

Seasonal Variation of the Physicochemical Quality of Water and the Structure of Benthic Macroinvertebrate Communities in the Middle Reach of the Chari River in Chad (Sudano-Saharan Zone-Central Africa)

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Abstract

Physicochemical analyses coupled with the study of benthic macroinvertebrate community structures constitute an excellent tool for assessing the ecological health status of lotic environments. However, very few studies have addressed the ecological characteristics and functioning of the Chari River, and the influence of anthropogenic pressures and seasonal variability on this group of bioindicators remains poorly understood. This study aimed to assess the seasonal trend of the physicochemical water quality and the benthic macroinvertebrate community structure of the middle course of the Chari River in Chad. Twelve sampling stations were selected along the middle reach of the Chari River. Data were collected monthly during the two climatic seasons, namely in November, February, March, and April during the dry season, and in May, August, September, and October during the rainy season. Water physicochemical parameters were measured both *in situ* and in the laboratory following standard methods, whereas benthic macroinvertebrates were collected following the multi-habitat approach, using a long-handled kick net. Water quality indices showed that waters of the middle reach of the Chari River fall within the good-to-moderate quality range, with moderate and mostly biodegradable organic pollution and high nitrogen contamination linked to anthropogenic inputs. Concerning macrofauna, a total number of 14,871 individuals,

distributed in 3 phyla, 7 classes, 17 orders, 82 families, and 136 genera, were identified. The orders Hemiptera, Coleoptera, and Gastropoda were the most abundant during the rainy season, while Ephemeroptera, Unionoida, and Odonata were dominant during the dry season. The analysis of interactions between abiotic and biotic factors revealed a seasonal structuring of the benthic macrofauna of the middle Chari along an ecological quality gradient. This gradient opposed well-oxygenated environments characterized by relative hydrological stability—associated with high taxonomic richness and high community diversity in the dry season—to environments enriched with nitrogenous compounds and organic matter of anthropogenic origin during the rainy season, where pollution-tolerant taxa such as Chironomidae dominate. Overall, these results show that the middle course of the Chari River remains moderately impacted by anthropogenic pressures, with fairly good water quality. These results highlight the importance of establishing a regular monitoring program, as well as controlling diffuse pollution sources in the Chari catchment, to prevent increasing degradation of this aquatic ecosystem.

Keywords

Benthic Macroinvertebrates, Physicochemical Water Quality, Ecological Indices, Seasonal Variations, Bioindicators, Middle Chari River

1. Introduction

The Chari River is one of the most important watercourses in Central Africa. It is a perennial river with numerous ecological services across its catchment, including domestic, economic, environmental, and cultural uses. More than 30 million people living in the Lake Chad Basin depend on its water resources for vital needs such as drinking water, agricultural irrigation, livestock watering, fishing, and other socio-economic activities [1]. This anthropogenic pressure, increasingly pronounced due to population growth, significantly affects the ecological health status of the Chari River, which crosses three ecological zones and receives multiple agricultural, domestic, urban, and industrial discharges along its course [2]. It is well documented that emerging pollutants persist in the environment, accumulate in food webs, and pose significant risks to aquatic ecosystems by affecting biodiversity and ecological functions [3] [4]. The continuous degradation of the Lake Chad wetlands, fed by tributaries such as the Chari, has already led to a considerable reduction of biodiversity and fishery resources, directly impacting the livelihoods of millions of people living there [5]. Scientific predictions highlight that, in the absence of concrete ecological restoration measures and integrated water resource management, these environmental and socio-economic pressures will continue to intensify to the detriment of local populations. However, studies specifically focusing on the integrated assessment of the ecological quality of Lake Chad and its main tributaries remain very limited, both in terms of spatial coverage and the ecological indicators employed [6].

Benthic macroinvertebrates are animal organisms visible to the naked eye (insects, mollusks, crustaceans, and annelids) living at the bottom of rivers and lakes. Due to their high taxonomic diversity, low mobility, and different ranges of sensitivity to environmental disturbances, they constitute excellent bioindicators of the ecological quality of aquatic ecosystems, allowing for the assessment of pollution status and the proper functioning of freshwater bodies [7] [8]. They are characterized by remarkable taxonomic diversity, with many species exhibiting varying degrees of tolerance to environmental stress, which strengthens the robustness of ecological data interpretation [9]. These characteristics confer upon benthic macroinvertebrates the status of effective local indicators of aquatic ecosystem health [10].

The ecological assessment of aquatic ecosystems, combining both environmental factors and benthic macroinvertebrate communities, is widely recognized as a reliable and effective method, due to its ability to integrate the cumulative effects of environmental pressures [11]. Therefore, this study aimed to assess the seasonal trend of the physicochemical water quality and the benthic macroinvertebrate community structure of the middle course of the Chari River in Chad.

2. Materials and Methods

2.1. Description of the Study Area and Sampling Sites

The Chari River is a transboundary watercourse of approximately 1,200 km that originates from the Central African Republic and flows through Chad (about 826 km in length within Chadian territory) and Cameroon. It is the main tributary feeding Lake Chad and, together with its major tributary, the Logone River, provides nearly 92% of the total water inflow to the Lake Chad Basin [12]. Upon entering Chad, the Chari River results from the confluence of three rivers originating from the Central African Republic: the Bamingui (356 km), the Gribingui (418 km), and the Bangora (355 km), which together drain a watershed of approximately 80,000 km². The river then flows northward, successively crossing the Sudanese and Sahelian zones before discharging into Lake Chad. It is characterized by a very low average slope of approximately 0.1 m/km between its confluence with the Bahr Aouk and Lake Chad over a distance of 826 km within Chad [13]. The low-water period of the Chari River generally extends from March to June, while the difference between flood and low-water levels is about 5 m [14] [15]. The Chadian part of the Chari watershed is mostly within a dry tropical climate of Sudano-Saharan type, characterized by a unimodal rainfall pattern comprising a short rainy season extending from May to October, with the heaviest rainfall occurring in July and August, and a long dry season lasting from November to April [16] [17].

The main activities carried out by local populations in the Middle Chari area include fishing, market gardening, trade, quarry exploitation, slaughterhouse activities, and various industrial operations. Assessing the economic importance of these activities, as well as their respective impacts on aquatic environments and

natural resources, is essential for understanding the anthropogenic pressures affecting the Chari hydrographic system.

To carry out this study, twelve (12) sampling stations were selected based on their ecological relevance, including habitat diversity and proximity to anthropogenic activity zones, while ensuring an adequate spatial distribution along the middle course of the Chari River. **Figure 1** presents the sampling sites located along the middle course of the Chari River.

