordingly, a rigorous pre-impoundment assessment is indispensable. It will (i) quantify the current hydro-ecological determinants of fish community structure, (ii) provide a defensible baseline against which post-dam changes can be attributed to altered flow regimes and connectivity, and (iii) inform adaptive operations, mitigation, and equitable benefit-sharing as hydropower regulation comes online. Guided by this need, our aim is to deliver a comprehensive, site-specific baseline for the Lower Gurara River before impoundment, integrating water-quality profiling with fish assemblage composition, diversity metrics, and habitat context to identify the environmental drivers that presently shape community structure in a human-influenced tropical river. We therefore test the following hypotheses: (H1) spatial gradients in physicochemical conditions (e.g. DO, conductivity, nutrients) are significant predictors of fish community composition and diversity; (H2) reaches exposed to greater anthropogenic disturbance exhibit lower richness and altered assemblage structure relative to less-impacted reaches; and (H3) impending hydropower regulation by altering flood-pulse dynamics and longitudinal lateral connectivity poses directional risks of community reorganization that can be anticipated from today's environment-biota relationships.

MATERIALS AND METHODS

Study area

The Gurara River is a major tributary of the Niger North drainage basin in central Nigeria, extending approximately 360 km from its headwaters in the uplands of Kagarko and Kachia in Kaduna State, flowing south-westward through the Federal Capital Territory (FCT) and Niger State before discharging into the River Niger. The upper reaches are characterized by steep gradients, rocky substrates, and gallery forests, while downstream sections broaden into alluvial floodplains. A prominent geomorphic feature along the river course is the Gurara Waterfall, which forms a high-energy, well-oxygenated rapids zone that transitions downstream into riffle-run-pool habitats supporting high aquatic biodiversity. The river provides important ecosystem services to riparian communities such as Jere, Bonu, Izom, and Gawu, where it is used for domestic water supply, small-scale irrigation, livestock watering, and artisanal fisheries.

The Gurara River basin lies within a tropical monsoonal climate zone, with a well-defined wet season from April to October and a dry season from November to March. This seasonal climate regime results in strong variability in river discharge, with peak flows during the rainy season and reduced base flows in the dry months. Hydrologically, the river supplies inflows to the Gurara Multipurpose Dam, a large composite earth- and rock-fill structure constructed across the Gurara River. The dam is approximately 52.5 m high and about 3 km long at the crest, impounding a reservoir with a storage capacity of approximately 880 million m³ and a surface area of about 61 km². The dam regulates a mean annual flow of approximately 36 m³sec⁻¹, supporting

water supply transfers to the Lower Usuma Dam, irrigation schemes downstream, and hydro-power generation (Okeleke 2004; Bello et al. 2024; GAC Gurara 2026)

The present study was conducted along the free-flowing lower stretch of the Gurara River upstream of the proposed hydropower impoundment, thereby minimizing direct reservoir effects on flow and habitat conditions (Fig. 1). Four sampling stations, namely Bonu, Gurara Waterfall, Izom, and Gawu, were selected to capture spatial variation in land use, channel morphology, and levels of human disturbance. Sampling was conducted monthly from February 2021 to November 2022.

Sampling stations

Station characteristics are summarized below:

Station 1 – Bonu (9.344546°N, 7.01141°E). Bonu serves as the minimally disturbed upstream reference site. The channel is narrow (15–25 m) with dry-season depths of 1.5–3 m, increasing to 4–6 m during peak flows. Water clarity is high, with coarse gravel-cobble substrates forming stable riffle–pool sequences. Intact riparian vegetation gallery forest, shrubs, and grasses stabilizes the banks and supplies organic matter. This site supports sensitive fish and macroinvertebrate taxa and functions as the ecological baseline for comparison.

Station 2 – Gurara waterfall (9.31237°N, 7.0209166°E). Downstream of the waterfall, the river widens to 20–30 m with sharp depth variation (< 0.5 m in riffles to > 5 m in plunge pools). Flow is highly turbulent and oxygen-rich, with substrates dominated by boulders, cobbles, and exposed bedrock. Steep rocky banks support sparse vegetation. This dynamic lotic habitat favours rheophilic and lithophilic species, making it a biodiversity hotspot.

Station 3 – Izom (9.2407°N, 7.0095°E). Izom is a mid-reach site impacted by domestic activities (washing, bathing, livestock access). The river broadens to 25–40 m with moderate flow and depths of 1–2.5 m. Substrates range from sand to gravel, with localized silt accumulation. Riparian vegetation is partly cleared, increasing erosion and reducing shading. Organic inputs from human use contribute to mild eutrophication, supporting tolerant and opportunistic biota characteristic of moderate disturbance.

Station 4 – Gawu (9.2122°N, 6.8418°E). Gawu reflects cumulative downstream impacts. The river expands to 40–60 m and deepens to 2–4 m, with reduced flow and dominance of fine sediments (silt, clay, sand). Banks are heavily used for agriculture, fishing, and irrigation, resulting in fragmented riparian vegetation and nutrient enrichment. Habitat quality is diminished, favouring generalist species over sensitive taxa.

Sampling frequency and field schedule

Sampling was carried out monthly from February 2021 to November 2022, covering a 22-month period designed to capture both intra-annual (seasonal) and inter-annual variation in the river's hydro-ecological conditions. Each sampling campaign followed a standardized field routine that incorporated the full suite of ecological measurements required for baseline characterization. During every monthly visit, the research team conducted in situ water-quality assessments, habitat and physicochemical evaluations, and fish community sampling, followed by specimen preservation and subsequent laboratory analyses. To reduce temporal bias and ensure comparability across months, all sampling events were performed at consistent intervals, typically within ± 3 days of the scheduled date.

Physicochemical water quality assessment

Physicochemical characteristics of the river were assessed through in situ water-quality measurements conducted at each sampling station between 08:00 and 11:00 hr to minimize diel fluctuations. During each field visit, key parameters were recorded using calibrated portable instruments. Water temperature was measured with a digital multiparameter probe, while pH was determined using a portable pH meter standardized with buffer solutions at pH 4, 7, and 10. Electrical conductivity was assessed with a conductivity meter, and dissolved oxygen (DO) concentrations were obtained using an optical DO meter. Additional measurements included turbidity, recorded with a portable turbidity meter; total dissolved solids (TDS) derived metrically; water velocity, determined with a flow meter or via float-tracking; and Secchi depth, which was used to gauge water transparency. To complement field measurements, 500-mL water samples were collected mid-stream using acid-washed polyethylene bottles and stored on ice for subsequent laboratory analysis. These samples were analyzed for nitrates (NO_3^- -N), phosphates (PO_4^{3-} -P), biochemical oxygen demand (BOD_5), and total alkalinity and hardness. All laboratory procedures followed the "Standard methods for the examination of water and wastewater" (Rice et al. 2017) to ensure analytical reliability and methodological consistency.

Habitat and substrate characterization

Habitat conditions were quantified at each station using standard fluvial assessment procedures. Channel width and depth were measured along a single transect, with depth taken at 25, 50, and 75% of the channel. Substrate composition was determined using a Wolman pebble count to classify dominant particle sizes. Flow type (riffle, run, pool) was noted based on surface turbulence, depth, and substrate features. Riparian condition was evaluated through visual estimates of vegetation cover and bank stability. Evidence of anthropogenic disturbance such as livestock access, washing points, sand mining, and bank modification was recorded to contextualize habitat integrity.

Fish sampling procedures

Fish communities in the Lower Gurara River were sampled using a multi-gear approach designed to capture the widest possible spectrum of species across the diverse habitats characteristic of mixed-substrate tropical rivers. A combination of monofilament gill nets (25–75 mm mesh; 30×1.5 m), cast nets with 15-mm mesh for nearshore habitats, baited traps for benthic and cryptic species, and hand nets for juveniles and shallow microhabitats ensured adequate representation of ecological guilds. To minimize gear selectivity bias and temporal variation in fish activity, all nets were deployed simultaneously at each station and soaked for 2–3 hr during early morning (06:00–09:00) and late afternoon (16:00–18:00), periods commonly associated with heightened fish movement. Upon retrieval, captured fish were immediately sorted by species, counted, weighed to the nearest 0.1 g, and measured for total and standard lengths. Species identification followed established regional taxonomic keys (Idodo-Umeh 2003; Olaosebikan & Raji 2004). Additional verification was carried out using FAO and other West African ichthyological references where necessary. Specimens that could not be conclusively identified in the field were preserved in 10% buffered formalin and later transferred to 70% ethanol for laboratory confirmation and long-term curation.

