Prepublished Copy

NATURE ENVIRONMENT AND POLLUTION TECHNOLOGY

Article In Press

PEER-REVIEWED PREPUBLISHED MANUSCRIPT

This is a peer-reviewed prepublished version of the paper to be published in **Vol. 26, No. 1, March 2027.**

Ecological status of Chari-Logone River Complex Using Benthic Macroinvertebrates and Physicochemical Variables

Safia Mahamat Tahir, Jean Dzavi, Mikail Abakar and Serge Hubert Zébazé Togouet

RECEIVED
8 January 2026

CITE THIS ARTICLE
Tahir, S.M., Dzavi, J., Abakar, M. and Togouet, S.H.Z., 2027. Ecological status of Chari-Logone River Complex Using Benthic Macroinvertebrates and Physicochemical Variables. *Nature Environment and Pollution Technology*, 26(1), D1909.

https://doi.org/10.46488/NEPT.2027.v26i01.D1909

EARLY-ACCESS STATEMENT

This manuscript, after peer review, is being released online in its original, unedited form to provide early access to its findings. Prior to final publication, it will undergo additional editing and formatting. Readers may note that, as an unedited version, the manuscript may have linguistic and other minor errors. The DOI will be active after the final publication of the paper.

PUBLICATION STATUS

PEER REVIEW	ONLINE VERSION	FINAL ISSUE
Completed	Prepublished	March 2027

Ecological status of Chari-Logone River Complex Using Benthic Macroinvertebrates and Physicochemical Variables

Safia Mahamat Tahir[1*], Jean Dzavi[2,3], Mikail Abakar[1], Serge Hubert Zébazé Togouet[3]

[1] University of N'Djamena, Laboratory of Animal Biology, P.O. Box 1117, N'Djamena, Chad

[2] Institute of Geological and Mining Research, Research Centre for Water and Climate Change, P.O. Box 4110, Yaounde, Cameroon

[3] University of Yaounde 1, Faculty of Science, Laboratory of Hydrobiology and Environment, P.O. Box 812, Yaounde, Cameroon

*Corresponding author: safiatima@yahoo.fr

Abstract: This study aims to inventory benthic macroinvertebrates within the Chari-Logone River complex, two tributary rivers of Lake Chad, for assessing the ecological status. The organisms and water were sampled monthly, from February to July 2023, at six stations. Benthic macroinvertebrates were sampled following the multihabitat approach developed by Stark using a kick net of 500 µm mesh porosity. Water was sampled in double-closure polyethylene bottles and their analyse revealed an average ecological quality based on Temperature (22.6 - 30.12 °C), pH (5.48 - 8.10 UC), Conductivity (86 - 240 µS/cm), dissolved Oxygen (54 - 95.20 %), Turbidity (14 - 72 FTU), color (130 - 570 Pt-Co), or Orthophosphates (0.1 - 3.7 mg/L). A total of 28 taxa belonging to 2 phyla (Arthropods, Molluscs), 5 classes (Gastropods, Bivalves, Hexapods, Crustaceans, and Arachnids), 12 orders, and 21 families were identified and gathered. Only the species *Melanoides tuberculata, Melanoides nodicincta,* and *Glabbiella tchadiensis* were respectively omnipresent, regular, and constant during the study. Pollutant-resistant organisms were most recurrent, and this finding shows the Chari-Logone River complex is disturbed. The presence of polluo-sensitive mollusc *C. africana* in the downstream suggests the progressive natural restoration of ecological conditions in the downstream after the City of N'Djamena. The physicochemical variables selected in this study are limited to have precise information on water quality since the organisms identified were pollutant-tolerant.

Keywords: Urban river, Physicochemical variables, Benthic macroinvertebrates, Pollution, Ecological status, Logone-Chari Complex