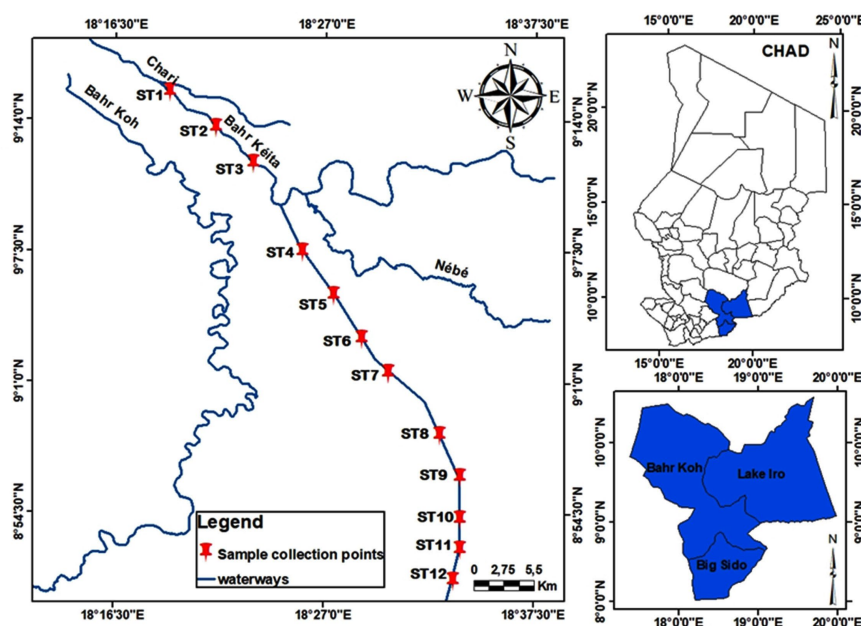


Figure 1. Location map of benthic macroinvertebrate sampling sites along the Middle Chari River (ST1 = Bridge; ST2 = Koumra; ST3 = Slaughterhouse; ST4 = Coton Tchad; ST5 = Hospital; ST6 = GNNT; ST7 = UDS; ST8 = Kemdéré; ST9 = Moudjirome; ST10 = Downstream CST; ST11 = CST outlet; ST12 = Upstream CST).

2.2. Abiotic Parameters Data

2.2.1. Measurement of Abiotic Parameters

Measurements of physicochemical parameters were carried out monthly during the two climatic seasons: in November, February, March, and April during the dry season, and in May, August, September, and October during the rainy season. These measurements were conducted both *in situ* and in the laboratory following the standard methods [18] [19]. Therefore, water temperature ($^{\circ}\text{C}$), pH, electrical conductivity ($\mu\text{S}/\text{cm}$), and dissolved oxygen content (mg/L) were measured *in situ* using a handheld multiparameter WTW 3430.

Likewise, water transparency (m) was determined using a Secchi disk. Water depth was measured using a graduated rope fitted with a Secchi disk weighted with a lead sinker and lowered vertically to the riverbed. Measurements were taken at several points within each sampling station, and the mean value was retained. For the parameters to be measured in the laboratory, water samples were collected at each station using a 500 mL precleaned and labeled container, stored in a cooler

at 4 °C, and transported to the laboratory for analysis.

Physicochemical parameters, including ammonium (NH_4^+) (mg/L), nitrite (NO_2^-) (mg/L), nitrate (NO_3^-) (mg/L), orthophosphate (PO_4^{3-}) (mg/L), biochemical oxygen demand (BOD_5) (mg/L), and chemical oxygen demand (COD) (mg/L), were then analyzed following standard laboratory procedures.

2.2.2. Calculation of Physicochemical Water Quality Indices

The Organic Pollution Index (OPI) [20] was calculated to assess the organic pollution of water at the different sampling stations during the study period. The OPI value ranges from one (1) to five (5), and its calculation is based on the concentrations of chemical parameters associated with organic pollution, such as ammonium ions, nitrites, phosphates, and BOD_5 (Table 1). Finally, the OPI corresponds to the average of the class numbers assigned to each measured parameter concentration. The OPI evaluates overall organic pollution based on oxygen demand and reduced nitrogen compounds [20].

The “Mean OPI Value” column corresponds to the index obtained by averaging the classes assigned to ammonium, nitrite, orthophosphate, and BOD_5 concentrations. This index ranges from 1 to 5 and provides a synthetic measure of the degree of organic pollution in water bodies. The “Level of Organic Pollution” column represents the ecological interpretation of OPI values. The highest values (4.6 - 5.0) indicate the absence or a very low level of organic pollution, whereas the lowest values (1.0 - 1.9) reflect very high organic pollution. Therefore, water quality progressively deteriorates as the OPI value decreases.

Table 1. Classification grid of the organic pollution index [20].

OPI Classes	Threshold values of the parameters				Mean values of OPI classes	Level of organic pollution.
	NH_4^+ (mg/L)	NO_2^- ($\mu\text{g/L}$)	PO_4^{3-} ($\mu\text{g/L}$)	BOD_5 (mg/L)		
5	<0.1	≤ 5	<15	<2.0	4.6 - 5.0	Null
4	0.1 - 0.9	6 - 10	16 - 75	2.1 - 5.0	4.0 - 4.5	Low
3	1.0 - 2.4	11 - 50	76 - 250	5.1 - 10.0	3.0 - 3.9	Moderate
2	2.5 - 6.0	51 - 150	251 - 900	10.1 - 15.0	2.0 - 2.9	High
1	>6.0	>150	>900	>15.0	1.0 - 1.9	Very high

Moreover, the index measuring the biodegradability of organic matter (COD/ BOD ratio), the Nitrogen Contamination Index (NCI) related to agricultural or domestic inputs, the Simplified Eutrophication Index (SEI), and the Water Quality Index (WQI) were respectively used to characterize the overall physicochemical quality of the water of the middle Chari River during the study period.

The Water Quality Index (WQI) was calculated by integrating several physicochemical variables representative of water quality, including pH, dissolved oxygen, electrical conductivity, nitrates, and phosphates. For each parameter, a quality sub-index (Q_i) was determined by comparing the mean value measured in the field (C_i) with the corresponding water quality standard (S_i), using the equation

$Q_i = (C_i/S_i) \times 100$. The standard values (S_i) used for the calculation of the quality sub-indices corresponded to the guidelines recommended by the World Health Organization [21], namely: 8.5 for pH, 5 mg/L for dissolved oxygen, 1000 $\mu\text{S}/\text{cm}$ for electrical conductivity, 50 mg/L for nitrates (NO_3^-), and 0.5 mg/L for phosphates (PO_4^{3-}). Relative weights (W_i) were then assigned to the different parameters according to their contribution to overall water quality, following the recommendations of Tyagi *et al.* [22]: 4 for pH, 5 for dissolved oxygen, 4 for electrical conductivity, 5 for nitrates, and 5 for phosphates.