To compare catches consistently across stations and years, we calculated catch per unit effort (CPUE) separately for each gear and as a single combined index using the standardized per-unit effort. Gear-specific CPUEs were expressed as $\text{fish} \cdot \text{net-hr}^{-1}$ for gill-nets (total catch divided by 4 net-hr), $\text{fish} \cdot \text{trap-night}^{-1}$ for baited traps (total catch divided by 2 trap-nights), and $\text{fish} \cdot \text{throw}^{-1}$ for cast nets (total catch divided by 10 throws). For an integrative comparison across

gears, we defined a combined effort unit per visit as the sum of net-hr (weight = 1), trap-nights (weight = 1), and cast-net throws (weight = 0.1), yielding seven effort units per visit; the combined CPUE was therefore computed as total catch $\div$ 7. Gear-specific and combined CPUEs were then summarized by station and year and used downstream to support diversity metrics and multivariate community analyses.

Diversity indices

Fish assemblage patterns were quantified using standard biodiversity metrics, including species richness (S), Shannon-Wiener diversity (H'), Simpson's dominance (D), Pielou's evenness (J'), relative abundance, and catch per unit effort (CPUE), following established ecological frameworks (Magurran 2004). Multivariate analyses were used to examine community structure: Bray-Curtis cluster analysis, non-metric multidimensional scaling (nMDS), and principal coordinates analysis (PCoA) were applied to visualize assemblage similarity and spatial gradients in species composition (Clarke & Warwick 2001). These procedures provided an integrated assessment of fish diversity and community organization across stations and seasons.

Statistical analyses

Environmental variables were tested for spatial variation using one-way ANOVA or Kruskal-Wallis, with relationships among parameters assessed using Pearson or Spearman correlations. Principal component analysis (PCA) was used to summarize environmental gradients (Clarke & Gorley 2015). Differences in fish assemblages were evaluated with PERMANOVA, while BIO-ENV analysis identified environmental variables best explaining community patterns. SIMPER determined species contributions to between-station dissimilarities, following standard multivariate ecological procedures (Clarke & Warwick 2001). All analyses were performed using PAST 4.0, PRIMER 7, and R (vegan package).

Ethical considerations

Fish handling followed institutional animal welfare protocols. Lethal sampling was minimized, and non-target species were released unharmed whenever possible. Community access points were sampled respectfully, with prior consultation with local residents.

RESULTS

Survey effort and catch overview

Over the 22-month sampling period (February 2021–November 2022), a total of 88 standardized station-visits were completed across the four study locations, with each station visited 22 times. Sampling effort was held constant across space and time with 4 net-hr, 2 trap-nights, and 10 cast-net throws per visit ensuring methodological comparability and enabling robust effort-standardized analyses of catch per unit effort (CPUE) across stations and years. Across all surveys, 3,831 fish were recorded, comprising 15 species from 11 families, with annual totals increasing from 1,555 individuals in 2021 to 2,276 in 2022. Station-specific two-year totals revealed consistently high catches at S1 Bonu (1,298) and S4 Gawu (985), intermediate values at S2 Gurara Waterfall (990), and the lowest totals at S3 Izom (558). Notably, all stations

exhibited year-to-year increases, ranging from + 32.2% (S1) to + 80.4% (S3), indicating a broad rise in fish availability or catchability.

Effort-standardized catch rates showed similarly strong increases. Combined CPUE values rose from 28.43–79.86 fish · effort-unit⁻¹ in 2021 to 51.29–105.57 fish · effort-unit⁻¹ in 2022, with S1 consistently producing the highest CPUEs, and S3 showing the largest proportional increase (Fig. 2). Gear-specific CPUE trends mirrored the combined metric with Gill-net CPUE increased from a station-mean of 97.19 to 142.25 fish · hr⁻¹, Trap CPUE increased from 194.38 to 284.50 fish · night⁻¹ and Cast-net CPUE increased from 38.88 to 56.90 fish · throw⁻¹ (Table 1). Paired statistical comparisons confirmed that these increases were both large and consistent across gears. Differences between 2021 and 2022 were highly significant under paired *t*-tests, with identical results for all three gears [$t(3) = 21.53$, $P < 0.001$], and extremely large effect sizes (Cohen's $d_z = 10.77$). Although the non-parametric Wilcoxon signed-rank test was conservative due to the small sample size (*n*) of four paired stations, the results nonetheless supported the same directional increase ($W = 10$, $P = 0.0625$ for all gears).

Physicochemical dynamics (spatio-seasonal)

Physicochemical conditions showed clear spatial and seasonal variation across the Lower Gurara River. Wet-season months (April–October) were marked by increased turbidity and reduced water transparency, whereas dry-season months (November–March) exhibited lower turbidity and more stable thermal conditions. Across stations, temperature increased downstream from 25.89 ± 2.48 °C at Bonu (S1) to 28.65 ± 1.05 °C at Gawu (S4), while dissolved oxygen remained high system-wide but reached its maximum at Gurara Waterfall (S2; 9.77 ± 2.81 mgL⁻¹). Nutrient levels displayed downstream elevation, with nitrate rising from 0.318–0.370 mgL⁻¹ at S1–S2 to 1.550 mgL⁻¹ at S4, and phosphate increasing from 0.105–0.125 mgL⁻¹ upstream to 0.255 mgL⁻¹ downstream (Table 2). ANOVA results indicated significant differences among stations for temperature ($F = 6.12$, $P = 0.014$), alkalinity ($F = 48.3$, $P < 0.001$), water depth ($F = 152.6$, $P < 0.001$), nitrate ($F = 27.9$, $P < 0.001$), sulphate ($F = 58.7$, $P < 0.001$), and hardness ($F = 18.4$, $P = 0.002$), while pH, TDS, DO, BOD, turbidity, conductivity, and phosphate showed no statistically significant spatial differences ($P > 0.05$). Tukey post-hoc groupings reflected these patterns, identifying S2 as the most distinct site for alkalinity and depth, and S4 as the site with the highest nutrient and hardness values (Table 2). PCA further separated stations along two principal gradients: a nutrient–ionic axis (PC1, 64.2% variance) and a hydraulic–oxygenation axis (PC2, 16.4% variance), with S4 aligned with higher nutrient loadings and S2 aligned with depth, alkalinity, and dissolved oxygen (Fig. 3, Table 3). Spatial and seasonal measurements revealed structured variation in temperature, turbidity, nutrients, alkalinity, and hydraulic conditions across the river system.

Habitat and substrate contrasts

Habitat structure varied distinctly across the four sampling stations, reflecting a clear hydraulic and substrate gradient along the Lower Gurara River. Station 1 (Bonu) was characterized by coarse substrates dominated by boulders and cobbles ($38.00 \pm 4.00\%$ and $29.00 \pm 3.00\%$, respectively), moderate velocities (0.42 ± 0.04 msec⁻¹), and the highest riparian cover ($78.00 \pm 5.00\%$). Station 2 (Gurara Waterfall) differed sharply from all other

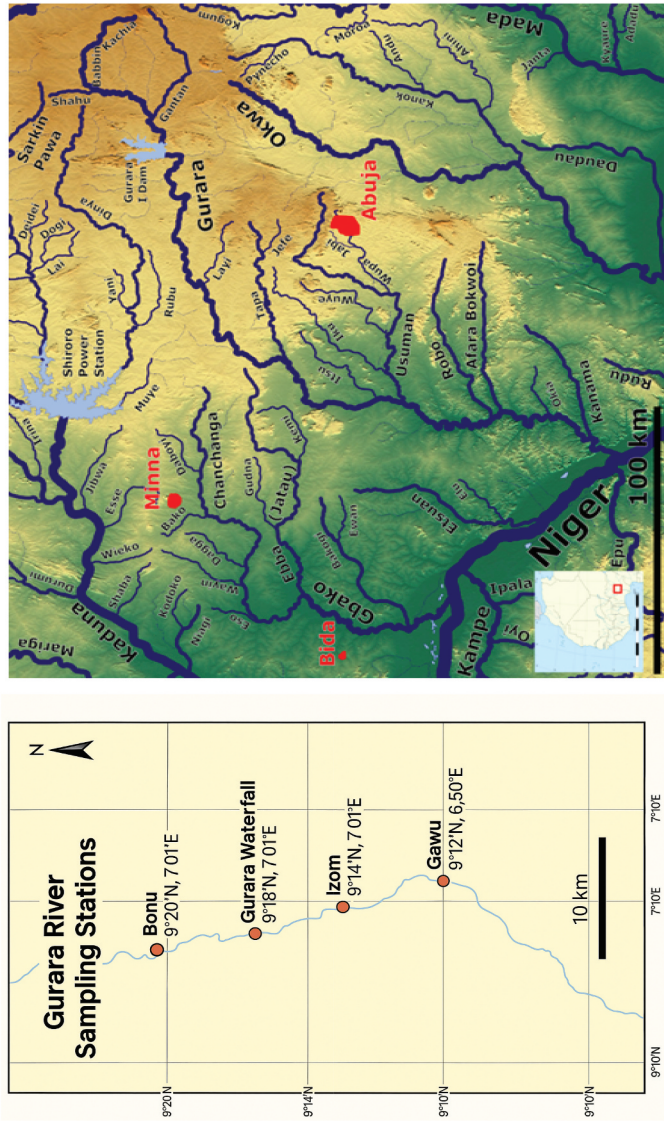


Fig. 1. — Map of Nigeria showing the location of Gurara river and on the left the Gurara river stretch showing the location of the sampling stations.