1. INTRODUCTION

One of the major challenges facing planet Earth in the 3rd millennium is the protection of its natural resources (Ochuka *et al.*, 2019; Allan *et al.*, 2021). Among these resources, water is of prime importance, as it is essential to life (Dos Santos *et al.*, 2017; Yates *et al.*, 2025). However, aquatic ecosystems are under many pressures, particularly anthropogenic, linked to population growth, climate change, and other factors, making them a vulnerable resource (Dos Santos *et al.*, 2017; Bowen and Currie, 2021; Temgoua Zemo *et al.*, 2023). Human pressures are present and hurt biodiversity and water quality (Ge *et al.*, 2022; Lactio *et al.*, 2026). The assessment of anthropogenic pollution/pressure on the biological integrity of aquatic systems follows an ecological approach, which follows environmental indicators and aquatic organisms such as phytoplankton, zooplankton, macroinvertebrates, and fish (Madomguia *et al.*, 2016; Kengne Tenkeu *et al.*, 2020; Mahamat Tahir *et al.*, 2020; Edegbene *et al.*, 2023). The assessment of ecological integrity of rivers and streams is based particularly on the analysis of the composition and abundance of different communities known as biological indicators, in relation to reference conditions corresponding to the natural state (Kelly *et al.*, 2025; Yates *et al.*, 2025; Lento *et al.*, 2026). Nowadays, benthic macroinvertebrates are the best bioindicators of flowing hydrosystems, because they are sedentary and spend a large part of their life cycle in water (Mboye *et al.*, 2020; Biram à Ngon *et al.*, 2024; Dzavi, 2024; Temgoua Zemo *et al.*, 2024; Nwaha *et al.*, 2026). Moreover, they are easy to sample, ubiquitous, and react in a variety of ways depending on the degree of pollution.

In SubAfrica, many studies focused on the assessment of the ecological quality of hydrosystems in various locations have been carried out using both physicochemical and biological analyses (Bagalwa, 2006; Foto Menbohan *et al.*, 2013; Tchakonté *et al.*, 2015; Onana *et al.*, 2016, 2021; Munganga Kilingwa *et al.*, 2020; Ochieng *et al.*, 2021; Mbaka and Aura, 2022; Edegbene *et al.*, 2023). In Chad, few studies were done in order to establish the ecological status of the hydrosystems, while the Chari-Logone River complex, the two major rivers in the country, are subjected to various forms of anthropogenic pollution that could affect their quality.

The waste found in the Logone–Chari river basin in Chad, which flows through Chad and Cameroon, comes mainly from agriculture, industry, households, and urban runoff. These inputs degrade the quality of the water, sediments, and aquatic organisms, particularly in areas close to major cities such as N'Djamena and Moundou (Saha *et al.*, 2021; Djikoloum Beosso *et al.*, 2024; Vicat *et al.*, 2025). Agriculture contributes to this pollution through fertilisers, pesticides, and organic matter washed away by rain. Industrial activities discharge liquid effluents and metallic substances, while household waste contributes sewage, rubbish, and faecal matter, thereby increasing organic and microbial pollution (Ngaram, 2011; Nambatingar *et al.*, 2017). Urbanisation exacerbates this situation by promoting soil sealing and erosion, as well as the rapid transport of pollutants to rivers. The river network is essential as it feeds Lake Chad, and is therefore under increasing pressure (Bouchez *et al.*, 2016). While water quality remains acceptable in some areas, the ecological balance remains fragile in the face of these multiple sources of contamination (Lemoalle and Brami-Hourtal, 1996; MEPDD, 2024). So, this study aims to assess the ecological status of the Chari-Logone River complex based on the structure of the benthic macroinvertebrates and the physicochemical quality of the water.

2. MATERIALS ET METHODS

2.1. Study site

The study was carried out in N'Djamena, the Capital of Chad, from February to June 2023. The city is located between 14°58'0‘’ and 15°9'0‘’ East Longitude and 12°1'0‘’ and 12°13'0‘’ North Latitude. It is bordered to the north by the Hadjer-Lamis Province, to the east and south by the Chari Baguirmi Province, and to the west by the Logone River (Fig. 1).

N'Djamena is running a tropical Sahelian climate characterised by two seasons: a long dry season from October to May, and a short rainy season from June to September (Ngaram, 2011). Annual temperature variations in the city of N'Djamena show a minimum temperature of 14 to 23°C and a maximum temperature of 33 to 42 °C. N'Djamena is characterised by a slightly flat relief dotted with areas of depression, consisting of bulges and flood plains. The soil has a sandy-clay to silt-clay texture. The city is subdivided into ten (10) administrative units called subdivisions. The population of 993,492 in 2009 (INSEED, 2009) is estimated to be over 2,451,344 today (Hassane Hemchi *et al.*, 2021). The Chari river originates in the Central African Republic, and the Logone river in the Adamawa Plateau in Cameroon. So, jointly together they flow into Lake Chad (Ngaram, 2011; Djikoloum Beosso *et al.*, 2024). They contribute more than 82% of the lake's water (Bouchez *et al.*, 2016). All along its course, this complex is subject to various forms of anthropogenic pollution that affect its quality. It is also subject to climatic hazards and serves as a receptacle for industrial effluents (Ngaram, 2011).