For each parameter, the product of the quality sub-index (Q_i) and its relative weight (W_i) was calculated. The sum of these products was then divided by the sum of the weights to obtain the Water Quality Index (WQI), according to the formula presented in Table 2. The resulting WQI values were interpreted based on the water quality classes provided in the same table. Table 2 summarizes the formulas used to calculate these indices, as well as the threshold values for interpreting each index and the corresponding references.

Table 2. Summary of the indices used for the assessment of the physico-chemical quality of water and their interpretation thresholds (COD/BOD ratio: biodegradability index of organic matter; NCI: Nitrogen Contamination Index; SEI: Simplified Eutrophication Index; WQI: Water Quality Index; NH_4^+ : ammonium ions; NO_2^- : nitrite ions; NO_3^- : nitrate ions; PO_4^{3-} : orthophosphate ions; BOD₅: Biochemical Oxygen Demand; COD: Chemical Oxygen Demand; Q_i represents the quality sub-index of each parameter, and W_i its relative weight).

Indice	Formules	Classes	References
COD/BOD ₅	COD/BOD ₅	<2: Biodegradable	[23]
		2 - 3: Moderate	
		>3: Poorly biodegradable	
NCI	$\text{NCI} = \text{NO}_2^- + \text{NO}_3^- + \text{NH}_4^+$	<3: Low	[24] [25]
		3 - 6: Moderate	
		>6: High	
SEI	$\text{SEI} = (\text{NO}_3^- + \text{NH}_4^+ + \text{PO}_4^{2-})/3$	<3: Low	[26]
		3 - 6: Moderate	
		>6: High	
WQI	$\text{WQI} = \frac{\sum q_i w_i}{\sum w_i}$	≥ 90 : Excellent	[21] [22]
		70 - 90: Good	
		50 - 70: Moderate	
		25 - 50: Poor	
		<25: Very poor	

2.3. Biological Data

2.3.1. Sampling of Benthic Macroinvertebrates

Similar to the abiotic parameters, benthic macroinvertebrates were sampled dur-

ing both climatic seasons, namely in November, February, March, and April during the dry season, and in May, August, September, and October during the rainy season. Sampling was carried out in shallow areas (especially along the river bank) characterized by a weak current with various sediment types (sand, clay, and plant debris) and/or beneath vegetation (floating macrophytes, emergent bank vegetation, and submerged roots). A handheld net consisting of a 120 cm handle and a collecting net with a circular opening of 30 cm diameter, 50 cm depth, and 400 μm mesh size was used to collect the macrofauna samples following the multi-habitat approach described by Stark *et al.* [27].

At each station, covering approximately 100 m, a total of 20 net drags were performed across different microhabitats (substrates). Floating debris, as well as roots of surface and bank macrophytes, were collected for organism sampling. The net contents were transferred into a basin and washed through a 40×20 cm sieve with a 400 μm mesh size. Collected organisms were preserved in labelled containers with 90% ethanol for each sampling site. Fine stainless-steel forceps and a hand lens were also used to facilitate specimen collection.

In the laboratory, samples were rinsed through a 400 μm mesh sieve with tap water, and all macroinvertebrate individuals were sorted into Petri dishes using fine forceps, under a Nikon SMZ745 stereomicroscope. During this process, the invertebrates were sorted, identified, counted, and preserved in labelled plastic containers with 90% ethanol. The organisms were identified to the genus and/or species level using taxonomic keys, specialized literature, and appropriate online resources [28]-[31].

2.3.2. Determination of Community Structure Indices

Shannon-Weaver diversity (H) and Pielou's evenness (J) indices were calculated to describe the overall structure of benthic macroinvertebrate communities. The Shannon-Weaver diversity index (H') is expressed in bits per individual. Subsequently, the Chironomidae Index (CI) and the Ephemeroptera-Plecoptera-Trichoptera (EPT) index, expressed as percentages, were used to assess the ecological quality of the water, based respectively on the sensitivity and tolerance of macroinvertebrates to water pollution.

Furthermore, the Hilsenhoff Biotic Index (HBI) and Margalef richness index (Mg) were used to evaluate the biological quality of the water, based respectively on the tolerance of macroinvertebrates to organic pollution and on species richness. Taxonomic richness (S), the EPT index, the Hilsenhoff Biotic Index (HBI), and the Chironomidae Index (CI) were calculated using taxa identified to the genus and/or species level, depending on the taxonomic resolution available for each group. **Table 3** presents the values of these indices as well as their ecological interpretation.

2.4. Statistical Analysis of Data

The Mann-Whitney U non-parametric test was used to compare abiotic parameters between the dry and rainy seasons, based on the monthly mean values obtained for each season. Differences were considered statistically significant at $p <$

0.05. All these non-parametric tests were performed using SPSS software version 21. To characterize seasonal variations in water quality, the structuring effect of abiotic parameters on the distribution of macroinvertebrate abundances was assessed using Principal Component Analysis (PCA). The scatter plot of variables and seasons, corresponding to a factorial correlation map, was used for result interpretation. No transformation was applied to the environmental and biological data matrices before performing the statistical analyses. The analyses were performed using XLSTAT software (version 2016).

Table 3. Summary of the biological indices used, formulas, interpretations, and references (p_i: proportion of taxon i; S: species richness; CA: Chironomidae abundance; TA: total abundance; N_{EPT}: total number of individuals belonging to the three EPT orders; EPT: Ephemeroptera, Plecoptera, Trichoptera; a_i: abundance of taxon i; t_i: tolerance value of taxon i (0 - 10); N: total number of individuals in the sample; ln: natural logarithm).