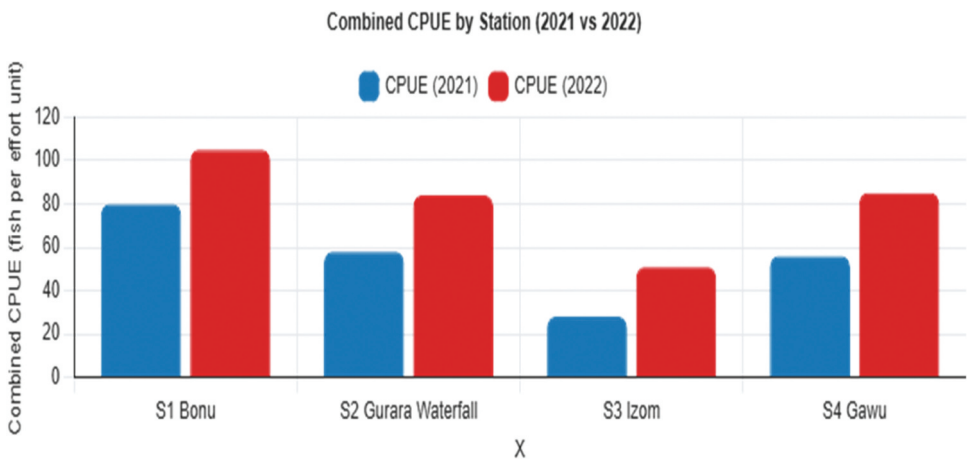


Fig. 2. — Combined CPUE by station in 2021 vs 2022. Bars show effort-standardized catch (fish per effort unit) derived from a fixed per-visit effort of 4 net-hr, two trap-nights, and 10 cast-net throws (combined effort = seven units).

Table 1.

Gear-specific CPUE by station and year (2021 vs 2022).

Station	Gill-net CPUE (fish hr ⁻¹)		Trap CPUE (fish night ⁻¹)		Cast-net CPUE (fish throw ⁻¹)	
	2021	2022	2021	2022	2021	2022
S1 Bonu	139.75	184.75	279.50	369.50	55.90	73.90
S2 Gurara Waterfall	101.25	146.25	202.50	292.50	40.50	58.50
S3 Izom	49.75	89.75	99.50	179.50	19.90	35.90
S4 Gawu	98.00	148.25	196.00	296.50	39.20	59.30

sites, with the highest proportion of boulder substrate ($62.00 \pm 5.00\%$), the greatest mean depth (9.11 ± 1.89 m), and the fastest flows (0.88 ± 0.07 msec⁻¹), corresponding to its riffle-run hydraulic setting (Table 4). Further downstream, Station 3 (Izom) exhibited a mixed sand-gravel substrate ($32.00 \pm 3.00\%$ sand; $34.00 \pm 4.00\%$ gravel), lower riparian cover ($33.00 \pm 3.00\%$), and higher disturbance scores (3.90 ± 0.40) reflecting recurrent domestic activities. Station 4 (Gawu) showed the most depositional conditions, with sand and silt/clay comprising over 78% of substrate, the widest channel (56.30 ± 3.20 m), the lowest flow velocities (0.28 ± 0.03 msec⁻¹), and the highest disturbance index (4.60 ± 0.30). These spatial differences illustrate a transition from coarse, fast-flowing, upstream habitats (S1–S2) to wider, slower, and increasingly depositional downstream environments (S3–S4), accompanied by increasing evidence of human disturbance.

Table 2.
Monthly mean variations of physico-chemical parameters of Gurara river (February 2021–November 2022).

Parameters	Site 1 (Bonu)	Site 2 (Gurara WF)	Site 3 (Izom)	Site 4 (Gawu)	F-value	P-value
Temperature (°C)	25.89 ± 2.48 ^a	27.19 ± 1.96 ^{ab}	28.25 ± 1.31 ^{ab}	28.65 ± 1.05 ^b	6.12	0.014
pH	7.65 ± 1.73 ^a	7.54 ± 1.24 ^a	7.82 ± 1.16 ^a	7.57 ± 1.05 ^a	0.48	0.70
TDS (mg/L)	172.62 ± 10.07 ^a	175.25 ± 12.24 ^a	183.50 ± 12.70 ^a	180.75 ± 14.06 ^a	2.55	0.12
DO (mg/L)	8.39 ± 4.62 ^a	9.77 ± 2.81 ^a	9.22 ± 3.86 ^a	8.52 ± 4.15 ^a	0.06	0.98
BOD (mg/L)	3.81 ± 2.37 ^a	4.22 ± 1.72 ^a	4.19 ± 1.17 ^a	3.69 ± 0.80 ^a	0.43	0.74
Turbidity (NTU)	4.33 ± 1.14 ^a	4.55 ± 1.22 ^a	3.88 ± 2.02 ^a	4.01 ± 1.18 ^a	1.22	0.35
Conductivity (µS/cm)	232.50 ± 48.38 ^a	247.87 ± 41.44 ^a	252.00 ± 45.01 ^a	249.25 ± 55.77 ^a	0.84	0.49
Total Alkalinity (mg/L)	568.75 ± 38.58 ^a	666.00 ± 25.31 ^b	374.12 ± 91.37 ^c	407.00 ± 91.31 ^c	48.3	< 0.001
Water Depth (m)	4.82 ± 0.53 ^a	9.11 ± 1.89 ^b	7.62 ± 1.57 ^c	7.12 ± 1.55 ^d	52.6	< 0.001
Nitrate (mg/L)	0.318 ± 0.15	0.370 ± 0.11	0.325 ± 0.15	1.550 ± 0.15	27.9	< 0.001
Phosphate (mg/L)	0.105 ± 0.11	0.125 ± 0.11	0.167 ± 0.11	0.255 ± 0.55	2.51	0.13
Sulphate (mg/L)	8.524 ± 0.75	12.165 ± 0.173	12.813 ± 0.13	16.398 ± 0.11	58.7	< 0.001
Total Hardness (mg/L)	38.000 ± 0.11 ^a	42.375 ± 0.11 ^a	38.000 ± 0.11 ^a	72.750 ± 0.11 ^a	18.4	0.002

Note: Values represent monthly means ± standard error for each station from February 2021 to November 2022. Different superscript letters within rows denote statistically significant differences among stations at $P < 0.05$, based on one-way ANOVA followed by Tukey HSD post-hoc tests (or Kruskal–Wallis with Dunn's test where assumptions were not met). Parameters with identical superscripts are not significantly different.