Index	Formula	Interpretation	References
Species richness (S)	$S = \text{Total monthly number of species}$	High S = species-rich environment	[32]
Shannon diversity index (H)	$H = -\sum p_i \ln(p_i)$	High H = high diversity Low H = low diversity	[33]
Pielou's evenness index (J)	$J = \frac{H}{\ln(S)}$	J close to 1 = well-balanced taxa distribution Low J = dominance of a few taxa	[33]
Chironomidae Index (CI)	$CI = \frac{CA}{TA}$	High CI = strong organic pollution	[34] [35]
EPT Index	$EPT(\%) = \frac{N_{EPT}}{N_{total}}$	High EPT = good water quality Low EPT = disturbed environment	[36] [37]
Hilsenhoff Biotic Index (HBI)	$HBI = \frac{\sum(n_i \times t_i)}{N}$	HBI ranges from 0 (very clean water) to 10 (heavily polluted water).	[38] [39]
Margalef Index (Mg)	$Mg = \frac{S-1}{\ln(N)}$	High Mg = high taxonomic richness Low Mg = low taxonomic richness	[40]

3. Results and Discussion

3.1. Results

3.1.1. Descriptive Analysis of Abiotic Parameters

Seasonal variations in physicochemical parameters are presented in **Table 4**. Water transparency ranged from 20 to 40 cm during the dry season, compared to 5 to 57 cm during the rainy season. Measured temperatures varied from 27.70°C to 33.50°C in the dry season, whereas during the rainy season, values fluctuated from 20.90°C to 33.00°C. Similarly, pH values ranged from 6.00 to 11.40 in the dry season, compared to 4.11 to 7.80 during the rainy season. Overall, the pH remained close to neutrality (7.38 ± 1.65) in the dry season, while it was slightly acidic during the rainy season (6.59 ± 0.81).

Conductivity values ranged from 1.80 to 145.50 µS/cm in the dry season, compared to 51.78 to 265.00 µS/cm during the flood season. The highest values were recorded during the dry season (106.71 ± 33.84 µS/cm on average), compared to the rainy season (79.30 ± 41.45 µS/cm on average) throughout the study period.

This difference was statistically significant (Mann-Whitney U test, $p = 0.00$).

Regarding dissolved oxygen, values ranged from 0.25 to 4.20 mg/L in the dry season and from 0.60 to 6.20 mg/L during the rainy season. Overall, concentrations remained low to moderate throughout the year. Statistically, mean dissolved oxygen values were significantly lower in the dry season (1.68 ± 1.20 mg/L) than in the rainy season (3.22 ± 1.58 mg/L) (Mann-Whitney U test, $p = 0.001$). The lowest mean chemical oxygen demand (COD) concentration was observed during the rainy season (85.89 ± 89.53 mg/L), whereas the highest was recorded during the dry season (86.12 ± 49.35 mg/L). However, COD did not show any significant variation between the two seasons ($p = 0.39$). Furthermore, COD exhibited comparable mean values between the dry season (86.12 ± 49.34 mg/L) and the rainy season (85.89 ± 89.53 mg/L).

For nitrates (NO_3^-), the mean concentration was 2.76 ± 2.63 mg/L during the dry season and 3.81 ± 2.09 mg/L during the rainy season. The mean nitrite (NO_2^-) concentration was 0.45 ± 10.80 mg/L in the dry season, compared to 2.64 ± 5.35 mg/L in the rainy season. Mean ammonium (NH_4^+) concentrations were 0.46 ± 0.72 mg/L during the dry season, significantly lower than those recorded during the rainy season (0.51 ± 0.55 mg/L) (Mann-Whitney U test, $p = 0.04$). Regarding orthophosphate (PO_4^{3-}), concentrations ranged from 0.11 to 36.30 mg/L in the dry season, compared to 0.80 to 13.05 mg/L during the rainy season. The lowest mean value was observed during the rainy season (5.18 ± 3.10 mg/L), whereas the highest was recorded during the dry season (8.19 ± 9.74 mg/L), although this difference was not statistically significant (Mann-Whitney U test, $p = 0.69$).

Table 4. Mean values of abiotic parameters according to seasons and Mann-Whitney comparison tests (Prof: depth; Tran: transparency; Temp: temperature; EC: electrical conductivity; O₂: oxygen saturation rate; NH_4^+ : ammonium ions; NO_2^- : nitrite ions; NO_3^- : nitrate ions; PO_4^{3-} : orthophosphate ions; BOD₅: biochemical oxygen demand; COD: chemical oxygen demand).

Variables	Dry season			Rainy season			Mann-Whitney U test	
	Mean	Min-Max	Standard deviation	Mean	Min-Max	Standard deviation	U	p-value
Tran	25.54	20.00 - 40.00	6.79	27.37	5.00 - 57.00	11.27	249.50	0.42
Temp	30.36	27.70 - 33.50	1.52	29.55	20.90 - 33.00	2.42	336.50	0.32
pH	7.38	6.00 - 11.40	1.65	6.59	4.11 - 7.80	0.81	345.00	0.24
EC	106.71	1.80 - 145.50	33.84	79.30	51.78 - 265.00	41.45	496.00	0.000
O₂	1.68	0.25 - 4.20	1.20	3.22	0.60 - 6.20	1.58	130.00	0.00
BOD₅	37.72	21.05 - 122.40	24.38	40.57	13.80 - 189.60	36.03	296.00	0.87
COD	86.12	54.35 - 238.50	49.35	85.89	18.90 - 435.00	89.53	330.00	0.39
NO₃⁻	2.76	0.10 - 7.20	2.63	3.81	0.25 - 7.20	2.09	207.50	0.09
NO₂⁻	4.50	0.00 - 49.00	10.80	2.64	0.03 - 24.70	5.35	211.00	0.11
NH₄⁺	0.46	0.00 - 3.82	0.72	0.51	0.20 - 3.00	0.55	189.00	0.04
PO₄³⁻	8.19	0.11 - 36.30	9.74	5.18	0.80 - 13.05	3.10	268.00	0.69

3.1.2. Assessment of Water Quality Based on Physicochemical Water Indices

Table 5 below presents the mean values and their associated interpretations of the physicochemical water quality indices according to seasonal variability. During the dry season, the Organic Pollution Index (OPI) showed a mean value of 2.46, with extremes ranging from 1.75 to 3.00, indicating moderate organic pollution (intermediate level). During the rainy season, the mean OPI value was 2.38, with variations ranging from 1.75 to 3.25, also reflecting moderate organic pollution, although slightly more variable. In the dry season, the COD/BOD₅ ratio showed a mean value of 2.33, with extremes ranging from 1.95 to 2.62, indicating predominantly biodegradable organic matter. During the rainy season, the COD/BOD₅ ratio was 1.95, with variations ranging from 0.69 to 2.75, reflecting high biodegradability of organic matter. Regarding the Nitrogen Contamination Index (NCI), it showed a mean value of 7.72, with extremes ranging from 0.31 to 51.63 during the rainy season, compared to a mean value of 6.96 during the dry season, with values ranging from 1.46 to 32.26.

The Simplified Eutrophication Index (SEI) exhibited a slightly higher mean value during the dry season (3.80), with extremes ranging from 0.31 to 14.31, reflecting moderate trophic enrichment. In comparison, during the rainy season, the mean SEI value was 3.17, with values ranging from 1.003 to 6.22, indicating slightly lower enrichment. Furthermore, the Water Quality Index (WQI) showed a mean value of 76.36, with extremes ranging from 50.30 to 89.70 during the dry season, indicating good water quality (class 70 - 90). During the rainy season, the WQI was 72.79, with values fluctuating between 48.75 and 84.38, reflecting water quality ranging from good to moderate, with more pronounced variability during the rainy season.

Table 5. Mean values and interpretations of physicochemical water quality indices according to seasonal dynamics (OPI: Organic Pollution Index; COD/BOD ratio: biodegradability index of organic matter; NCI: nitrogen contamination index; SEI: eutrophication index; WQI: water quality index).

Indices	Seasons	Mean	Min-Max	Interpretations
OPI	Dry season	2.46	1.75 - 3.00	Moderate organic pollution
	Rainy season	2.38	1.75 - 3.25	
COD/BOD₅	Dry season	2.33	1.95 - 2.62	Moderate biodegradability
	Rainy season	1.95	0.69 - 2.75	High biodegradability
NCI	Dry season	6.96	1.46 - 32.26	High index
	Rainy season	7.72	0.31 - 51.63	
SEI	Dry season	3.80	0.31 - 14.31	Moderate trophic enrichment
	Rainy season	3.19	1.00 - 6.22	
WQI	Dry season	76.36	50.30 - 89.70	Good water quality
	Rainy season	72.79	48.76 - 84.38	Good to moderate water quality

3.1.3. Diversity and Structure of Benthic Macroinvertebrate Communities

1) Taxonomic composition and abundance

A total of 14,871 individuals were recorded, distributed across 3 phyla, 7 classes, 17 orders, 82 families, and 136 genera. At the class level, insects were the most abundant group, accounting for 69.90%, followed by gastropods (22.10%) and bivalves (7.20%). However, the analysis of benthic macroinvertebrate communities in the Middle Chari Basin revealed a marked structuring at both the order and family levels, with strong variability according to seasonal changes (**Figure 2**).

Overall, several taxonomic groups were identified, the main ones belonging to the orders Hemiptera, Coleoptera, Diptera, Ephemeroptera, Odonata, and Gastropoda. During the rainy season, Hemiptera (30%), Coleoptera (25%), and Mesogastropoda (23%) were dominant. Other orders, such as Diptera (9%), also contributed to the structure of the macroinvertebrate community. During the dry season, the macroinvertebrate structure was clearly distinguished by the dominance of Ephemeroptera (19%), Unionoida (15%), and Odonata (10%). Comparison between the two seasons showed a significant redistribution of relative abundances. Ephemeroptera and Unionoida strongly decreased during the rainy season, whereas Hemiptera, Coleoptera, and Gastropoda conversely increased. **Figure 2(A)** illustrates the seasonal variation in the relative abundance of macroinvertebrate orders collected during the study.

At the family level, the rainy season was characterized by a strong dominance of Notonectidae with 46% relative abundance, followed by other families such as Corixidae (12%), Bythinidae (7%), and Noteridae. The predominance of Notonectidae was further confirmed by their high total abundance (7,616 individuals). During the dry season, family distribution was more balanced. The main identified families consisted of Corbulidae (11%), Chironomidae (8%), Baetidae (6%), and Coenagrionidae (5%). The other families each represented less than 5% of the total abundance throughout the study. Overall, the rainy season was characterized by a simplification of community structure, dominated by a limited number of families. In contrast, the dry season showed a more balanced distribution among the different groups. **Figure 2(B)** illustrated the seasonal variation in the relative abundance of macroinvertebrate families collected during the study.

2) Community structure

Table 6 illustrates the monthly and seasonal variations of the Shannon index, Pielou's evenness, and species richness, as well as the dynamics of biological diversity indices and their synthetic interpretations. During the study, diversity indices and biological water quality indices exhibited marked monthly and seasonal variability between the dry and rainy seasons.

During the dry season, species richness (S) was generally higher and remained relatively stable throughout the study period, with values ranging from 53 to 94. Similarly, the Margalef index (Mg) showed high values, ranging from 7.32 to 12.16 within the study area. Diversity indices, particularly the Shannon diversity index and Pielou's evenness index, ranged respectively from 3.28 (April) to 3.97 (February) and

from 0.83 (April) to 0.91 (February) throughout the study period. The calculated biological indices varied across months, with the HBI ranging from 3.98 to 5.93, the Chironomidae index (CI) ranging from 1.16 to 4.94, and the EPT index varying between 6 and 11, respectively, with a marked improvement observed in April.

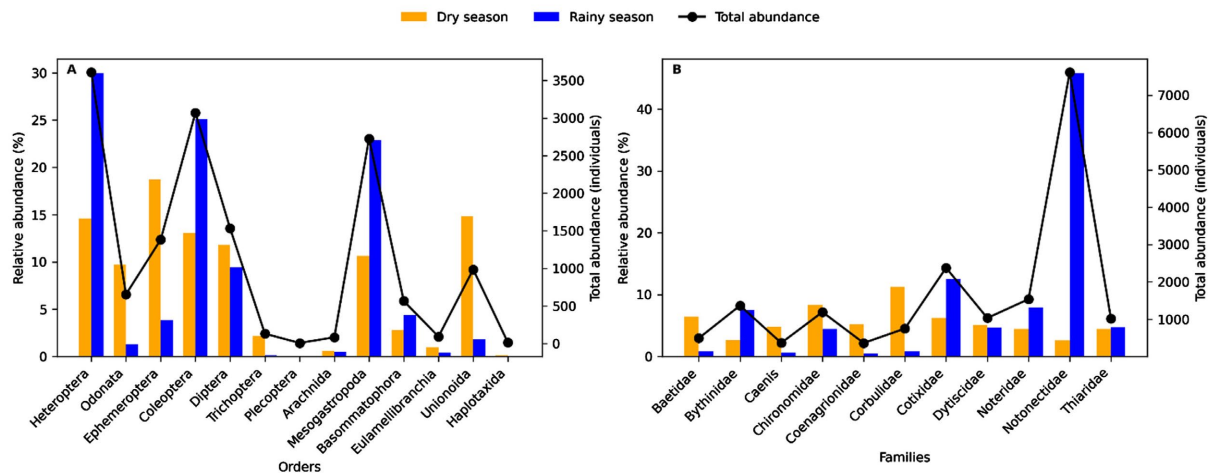


Figure 2. Seasonal variation in the relative abundance and total abundance of benthic macroinvertebrates in the Middle Chari Basin. (A) Distribution at the order level; (B) distribution at the family level. Bars represent relative abundance (%), while the line indicates total abundance (individuals).