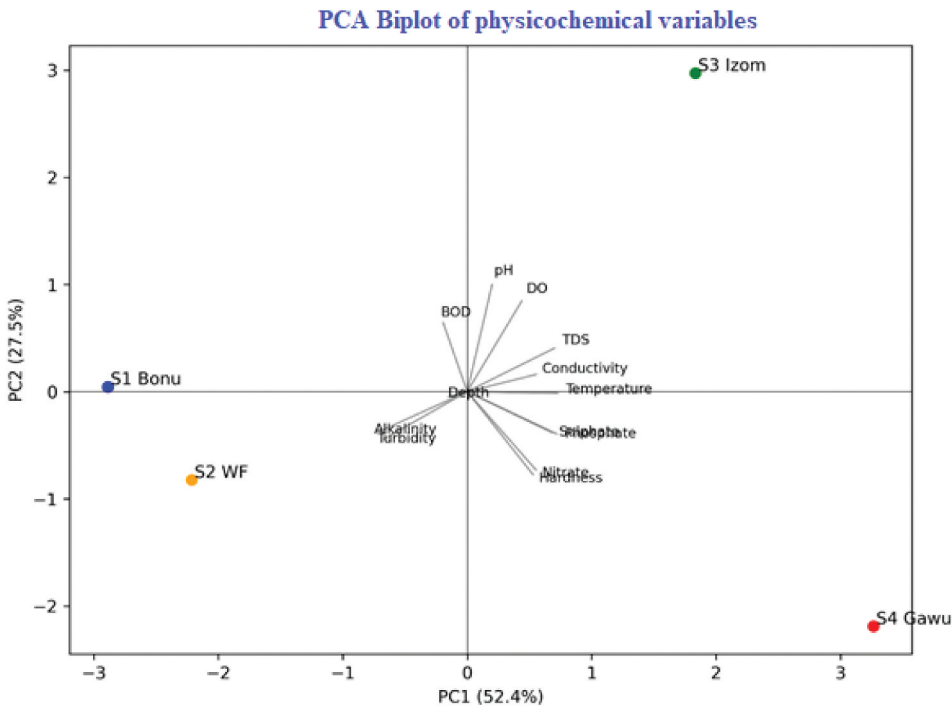


Fig. 3. — Principal component analysis (PCA) biplot illustrating spatial variation in physicochemical conditions across the four sampling stations of the Lower Gurara River (arrows represent variable loadings on the PCA axes, with arrow length indicating the relative strength of each variable's contribution to the ordination).

Fish assemblage composition and richness

Across the 2-year survey (N = 3,831 individuals), the fish assemblage comprised 15 species from 11 families, with Cichlidae, Cyprinidae, Distichontidae, Alestidae, and Mormyridae contributing most of the total catch. The most abundant taxa were *Tilapia zillii* (364; 9.50%), *Barbus occidentalis* (298; 7.78%), *Distichodus rostratus* (288; 7.52%), *Labeo coubie* (282; 7.36%), and *Alestes macrolepidotus* (262; 6.84%), followed closely by *Synodontis clarias* (260; 6.79%) and *Coptodon zillii* (260; 6.79%). Predatory components were represented by *Lates niloticus* (310; 8.09%) and the pelagic predator *Hydrocynus vitalis* (222; 5.80%), while electrogenic/electrosensory benthic taxa (*Malapterurus electricus* 60; 1.57%, *Mormyrus rume* 254; 6.63%, *M. deliciosus* 252; 6.58%) were consistently recorded. Guild composition reflected a mixture of generalist-tolerant detritivores/omnivores (e.g. *Tilapia/Coptodon*, *Barbus*, *Schilbe*) and benthic grazers/foragers (e.g. *Labeo*, *Synodontis*, *Mormyrus*), with pelagic predators and large apex predators present at lower relative abundances (Table 5). All recorded species are native to West African river systems, with no endemic taxa detected; however, the presence of *Lates niloticus*, a species native to parts of the Niger Basin but widely recognized as invasive outside its natural range.

Table 3.

Principal component loadings for physicochemical variables in the Lower Gurara River.

Variable	PC1 Loading	PC2 Loading
Eigenvalue	8.35	2.13
% Variance explained	64.20%	16.40%
Cumulative %	64.20%	80.60%
Temperature	+ 0.31	– 0.12
pH	+ 0.28	+ 0.05
TDS	+ 0.36	– 0.14
Dissolved oxygen (DO)	+ 0.11	+ 0.62
BOD	– 0.22	– 0.20
Turbidity	– 0.09	+ 0.03
Conductivity	+ 0.35	– 0.13
Alkalinity	– 0.08	+ 0.69
Depth	– 0.12	+ 0.71
Nitrate	+ 0.41	+ 0.07
Phosphate	+ 0.39	+ 0.11
Sulphate	+ 0.43	+ 0.09
Hardness	+ 0.40	– 0.04

Note: Loadings are scaled to facilitate interpretation; the sign indicates correlation direction, and larger absolute values denote stronger contributions of a variable to the corresponding principal component. Eigenvalues and percentage variance explained refer to the proportion of total variance captured by each axis.

Spatially, station signatures were distinct. The rheophilic waterfall site (S2) supported higher counts of boulder-affiliated and pelagic/rheophilic taxa (e.g. *Hydrocynus*, *Mormyrus* spp.), whereas S3–S4 exhibited greater proportions of generalist-tolerant and depositional-affiliated taxa (e.g. *Coptodon*, *Tilapia*, *Citharinus*), alongside consistent occurrences of benthic omnivores/grazers (*Synodontis*, *Labeo*). Station-year totals reflected the network-level rise in abundance from 2021 (N = 1,555) to 2022 (N = 2,276) at all sites, with S1 Bonu remaining the highest-yield station overall and S3 Izom showing the largest proportional increase. The station-by-year breakdown in Table 5 details these patterns, including the distribution of predators (P/PP), generalist-tolerant (GT/GO/GD), and benthic functional groups (BO/BG/BD/EBF/DH/H) across the longitudinal gradient.

Diversity indices

Across pooled seasons, species richness (S) remained 15 at all stations, and Shannon diversity (H') and Pielou's evenness (J') showed consistently higher values

Table 4.
Habitat and substrate metrics by station (mean ± SE) for the Lower Gurara River (Feb 2021–Nov 2022).

Metric	S1 Bonu (Upstream reference)	S2 Gurara WF (Waterfall/Riffle-Run)	S3 Izom (Mid-reach, Domestic use)	S4 Gawu (Downstream, Depositional)
Substrate composition (%)				
Boulder	38.00 ± 4.00	62.00 ± 5.00	8.00 ± 2.00	4.00 ± 1.00
Cobble	29.00 ± 3.00	21.00 ± 3.00	12.00 ± 2.00	6.00 ± 1.00
Gravel	18.00 ± 2.00	9.00 ± 1.00	34.00 ± 4.00	12.00 ± 2.00
Sand	10.00 ± 2.00	5.00 ± 1.00	32.00 ± 3.00	51.00 ± 5.00
Silt/Clay	5.00 ± 1.00	3.00 ± 1.00	14.00 ± 2.00	27.00 ± 4.00
Mean depth (m)	4.82 ± 0.53	9.11 ± 1.89	7.62 ± 1.57	7.12 ± 1.55
Mean width (m)	32.40 ± 2.10	28.70 ± 1.40	41.90 ± 2.60	56.30 ± 3.20
Velocity (msec ⁻¹)	0.42 ± 0.04	0.88 ± 0.07	0.36 ± 0.05	0.28 ± 0.03
Riparian cover (%)	78.00 ± 5.00	54.00 ± 4.00	33.00 ± 3.00	21.00 ± 4.00
Bank stability (score 1–5)	4.30 ± 0.20	3.90 ± 0.30	2.60 ± 0.40	1.80 ± 0.30
Disturbance index (0–5)	0.80 ± 0.20	1.20 ± 0.30	3.90 ± 0.40	4.60 ± 0.30
Human access frequency	Low	Low–Moderate	High	High
Dominant hydraulic type	Run–Pool	Riffle–Run	Run	Run–Pool (Depositional)
Overall mesohabitat class	Coarse, shaded, upstream	Turbulent, rocky, high-energy	Sand–gravel, impacted	Sandy–silty, low-energy, impacted

Note: Substrate proportions were derived from Wolman pebble counts. Depth and width values represent monthly transect means; velocity was measured at mid-column using a portable flow meter. Riparian cover (%) was visually estimated along a 50 m reach at each station. Disturbance index reflects domestic activity, bank trampling, livestock access, and visible channel modification. Values shown are mean ± SE across 22 sampling events (February 2021–November 2022).

Table 5.
Species composition, abundance by station and year (2021 and 2022), and ecological guilds (N = 3831).

Family	Species	Guild	S1		S2		S3		S4		Total	%
			2021	2022	2021	2022	2021	2022	2021	2022		
Nandidae	<i>Lates niloticus</i>	P	48	60	42	54	17	29	24	36	310	8.09
Cichlidae	<i>Coptodon zillii</i>	GT	26	38	17	29	6	18	57	69	260	6.79
Cichlidae	<i>Tilapia zillii</i>	GT	48	60	38	50	17	29	55	67	364	9.50
Mochokidae	<i>Synodontis clarias</i>	BO	47	59	25	37	13	25	21	33	260	6.79
Latidae	<i>Labeo senegalensis</i>	BD	39	51	19	31	14	26	20	32	232	6.06
Mormyridae	<i>Mormyrus rume</i>	EBF	38	50	24	36	13	25	28	40	254	6.63
Mormyridae	<i>Mormyrus deliciosus</i>	EBF	40	52	29	41	13	25	20	32	252	6.58
Alestidae	<i>Hydrocynus vitalis</i>	PP	26	38	27	39	17	29	17	29	222	5.80
Alestidae	<i>Alestes macrolepidotus</i>	PO	34	46	30	42	12	24	31	43	262	6.84
Cyprinidae	<i>Barbus occidentalis</i>	GD	48	60	38	50	17	29	22	34	298	7.78
Cyprinidae	<i>Labeo coubie</i>	BG	44	56	34	46	17	29	22	34	282	7.36
Distichontidae	<i>Distichodus rostratus</i>	H	49	61	29	41	17	29	25	37	288	7.52
Citharinidae	<i>Citharinus citharus</i>	DH	31	43	19	31	14	26	22	34	220	5.74
Malapteruridae	<i>Malapterurus electricus</i>	EP	3	15	2	14	0	12	1	13	60	1.57
Clupeidae	<i>Schilbe mystus</i>	GO	38	50	32	44	12	24	27	39	266	6.94

Note: Ecological guild codes; p = Predatory, PP = Pelagic predator, GT = Generalist–tolerant, GO = Generalist omnivore, GD = Generalist detritivore, BO = Benthic omnivore, BG = Benthic grazer, BD = Benthic detritivore, EBF = Electrosensory benthic forager, PO = Pelagic omnivore, DH = Detritivore–herbivore, EP = Electrogonic predator, H = Herbivore.

at S1–S3 than at S4. In the wet season (pooled 2021–2022), H' ranged from 2.624 to 2.673, highest at S3 (2.673) and lowest at S4 (2.624); J' ranged from 0.969 to 0.987, again highest at S3 (0.987) and lowest at S4 (0.969) (Fig. 4). The dry season reproduced the same pattern (H' : 2.624–2.673; J' : 0.969–0.987), with S3 consistently maximal and S4 minimal for both indices. These station-wise seasonal patterns are visible in the seasonal boxplots (Fig. 5) Simpson dominance (D) remained lowest at S1–S3 (0.070–0.072) and highest at S4 (0.078) in both seasons, indicating a relatively more dominant assemblage at the downstream station. Seasonal totals (N) were larger in the wet than in the dry pool at every station (e.g. S1: 826 vs 472; S2: 630 vs 360; S3: 367.8 vs 210.2; S4: 613.5 vs 350.5), consistent with the proportional wet/dry aggregation applied to the 2-year series.

Links between environment and biota (hypothesis tests)

PERMANOVA on Bray–Curtis dissimilarities of the station $\times$ season assemblage matrix indicated no significant station effect ($F = 1.423$, $df = 3,4$, $P = 0.359$), while the season effect approached significance ($F = 4.073$, $df = 1,6$, $P = 0.067$; 999 permutations). The Station $\times$ Season interaction was not tested due to a single pooled observation per cell under the wet–dry aggregation scheme (Table 6). The BEST (BIO-ENV) procedure identified Temperature + DO as the best-matching subset of environmental variables to the biotic resemblance matrix ($\rho = 0.144$; Spearman correlation, subsets up to $k = 4$). Envfit vectors overlaid on the nMDS ordination highlighted the strongest environmental alignments with community structure: Temperature, TDS), Phosphate, and Sulphate Additional vectors included Conductivity, Alkalinity ($r^2 = 0.675$, $P = 0.096$), Turbidity and Nitrate (Table 7). The vector orientations and lengths are shown on Fig. 6 for visual alignment.

DISCUSSION

Survey effort and catch overview

The uniform and evenly distributed sampling regime applied across the 22-month study period provides a rigorous foundation for interpreting spatial and temporal variation in fish assemblages of the Lower Gurara River. By maintaining identical net hours, trap nights, and cast-net throws during each visit, the design minimizes sampling bias and enhances comparability of CPUE across stations and years, aligning with long-standing best practices in fishery monitoring (Fausch et al. 2002; Kennard et al. 2010). Such standardized effort is essential in tropical rivers, where catch rates are sensitive to variation in sampling intensity and gear deployment (Holzlöhner et al. 2004; Olopade et al. 2017). The consistent rise in catch and CPUE between years, observed across all gear types, suggests a system-wide increase in fish availability rather than a methodological artifact. Because gill nets, traps and cast nets each target distinct behavioural and ecological guilds, parallel increases across gears indicate broad-scale ecological shifts rather than gear-specific anomalies. Similar multi-gear coherence has been documented in Nigerian rivers such as the Cross River Estuary and Bonny River, where uniform CPUE increases have been linked to favourable hydrological conditions, recruitment pulses, or reductions in fishing pressure (Lowenberg & Künzel 1991; Abiodun & John 2017). Spatial differences in catch

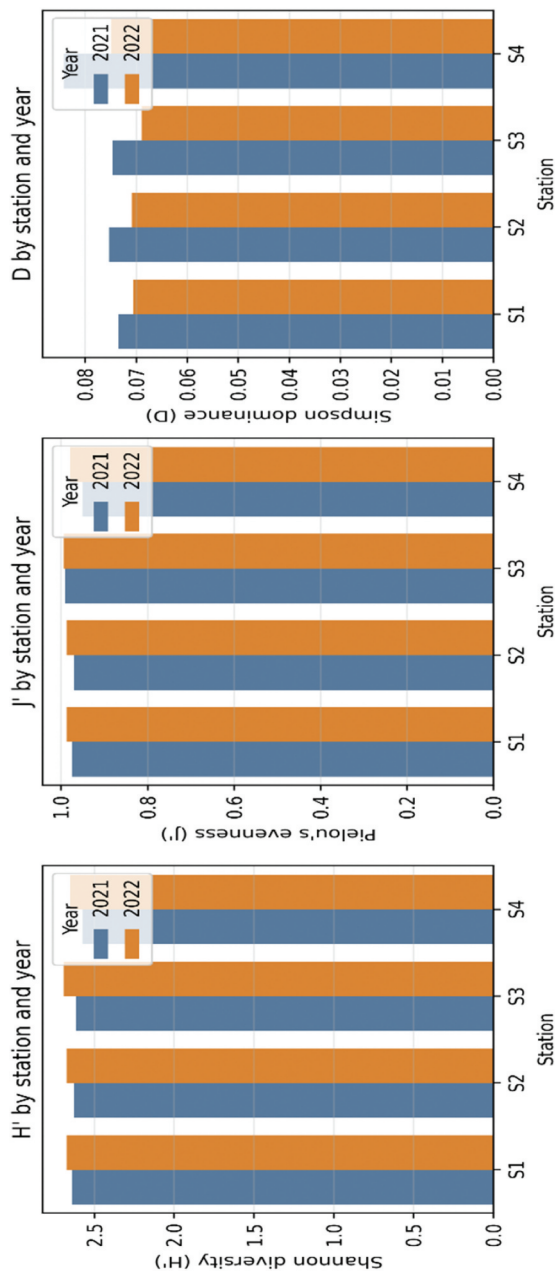


Fig. 4. — Diversity indices by station and year. Bars show Shannon diversity (H'), Pielou's evenness (J'), and Simpson dominance (D) computed from station-level species counts for 2021 and 2022. H' and J' increase modestly from 2021 to 2022 at all stations, while D remains lowest at upstream/rheophilic sites.

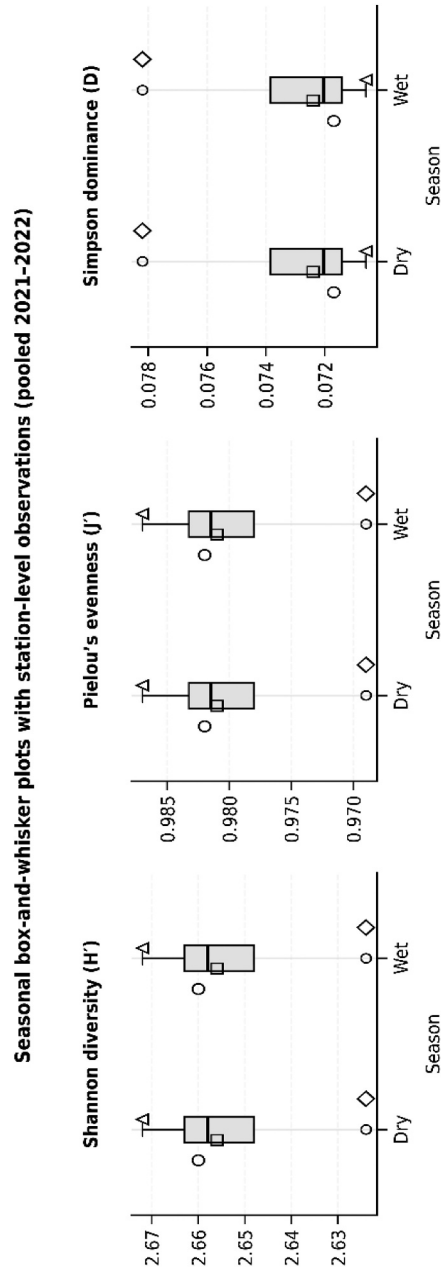


Fig. 5. — Seasonal diversity indices. Panels show Shannon (H'), Pielou's evenness (J'), and Simpson dominance (D) as wet (7/11 months) vs dry (4/11 months) pooled across 2021–2022.