In contrast, during the rainy season, an overall decrease in these indices was observed. Species richness values fluctuated between 62 and 74, while the Margalef index ranged from 8.06 to 9.48, with maximum values recorded in August. Shannon diversity index values varied between 2.25 and 3.15, whereas Pielou's evenness index ranged from 0.52 to 0.76. Furthermore, biological indices showed strong monthly variations during the rainy season, with the HBI ranging from 5.99 to 7.91, the Chironomidae index (CI) ranging from 1.15 to 9.13 (with the maximum value recorded in September), and the EPT index varying between 1 and 7, respectively.

Table 6. Temporal dynamics of species richness and biological diversity indices with their synthesized interpretations (S: species richness; H: Shannon index; J: Pielou's evenness; Mg: Margalef index; HBI: Hilsenhoff Biotic Index; CI: Chironomidae Index; EPT (%): EPT index).

Seasons variation	Monthly variation	S	Mg	H	J	HBI	CI	EPT	Interpretation
Dry season	November	81	10.72	3.66	0.83	5.30	2.30	11	Moderate
	February	79	11.01	3.97	0.91	5.16	4.94	9	Moderate
	March	79	11.28	3.84	0.88	5.82	4.27	6	Moderate
	April	53	7.32	3.28	0.83	3.98	1.16	8	Excellent
Rainy season	May	94	12.16	3.86	0.85	5.93	3.48	8	Moderate
	August	74	9.48	2.25	0.52	7.42	9.13	7	Poor
	September	62	8.12	3.15	0.76	7.91	1.15	1	Poor
	October	67	8.06	2.62	0.62	5.99	1.37	2	Fair

3.1.4. Analysis of Interactions between Abiotic and Biotic Factors in the Waters of the Middle Chari

The seasonal distribution of benthic macroinvertebrate abundances in the Middle Chari in relation to the physicochemical parameters of the water on the factorial map is presented in **Figure 3**. Principal Component Analysis (PCA) explained 41.71% of the total variance and highlighted a clear structuring of benthic communities along a dominant water quality gradient. The factorial map made it possible to distinguish two clusters of points along the F1 axis (22.16%).

On the positive coordinates of the F1 axis, this axis was characterized by well-oxygenated waters, correlated with dominant taxa such as *Noterus* sp., *Plea* sp., *Hydrometra* sp., and *Naucoris* sp., as well as certain gastropods such as *Lanistes ellipticus*. This structuring was particularly marked during the dry season, reflecting their affinity for slightly disturbed environments with good ecological quality. In contrast (negative coordinates), the F1 axis was characterized by waters relatively rich in organic matter, correlated with BOD₅, COD, and nitrogenous forms (NO_2^- , NO_3^-), and associated with tolerant taxa such as *Chironomus* sp., *Polypedilum* sp., *Ceratopogonum* sp., and *Corbula* sp. This configuration reflects their adaptation to stressed environmental conditions and environments enriched with organic pollution.

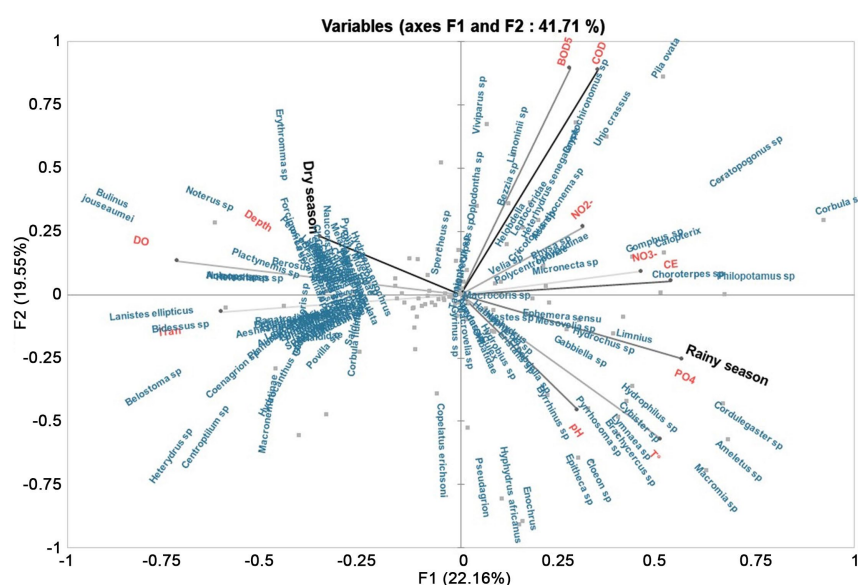


Figure 3. Representation on the principal component factorial plane of the relationships between abiotic water variables (in red) and the seasonal distribution (in black) of benthic macroinvertebrate taxa (in blue) during the study.

The F2 axis (19.55%) reflected a secondary gradient related to mineralization and nutrient enrichment, dominated by electrical conductivity (EC) and phosphates (PO_4^{3-}). Taxa such as *Choroterpes* sp., *Philopotamus* sp., *Cordulegaster* sp., and *Macrobrachium* sp. were associated with these enriched conditions. In contrast, some species positioned near the origin of the factorial plane, such as *Gomphus* sp., *Baetis* sp., *Hydropsyche* sp., and *Physa* sp., exhibited broader eco-

logical tolerance, reflecting low sensitivity to mineralization variations and an ability to adapt to intermediate environmental conditions. These taxa, considered euryecious, are capable of persisting in environments that are neither heavily polluted nor strictly oligotrophic, which explains their central position in the PCA. Overall, seasonal structuring was clearly highlighted by the distribution of individuals on the factorial plane.

3.2. Discussion

3.2.1. Physicochemical Characteristics of the Waters of the Middle Chari

The results of the abiotic parameter analyses in the Middle Chari generally revealed marked seasonal variability during the study period.

During the dry season, water transparency, ranging between 20 and 40 cm, was relatively stable, reflecting low resuspension of particles and relatively calm waters. In contrast, during the rainy season, transparency values fluctuated considerably (5 - 57 cm), reflecting the combined effects of runoff, suspended matter inputs, and rainfall variability within the study area. Heavy rains indeed promote soil erosion and the transport of fine particles into water bodies. Recent studies have also highlighted the influence of rainfall variability on water transparency in the Lake Chad Basin [41] [42]. The relatively wide temperature range observed in the Middle Chari during the rainy season (20.90°C to 33.00°C) confirms the influence of rainfall and the input of cooler runoff waters during this period, thereby contributing to temporary thermal regulation of the hydrosystem. Indeed, rainfall and increased discharge enhance water mixing and modify the thermal dynamics of rivers [42]-[44].