Table 6.

PERMANOVA summary (Bray–Curtis on station $\times$ season matrix; 999 permutations).

Factor	df (between, within)	F (pseudo-F)	<i>P</i> -value	Permutations
Station (S1–S4)	3, 4	1.423	0.359	999
Season (Wet vs Dry)	1, 6	4.073	0.067	999

Note: The Station $\times$ Season interaction was not tested because only one pooled observation per cell was available under the Wet/Dry aggregation scheme.

Table 7.

Envfit vectors on nMDS (999 permutations).

Variable	r^2	<i>P</i> (perm)
Temperature	0.924	0.038
TDS	0.887	0.042
Phosphate	0.854	0.035
Sulphate	0.821	0.046
Conductivity	0.678	0.074
Alkalinity	0.675	0.096
Turbidity	0.646	0.131
Nitrate	0.636	0.087

Note: Vectors are shown on the ordination in Fig. 6 (arrows scaled to correlation length; station symbols coloured by station and shaped by season).

patterns further reflect longitudinal habitat gradients within the Gurara system. High CPUE at Bonu (S1) corresponds with patterns reported for structurally complex upstream reaches of the Niger and Anambra river basins, where higher turbulence and oxygenation enhance fish encounter rates (Laë et al. 2004; Odo et al. 2009). In contrast, the pronounced year-to-year increases at Izom (S3) parallel findings from mid-reach sections of the Benin and Lower Niger rivers, where localized improvements in flow connectivity or nutrient dynamics can temporarily bolster fish recruitment and catchability (Adeniyi 2021; Ogbeibu & Okeke 2024).

The inter-annual CPUE increases observed across stations are also consistent with hydrological explanations widely reported in African river systems. Multi-year flood cycles, shifts in seasonal flow, and changes in habitat availability are known to drive basin-wide changes in fish biomass and behavior (Comte & Olden 2017; Dudgeon 2019). Tropical river studies frequently note that favourable hydrological periods lead to marked increases in catchability and abundance, particularly following strong recruitment years, as seen in hydrological assessments across West Africa (White et al. 2012; Adeyeri et al. 2024). Strong statistical effect sizes further reinforce the ecological significance of these CPUE changes. Although limited replication reduces the power of non-parametric tests, a common challenge in Nigerian river

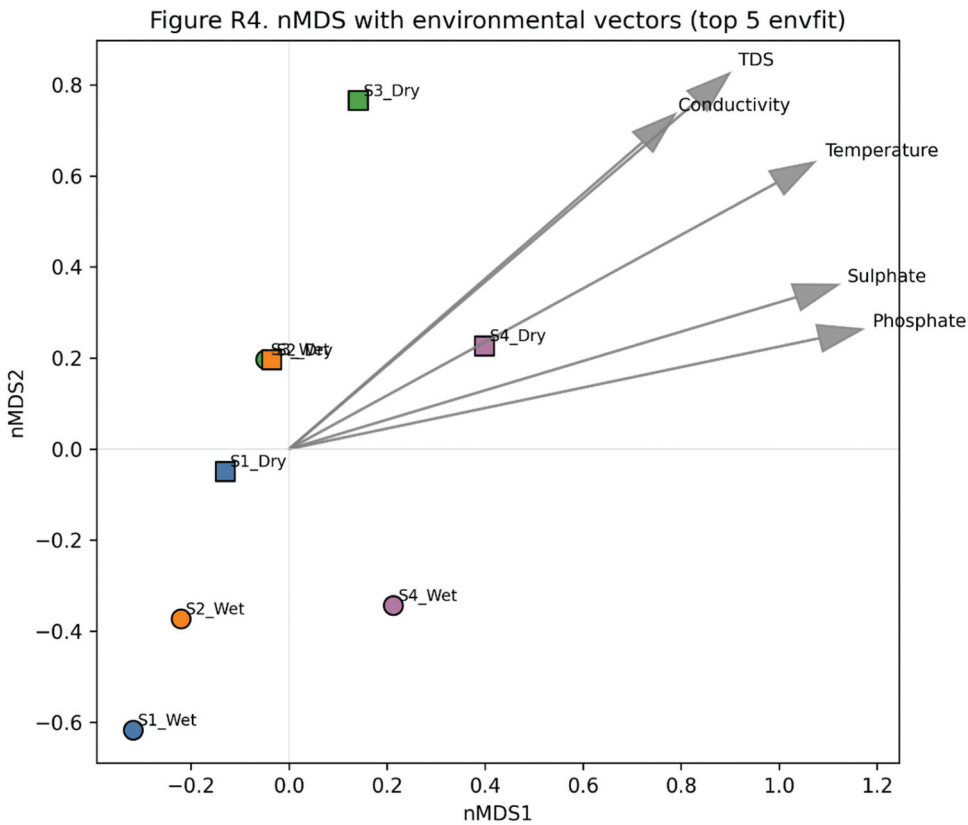


Fig. 6. — nMDS ordination of fish assemblages with fitted environmental vectors. Points represent station–season samples (S1–S4; wet = circles, dry = squares), and arrows indicate the top five environmental variables, with arrow length proportional to correlation strength.

assessments (Adedeji et al. 2017), the consistency across methods strengthens confidence in the observed trends. Moreover, because CPUE integrates abundance, behaviour, and habitat accessibility, its clear upward trajectory provides a crucial baseline for future impact assessment. This is especially important given the imminent hydropower developments expected to alter flow structure, habitat connectivity, and community dynamics, as documented in other regulated African rivers (Laë et al. 2004).

Physicochemical dynamics (spatio-seasonal) and habitat–substrate gradients

The physicochemical structure of the Lower Gurara River reflects the combined influence of seasonality and longitudinal position. As in tropical river systems, wet-season runoff increases turbidity and reduces transparency through sediment mobilization, whereas dry-season conditions promote clearer water, longer residence times,

and greater thermal stability (Siddha & Sahu 2022). These seasonal dynamics represent classic flood pulse forcing, providing the temporal template for productivity and biotic turnover (Fausch et al. 2002; Junk & Wantzen 2006; Tockner et al. 2010; Ngor et al. 2018; Banăduc et al. 2024). Superimposed on this pattern are longitudinal riverscape gradients linked to geomorphology and downstream accumulation. Downstream warming reflects wider channels, reduced slope, higher insolation, and longer residence times, while the waterfall reach shows a distinct hydraulic–oxygenation signature driven by turbulence and enhanced gas exchange. These gradients interact with localized anthropogenic pressures, including riparian land use and in-stream exploitation that intensify downstream. Together, natural and human influences structure physicochemical conditions and assemblage patterns along a longitudinal continuum rather than as isolated station effects.

Water temperature increased downstream from S1 to S4, reflecting longitudinal changes in channel morphology and hydrology. Upstream reaches are shallower, faster flowing, and partially shaded, promoting thermal buffering, whereas downstream sections exhibit wider channels, slower currents, longer water residence time, and reduced canopy cover, enhancing solar heating. Such downstream warming is characteristic of tropical river continua and reflects natural riverscape organization rather than site-specific anomalies (Koster et al. 2021; Gudmundsson et al. 2025). Although stations differ thermally, comparisons remain ecologically valid because temperature is an intrinsic structuring variable, and evaluating responses along this gradient captures realistic environmental filtering processes operating across the river system. Longitudinal temperature itself can deviate from simple asymptotic warming when local hydroclimate or channel form impose thermal complexity, underscoring the need for reach-scale observation (Kennard et al. 2010; Fullerton et al. 2015). The ANOVA contrasts with significant among station differences in temperature, alkalinity, depth, nitrate, sulphate, and hardness resolve into an ecologically consistent gradient: S2 functions as a hydraulic–alkalinity end-member (deep, turbulent, well-aerated), whereas S4 expresses a nutrient–ionic end-member indicative of cumulative downstream inputs and greater accessibility. Comparable downstream enrichment of nutrients and major ions, and upstream hydraulic distinctiveness, are repeatedly reported for large West African rivers where land-use pressure, floodplain exchange, and channel morphology co-shape water chemistry and habitat templates (Laë et al. 2004; Kennard et al. 2010). The PCA consolidates these outcomes into two orthogonal environmental axes: PC1 (nutrient–ionic) separating stations by cumulative solute/nutrient status, and PC2 (hydraulic–oxygenation) isolating the waterfall reach by depth, alkalinity, and DO. Such two-axis structures are characteristic of ecohydrological classifications and ordinations used in environmental-flow science: hydrology and geomorphology set the physical template, and catchment use with longitudinal position shape the ionic/nutrient field (Kennard et al. 2010; Humphries et al. 2014).

Ecologically, these gradients set mechanistic expectations for fish assemblages. Hydraulic–oxygenation environments like S2 typically favour rheophilic, oxygen-demanding taxa with high aerobic scope, whereas warmer, depositional, nutrient-enriched downstream reaches (S4) more often support generalist/tolerant guilds and detritivores. This rheophile-to-generalist transition is well documented across tropical rivers where flow regime, temperature, and solute loads co-vary with longitudinal position and local habitat state (Stoffers et al. 2022; Šmejkal et al. 2023).

The seasonal overlay modulates primary production and resource pathways. Wet-season turbidity pulses imply periodic light limitation and shifts among producer

niches, while dry-season stability often promotes more predictable foraging habitats and altered predator–prey encounter rates. In floodplain rivers, hydrological connectivity among channels, benches, and slackwaters affects when and where depositional patches are inundated or isolated, mediating organic-matter retention and nursery conditions; consequently, community composition co-varies with connection history across wet–dry phases (Leigh & Sheldon 2009; Allan et al. 2021). The Gurara stations also express a coherent hydraulic substrate continuum: S1–S2 are coarse and fast (boulder–cobble; riffle–run and plunge-pool hydraulics), S3 transitions to mixed sand–gravel with reduced riparian cover and higher local disturbance, and S4 is wide, slow, and depositional (sand–silt). This upstream–downstream sequence reflects declining channel slope and shear stress, progressive winnowing of coarse substrates, and increased deposition of fine sediments, with human access further altering bank and littoral conditions at S3–S4. Within a riverscape context, such geomorphic heterogeneity, interacting with flow, generates patchy hydraulic habitats that shape biotic distribution and ecological opportunities (Fausch et al. 2002; Mondal & Patel 2022; Yarnell & Thoms 2022). From a flow-ecology standpoint, the upstream–downstream shift in substrate, cover, and hydraulics is the habitat expression of the flow regime (Palmer & Ruhi 2019). Environmental flow classifications therefore anticipate different ecological sensitivities at S2 (risk to turbulence/oxygenation and carbonate buffering) vs S4 (risk of enrichment/retention and warming), guiding indicator selection and sentinel-site monitoring as regulation proceeds (Kennard et al. 2010; Poff et al. 2010; Dutta et al. 2017).

Fish assemblage composition, richness, and diversity

The fish assemblage was dominated by native, non-endemic West African species, indicating a community structured primarily by natural riverscape processes rather than biogeographic restriction. However, the presence of *Lates niloticus* is ecologically notable. Although native to parts of the Niger Basin, it is widely recognized as invasive outside its indigenous range and capable of exerting strong predatory control on fish communities. Its occurrence therefore has important conservation implications, particularly under future hydrological alteration, where large predatory generalists may disproportionately shape assemblage structure (Winemiller et al. 2016).

The pronounced increase in fish abundance between 2021 and 2022 of nearly 700 additional individuals recorded under identical sampling effort and methodology strongly suggests underlying ecological variability rather than methodological artefacts. The fact that all stations exhibited year-to-year increases indicates the influence of basin-scale drivers affecting fish availability or catchability. Interannual hydroclimatic variability is a parsimonious explanation, as fish populations in tropical rivers are highly responsive to changes in rainfall, discharge magnitude, and flood duration, which directly influence recruitment success, habitat availability, and food production (Winemiller et al. 2016). Productive hydrological years are known to enhance floodplain connectivity and nursery habitat, leading to strong cohort formation and subsequent increases in abundance without corresponding shifts in species richness (Castello et al. 2013; Machado et al. 2022).

Hydrological conditions may also have increased catchability in 2022 by altering water depth, current velocity, and habitat compression during receding flows, thereby

concentrating fish in marginal and depositional zones where sampling efficiency is greater (Bozeman et al. 2025; Chemagin et al. 2025). This mechanism is particularly relevant in tropical river systems, where seasonal contraction of wetted habitat can amplify capture rates independently of true population size. The disproportionately large proportional increase observed at S3 Izom (+ 80.4%), despite its relatively low total abundance, suggests that this reach may be especially sensitive to favourable hydrological conditions, potentially due to the relaxation of local constraints such as shallow depth or limited habitat complexity under wetter conditions (Ugbor et al. 2023). Collectively, these patterns indicate that short-term climatic variability acting through habitat expansion, enhanced productivity, and changes in fish distribution rather than assemblage composition is the most likely driver of the observed inter-annual increase in abundance.

Across the 2-year survey ($N = 3,831$), the Gurara River supported 15 species in 11 families, dominated by generalist detritivores/omnivores (*Tilapia/Coptodon*, *Barbus*, *Schilbe*), benthic foragers (*Labeo*, *Synodontis*, *Mormyrus*), and low-abundance predators (*Hydrocynus*, *Lates*), consistent with seasonal West African rivers (Duarte et al. 2022; van der Sleen & Rams 2023). This trophic structure aligns with flood-pulse dynamics and longitudinal habitat heterogeneity, which mediate energy pathways and foraging opportunities (Duarte et al. 2022; van der Sleen & Rams 2023). Functional trait studies similarly show that hydraulic–substrate mosaics sustain broad feeding strategies (Walsh et al. 2022; López Delgado et al. 2024). Electrogonic and benthic taxa (*Mormyrus*, *Malapterurus*) and benthic foragers (*Synodontis*, *Labeo*) indicate structurally diverse low-light benthic habitats, matching trait-based predictions for coarse, turbulent environments (Walsh et al. 2022; López Delgado et al. 2024). Predators (*Hydrocynus*, *Lates*) occurred at modest abundances, typical of size-structured tropical food webs; Lower Benue diet studies corroborate flexible omnivore–detritivore feeding in *Citharinus* and *Mormyrus* and carnivory in *Hydrocynus* (Tseveda et al. 2024).

The rheophilic waterfall reach (S2) supported higher counts of coarse-substrate-associated taxa (*Hydrocynus*, *Mormyrus*), consistent with surveys showing turbulence and coarse bedforms maintain multiple foraging modes (Walsh et al. 2022; López Delgado et al. 2024). Downstream depositional sites (S3–S4) showed greater proportions of generalist–tolerant taxa (*Coptodon*, *Tilapia*, *Citharinus*), reflecting effects of fine substrates and human access documented in African rivers (Shechonge et al. 2024; Ngcobo et al. 2025). Although richness ($S = 15$) was constant across stations, evenness (J') and dominance (D) varied: H' and J' were higher at S1–S3 and lowest at S4, where dominance was greatest, a pattern typical of low-energy reaches favouring tolerant generalists (Walsh et al. 2022; López Delgado et al. 2024). Seasonally, wet-season abundance increased at all stations, reflecting pulse-driven recruitment, while H' , J' , and D changed little consistent with findings that flood pulses alter abundance but not short-term evenness/richness (Duarte et al. 2022). System-wide abundance increased from 2021 to 2022, reflecting year-to-year hydrological variability typical of tropical rivers; similar climate-driven flow alterations are projected for the Upper Niger system (Rameshwaran et al. 2021; Thompson et al. 2021). The prominence of *Coptodon/Tilapia* downstream matches Nigerian studies showing strong condition and environmental tolerance in *Coptodon zillii* (Urom et al. 2025; Usman et al. 2025). Disturbance-gradient studies elsewhere in Nigeria similarly report shifts toward generalist cichlids under mining, urbanization, and gear pressure (Edegbene et al. 2025; Ngcobo et al. 2025). These patterns support sentinel monitoring focused on evenness/

dominance indices ($H'/J'/D$), nutrients, and habitat metrics under future flow regulation scenarios (Bonjoru et al. 2023; FAO 2023, 2024).