Furthermore, although the rainy season showed a more pronounced variation in electrical conductivity (51.78 to 265.00 $\mu\text{S}/\text{cm}$), the mean value was lower (79.30 ± 41.45 $\mu\text{S}/\text{cm}$) compared to the dry season (106.71 ± 33.84 $\mu\text{S}/\text{cm}$). This variability can be explained by the combined effect of dissolved salt dilution resulting from rainfall inputs, as well as occasional ionic inputs originating from surface runoff, watershed leaching, and sediment remobilization. The significant difference observed between the two seasons confirms the determining effect of seasonality on water mineralization. Studies conducted in various aquatic ecosystems have also reported seasonal variability in electrical conductivity [45].

Dissolved oxygen concentrations exhibited marked seasonal variability, ranging from 0.25 to 4.20 mg/L during the dry season and from 0.60 to 6.20 mg/L during the rainy season. Overall, these levels remained low to moderate, reflecting generally poorly oxygenated conditions likely to limit the development of certain sensitive invertebrates. Higher dissolved oxygen concentrations during the rainy season (3.22 ± 1.58 mg/L) may be explained by improved water mixing, runoff inputs, and a relative decrease in temperatures, thereby favoring better oxygenation of the environment, as reported in several studies conducted in the Lake Chad Basin and tropical hydrosystems [44] [46] [47]. Indeed, increased discharge during the rainy season promotes air-water exchanges and limits thermal stratifica-

tion, thereby improving oxygen dissolution [48] [49]. The significant difference observed between the two seasons (Mann-Whitney U test, $p = 0.001$) confirms the influence of seasonality on dissolved oxygen dynamics in this study. However, dissolved oxygen values remained moderate, suggesting that despite improved oxygenation during the rainy season, organic matter inputs and decomposition processes continue to exert pressure on oxygen availability in the environment [50] [51].

Moreover, although the rainy season exhibited a more pronounced variation in the nitrogen contamination index (NCI = 0.31 - 51.63) compared to the dry season (1.46 - 32.26), the mean values of this index were practically identical and high for both seasons, indicating strong contamination of the Chari River by nitrogen compounds (ammonium, nitrites, nitrates). Studies by Ngatcha and Daira [52] had already reported severe contamination of groundwater, sometimes exceeding 50 mg/L, within the Lake Chad watershed. However, the high variability of NCI values during the rainy season may be associated with exogenous inputs of anthropogenic nitrogen compounds, mainly related to intensified agricultural activities and uncontrolled urbanization observed in these areas served by obsolete or non-existent sewage systems. Nitrate (NO_3^-) concentrations, which were much higher during the rainy season (3.81 ± 2.09 mg/L) than during the dry season (2.76 ± 2.63 mg/L), confirm that rainfall promotes the transfer of nitrogen compounds into the aquatic environment, even though their concentration may be partially diluted by increased water volume. The same applies to the eutrophication index (EI), whose mean values did not vary significantly between the seasons during the study period. This relative stability suggests that the effects of rainfall on nutrient inputs remained occasional and insufficient to induce a lasting modification of the trophic status of this hydrosystem [42] [53].

Similarly, the mean values of the Organic Pollution Index (OPI) observed during the dry season (OPI = 2.458) and the rainy season (OPI = 2.385) both fell within an intermediate class, without significant seasonal variation. These results overall indicate a relatively moderate organic load, not negligible but remaining below the critical thresholds of severe pollution, although slightly more variable during the rainy season. Regarding the COD/BOD₅ ratio, the recorded values provide important information about the nature of organic matter. During the rainy season, the decrease in the mean ratio (COD/BOD₅ = 1.953) reflects improved biodegradability of organic matter easily assimilated by microorganisms, mainly dominated by domestic effluents. This could be explained by recent inputs of fresh organic matter derived from plant debris and domestic effluents transported by runoff waters during rainfall events, thereby promoting microbial activity [42] [54] [55]. Nevertheless, the wide variation range observed during the rainy season (COD/BOD₅ = 0.69 - 2.75) indicates heterogeneous inputs, alternating between highly biodegradable materials and more resistant substances, as highlighted by the work of Ngarbaroum *et al.* [2] on the Chari River.

Overall, the mean values of the Water Quality Indices (WQI) observed across

seasons indicate generally good water quality in the Middle Chari. This situation suggests that the river maintains relatively stable ecological functioning despite the seasonal influence of rainfall and anthropogenic allochthonous inputs. Thus, some water points retain good quality, whereas others shift toward moderate or borderline quality. Indeed, most physicochemical parameters recorded significantly higher values during the dry season than during the rainy season, corroborating the findings reported by Ngarbaroum *et al.* [2].

3.2.2. Biological Characterization of Water Quality in the Middle Chari

A total of 14,871 individuals were recorded during the study period, distributed across 17 orders, 82 families, and 136 genera. The strong dominance of the class Insecta (69.9%), followed by Gastropoda (22.1%) and Bivalvia (7.2%), is consistent with several studies conducted in tropical aquatic ecosystems, where insects constitute the most diverse and abundant group of benthic macrofauna [9] [56] [57]. This predominance of insects may be explained by their high adaptive capacity to environmental variations, as well as the diversity of ecological niches they occupy [31] [58].

However, the dry season was characterized by the predominance of Ephemeroptera, represented by the family Baetidae, Unionoida (Unionidae), and Odonata (Coenagrionidae), reflecting more stable and ecologically favorable environmental conditions. Ephemeroptera are recognized as pollution-sensitive organisms associated with well-oxygenated, slightly disturbed environments and better ecological water quality [59] [60]. Likewise, Unionoida are well adapted to relatively stable and weakly silted benthic substrates, conditions typical of low-flow periods in rivers [61]. Odonata, particularly Coenagrionidae, are generally associated with relatively well-oxygenated aquatic environments subjected to low to moderate disturbance [62] [63]. This observation is consistent with the known sensitivity of macroinvertebrates to habitat stability and flow regime, which are major structuring factors in tropical hydrosystems.

The high taxonomic richness ($S = 53 - 94$ taxa), associated with high Margalef index values ($Mg = 7.32 - 12.16$) during the dry season, confirms the significant taxonomic diversity and good structuring of the Chari River macrofaunal communities during this period. In contrast, Ephemeroptera and Unionoida strongly declined during the rainy season, whereas Hemiptera, particularly the family Notonectidae (7616 individuals), Coleoptera, and Gastropoda conversely increased in abundance, suggesting a greater adaptive capacity to hydrological conditions during this period. Similar studies have interpreted this trend as reflecting the ability of macroinvertebrates to respond to seasonal and hydrological variations in water regimes [59] [64].

The Hilsenhoff Biotic Index values ($HBI = 3.98 - 5.93$) indicated biological water quality ranging from excellent to moderate during the dry season. For example, in April, ecological conditions were relatively more favorable, with a low HBI value (3.98), associated with a low Chironomidae Index ($CI = 1.16$) and a relatively high EPT index value (8). This trend suggests low organic pollution and

environmental conditions favorable to the persistence of pollution-sensitive taxa, as also observed in November (EPT = 11) and February (EPT = 9).

A high diversity index reflects a structured and mature community characterized by high species richness and a relatively balanced distribution of individuals among taxa [50] [61]. The high diversity index values ($H = 3.28 - 3.97$; $J = 0.83 - 0.91$) recorded during the dry season indicate that, during this period, the Chari River supported a highly diversified macrofauna associated with a good distribution of individuals among taxa. The maximum observed in February ($H' = 3.97$; $J = 0.91$) probably corresponds to a phase of optimal ecological stability, whereas the slight decrease observed in April may reflect a transition toward the rainy season, marked by the first hydrological disturbances. Studies such as those of Boulton *et al.* [65] and, more recently, Nyamsi-Tchatcho *et al.* [66] explain that the onset of rainfall generally increases runoff, thereby affecting the structure of benthic macroinvertebrate communities.

Indeed, the rainy season was characterized by an overall decrease in diversity indices ($H' = 2.25 - 3.15$; $J = 0.52 - 0.76$), reflecting a relative simplification of community structure and a temporary imbalance caused by hydrological disturbances induced by rainfall, particularly allochthonous organic matter inputs through runoff, increased turbidity, and instability of benthic substrates [41] [42]. The HBI values, which reached 7.42 in August and 7.91 in September, together with the very high Chironomidae Index value recorded in August ($CI = 9.13$), are complementary indicators reflecting both the strong proliferation of pollution-tolerant taxa and, overall, the poor biological water quality prevailing during the rainy season throughout this study.

3.2.3. Ecological Assessment of Water Quality

The results show that species diversity and functional diversity of macroinvertebrates are significantly influenced by seasonality. Principal Component Analysis (PCA) indicated that dissolved oxygen, electrical conductivity, biochemical oxygen demand, orthophosphates, and nitrogenous nutrients are the main factors determining the functional diversity of macroinvertebrates [50]. The association along the F1 axis between well-oxygenated waters and taxa such as *Noterus* sp., *Plea* sp., *Hydrometra* sp., *Naucoris* sp., as well as the gastropod *Lanistes ellipticus*, reflects favorable and relatively stable environmental conditions. These organisms are generally associated with slightly disturbed environments where oxygenation is sufficient and substrates are weakly silted [7] [44] [67]. Their abundance and high diversity during the dry season confirm that this period corresponds to a phase of hydrological stabilization in the Sahelian zone, characterized by low turbidity, improved light penetration, and increased dissolved oxygen availability, thereby promoting the development of a well-diversified and relatively balanced benthic macrofaunal community.

In contrast, the negative coordinates of the F1 axis are associated with waters relatively enriched in organic matter, as indicated by correlations with BOD₅, COD, and nitrogen nutrients (NO_2^- , NO_3^-). The association along this axis of

these variables with taxa such as *Chironomus* sp., *Polypedilum* sp., *Ceratopogonum* sp., and *Corbula* sp. highlights the ability of this benthic macrofaunal community to withstand hydric stress conditions mainly of natural origin due to the conditions prevailing during the dry season in tropical Sahelian zones. These taxa are well known for their ability to colonize eutrophic or disturbed environments, often characterized by organic matter accumulation and fluctuations in physico-chemical parameters [68] [69]. Overall, this opposition along the F1 axis therefore reflects a gradient of ecological quality, ranging from oligotrophic or moderately disturbed conditions to more eutrophic and degraded conditions. It also illustrates the differential response of macroinvertebrates to environmental pressures, with some groups acting as indicators of good quality environments (sensitive or moderately tolerant taxa), whereas others indicate environmental degradation [11] [70].

Furthermore, the F2 axis (19.55%) corresponds to a secondary gradient of mineralization and nutrient enrichment, complementary to the main organic pollution gradient represented by the F1 axis. The positive correlation of this axis with electrical conductivity (EC) and phosphates (PO_4^{3-}) reflects the relative influence of natural or anthropogenic inputs, such as soil leaching, agricultural activities, or domestic discharges, likely to modify the structure of biological communities and the ecological functioning of hydrosystems in the Sahelian zone [41] [42]. The affinity of taxa such as *Choroterpes* sp., *Philopotamus* sp., *Cordulegaster* sp., and *Macrobrachium* sp. for this axis could be explained by their ecological preference for mesotrophic environments characterized by moderate nitrogen and phosphorus availability. These taxa are generally associated with relatively stable habitats and are common in aquatic environments of intermediate quality [69] [70]. These organisms are neither strictly confined to oligotrophic environments nor restricted to polluted habitats, which explains their limited contribution to the structuring of this axis.

Conversely, some taxa positioned near the origin of the factorial plane, such as *Gomphus* sp., *Baetis* sp., *Hydropsyche* sp., and *Physa* sp., represent organisms capable of adapting to intermediate environmental conditions. These taxa, considered euryecious, are able to persist in environments that are neither heavily polluted nor strictly oligotrophic [71]-[73]. This explains the central position of these taxa on the PCA plot.

4. Conclusion

At the end of this study, whose main objective was to assess the ecological status of the middle course of the Chari River using benthic macroinvertebrate communities, the results showed that the physicochemical parameters of the Middle Chari revealed strong seasonal variability, marked by the relative dilution of dissolved salts during the rainy season, whereas the dry season was characterized by higher mineralization and nutrient enrichment, as well as more stable hydrological conditions. Thus, the waters of the Middle Chari were generally of good to

moderate quality, characterized by moderate organic pollution, predominantly biodegradable organic matter, and moderate trophic enrichment, with more pronounced seasonal variability during the rainy season. The structure and diversity of benthic macroinvertebrate communities in the Middle Chari reflected better ecological quality during the dry season, whereas the rainy season was characterized by a relative simplification of communities and an increase in pollution-tolerant taxa under the influence of hydrological disturbances and organic inputs. The analysis of interactions between abiotic and biotic factors highlighted a seasonal structuring of benthic macrofauna in the Middle Chari according to an ecological quality gradient, opposing well-oxygenated and slightly disturbed environments to environments enriched in organic matter and subjected to anthropogenic pressures. Overall, these results show that the studied system remains moderately impacted, with generally good but fragile water quality. This highlights the importance of regular spatial and seasonal monitoring, as well as the control of diffuse pollution sources, in order to prevent a progressive degradation of water quality.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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