Obviously, the Gurara assemblage reflects a riverscape-driven gradient: rheophiles and benthic foragers dominate coarse, turbulent upstream habitats (S1–S2), generalist–tolerant taxa dominate depositional downstream reaches (S3–S4), and predators remain consistently low. Interannual and seasonal abundance trends are consistent with flow-variability controls on tropical river communities (Albert et al. 2021; Walsh et al. 2022; López Delgado et al. 2024; Shechonge et al. 2024).

Links between environment and biota

Multivariate analyses show that environmental gradients and human-related pressures structure fish assemblages in the Lower Gurara River. Despite differences in statistical strength among methods, the overall pattern aligns with established tropical river ecology: communities respond to hydrological seasonality, physicochemical conditions, and habitat alteration (Junk et al. 1989; Dudgeon 2019; Arimoro et al. 2025, 2026). Seasonal influences were evident, consistent with flood-pulse systems where wet-season expansion enhances dispersal and recruitment, and dry-season contraction intensifies biotic interactions (Junk & Wantzen 2006; White et al. 2012). Even moderate seasonal differences therefore remain ecologically meaningful.

Spatial gradients were also detectable. Variables highlighted by BEST and ordination temperature, dissolved oxygen, dissolved solids, and nutrients are classic drivers of longitudinal fish assemblage shifts, differentiating cooler, fast-flowing upstream reaches from warmer, depositional downstream zones (Kennard et al. 2010; Comte & Olden 2017). Such gradients typically correspond to transitions from rheophilic species upstream to tolerant omnivores and detritivores downstream, a pattern well documented in African rivers (Arimoro & Ikomi 2009; Meulenbroek et al. 2019; Arimoro et al. 2026). Nutrient-associated variables (e.g. phosphorus, sulphate) among the strongest correlates indicate localized disturbance. These parameters commonly rise with riparian degradation, domestic runoff, and bank modification, conditions also observed at downstream sites and are frequently linked to shifts toward generalist, disturbance-tolerant assemblages (Fausch et al. 2002; Dudgeon 2022). Overall, the results support the central hypothesis that physicochemical gradients shaped by hydrology, geomorphology, and human influence are key determinants of fish community structure in the Lower Gurara River. Although finer-scale temporal and spatial sampling would strengthen inference, the detected patterns are directionally robust and consistent with broader tropical river theory and comparative studies.

Implications for management: pre-impoundment baselines and early post-regulation surveillance

A defensible pre-impoundment baseline for the Gurara River must index its two dominant environmental axes, a hydraulic–oxygenation axis (depth, velocity, turbulence, DO) and a nutrient–ionic axis (nitrate, phosphate, sulphate, conductivity/TDS), both strongly shaped by wet–dry seasonality. This reflects established hydrology–ecology linkages in environmental-flow and riverscape frameworks (Junk et al. 1989; Fausch et al. 2002; Kennard et al. 2010; Poff et al. 2010). The need is heightened by

projected non-stationary low flows and shifting flood extents in West Africa (Rameshwaran et al. 2021; Thompson et al. 2021) and by global freshwater biodiversity declines that demand early-warning indicators (Albert et al. 2021). A streamlined indicator suite should include: (i) hydraulic–oxygenation variables (stage/depth, velocity/turbulence proxies, DO, alkalinity) to detect early changes in aeration and riffle–run integrity (Fausch et al. 2002; Kennard et al. 2010); (ii) nutrient–ionic measures (nitrate, phosphate, sulphate, hardness, conductivity/TDS, temperature) to track downstream enrichment or warming (Kennard et al. 2010; Poff et al. 2010); and (iii) turbidity/Secchi as a seasonal sediment delivery sentinel with implications for light, production, and trophic pathways (Junk et al. 1989; Duarte et al. 2022). These variables map directly onto the Gurara PCA gradients (PC1 nutrient–ionic; PC2 hydraulic–oxygenation) and align with best practice in environmental flow assessments (Kennard et al. 2010; Poff et al. 2010).

A four-station sentinel network captures expected regulation signals: S2 (Gurara Waterfall) as the hydraulic–oxygenation sentinel; S4 (Gawu) as the enrichment/warming sentinel; S1 (Bonu) as upstream reference; and S3 (Izom) as a mid-reach integrator reflecting propagation of regulation effects (Walsh et al. 2022; López Delgado et al. 2024). Early warning triggers should be season-specific. In the wet season, investigate if turbidity exceeds the pre-project 75th percentile for ≥ 2 months and if nitrate/phosphate at S4 cross their 75th percentiles, signalling light limitation or incipient eutrophication (Junk et al. 1989; Duarte et al. 2022). In the dry season, investigate if mean DO at S2 falls below the pre-project 25th percentile or if S3–S4 temperatures exceed 75th percentiles, reflecting aeration and thermal risks typical of flow alteration (Poff et al. 2010; Thompson et al. 2021). Trigger responses should include diel DO/temperature profiles, nutrient tracing, and targeted velocity/habitat transects, alongside potential adjustments to environmental releases (Poff et al. 2010).

Monitoring should follow a monthly core cadence, with bi-weekly wet-season checks for turbidity and DO. Co-registered biotic sampling (standardized CPUE and diversity indices) will track ecological responses along the physicochemical axes, consistent with evidence of seasonal restructuring in tropical rivers (Duarte et al. 2022) and the need for standardized gears in Nigerian systems (Bonjoru et al. 2023; Shechonge et al. 2024). Analytical outputs should translate into management actions by expressing each sampling event as PC1–PC2 station scores and using threshold-linked dashboards. Annual scorecards should compare pre- vs post-regulation conditions, integrating physicochemical shifts with changes in evenness/dominance and guild transitions, as recommended by trait-based Afrotropical studies (Walsh et al. 2022; López Delgado et al. 2024). Given projected dry-season flow changes in West Africa and ongoing global freshwater biodiversity declines, establishing this hydraulics and nutrients anchored baseline complete with seasonal triggers and biotic co-monitoring, is the minimum necessary to safeguard ecosystem function and fisheries value through and after impoundment (Albert et al. 2021; Rameshwaran et al. 2021).

CONCLUSION

This study provides a robust pre-impoundment baseline for the Lower Gurara River, demonstrating that ecosystem structure is organized along two primary physicochemical gradients: a hydraulic–oxygenation axis strongest at the waterfall reach, and a nutrient–ionic axis that intensifies downstream, both modulated by pronounced wet–dry seasonality. These gradients align with environmental-flow and riverscape

theory, offering a clear mechanistic framework for detecting ecological change once regulation begins. Fish assemblage patterns mirrored these environmental axes. Coarse, high-energy upstream habitats (S1–S2) supported rheophilic and benthic foraging taxa, whereas depositional downstream reaches (S3–S4) were dominated by generalist and tolerant species. Although richness remained constant across stations, evenness declined and dominance increased downstream, and wet-season abundance rose without substantial shifts in α -diversity responses characteristic of tropical rivers governed by flood-pulse dynamics and longitudinal habitat filtering. The system-wide increase in abundance from 2021 to 2022 is consistent with regional hydroclimatic variability, particularly the sensitivity of low flows and flood extent. Together, these findings highlight the need for continued monitoring of key hydraulic–oxygenation (S2) and nutrient–ionic (S4) sentinel sites using PC-axis-based dashboards and pre-defined thresholds to support timely ecological assessment following hydropower regulation.

ACKNOWLEDGEMENTS

We thank the local communities along the Lower Gurara River and the hired fishermen for their support during field activities. We also acknowledge the assistance of field and laboratory staff from the Federal University of Technology, Minna. Constructive inputs from colleagues and reviewers greatly improved this manuscript.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

AUTHOR CONTRIBUTION

F.O. Arimoro conceptualized the study alongside D.S. Abubakar, while F.O. Arimoro, D.S. Abubakar, Y.I. Auta, and A.V. Ayanwale were responsible for designing the field methodology and fish surveys. D.S. Abubakar and Y.I. Auta co-conceptualized the study, coordinated field logistics, and wrote the initial draft of the manuscript. F.O. Arimoro also served as the academic supervisor, providing oversight throughout the research process, including study design, methodological refinement, and critical review of the manuscript. All authors contributed to data interpretation, manuscript revisions, and approved the final version.

ETHICAL STANDARD

All field procedures in this study complied with institutional, national, and international guidelines for the ethical handling of fish and aquatic wildlife. Sampling methods were non-destructive, and fish were handled carefully to minimize stress, injury, and exposure time before release. No endangered or legally protected species were harmed during the study. Permissions for field sampling along the Lower Gurara River were obtained from the appropriate state and local authorities, and all research activities were conducted in accordance with the ethical standards of the Federal University of Technology, Minna, and relevant Nigerian environmental regulations.

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