2.2. Sampling stations

Based on accessibility and the proximity to pollution sources, six (6) sampling stations were chosen. The first two stations (S1 and S2) are located in the area of fishing and vegetable crops activities, and the other three (S3, S4, and S5) receive effluents from the N'Djamena industrial zone. These stations will make it possible to assess the effect of a number of industrial effluents, mainly the wastewater evacuation channels of the National Reference University Hospital Center (S3), Breweries of Chad (S4), and Slaughterhouses (S5). The last station (S6) is located downstream from the N'Djamena town in an area where there is less human activity, with vegetable crops (Fig. 1 and Table 1). The characteristics of these sampling stations are as follows: N'DJAM (S1) – located at the eastern entrance to the town of N'Djamena; PDV (S2) – at the level of the dual carriageway bridge and is located 5.46 Km from E N'DJAM sampling; CDHC (S3) – located next to the Presidency of the Republic of Chad, 6.73 Km from PDV sampling station; BRTEX (S4) – the outlet of the breweries (BR) in Chad, which is located 5.13 Km from the CDHC sampling station; ABEX (S5) – the outlet for the slaughterhouses (AB), which is a modern meat-packing company and located 1.71 Km from BRTEX and S N'DJAV (S6) – located 2.32 Km from ABEX and located in downstream sampling point after N'Djamena town.

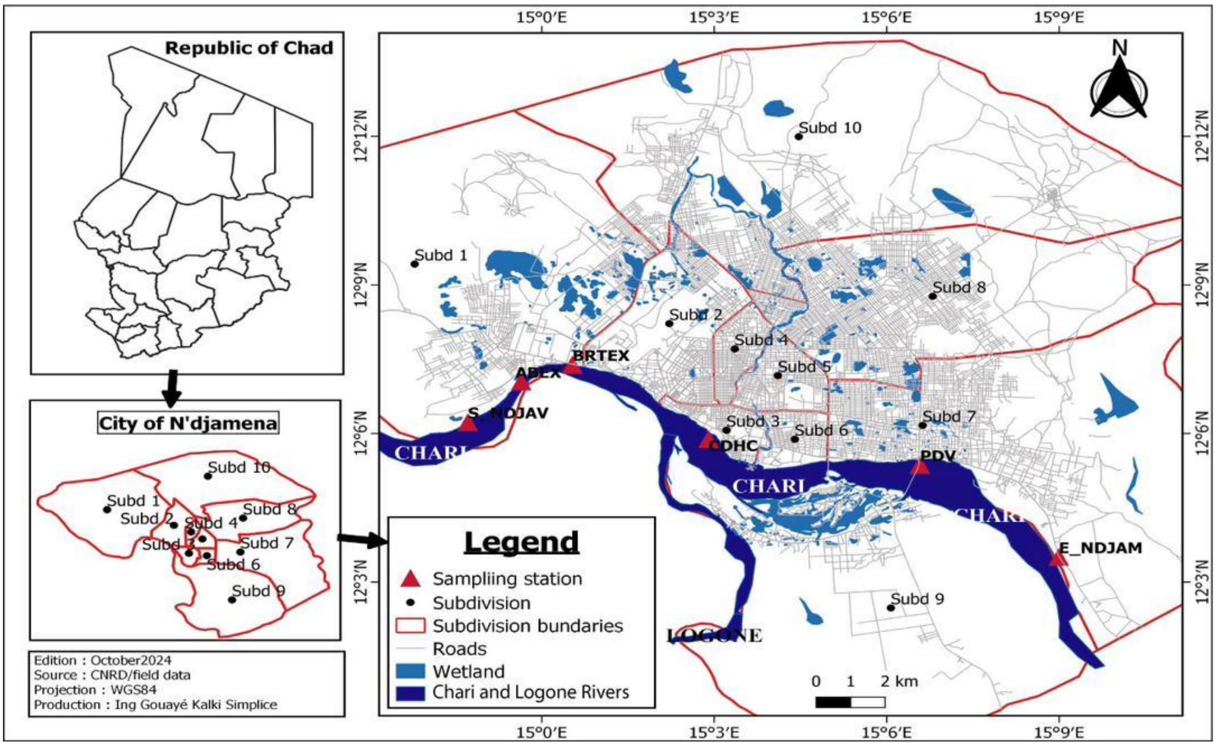

Figure 1: Map showing the sampling stations

Table 1: Summary characterisation of sampling stations in Chari-Logone River complex

Stations	Code	Coordinates	Main activities	Dominant substrates	Main macrophytes
S1	E N'DJAM	12°3'30.426''N 15°8'59.484"E	Fishing, vegetable crops	Medium sand, clays	
S2	PDV	12°5'21.894''N 15°6'34.692"E	Fishing, vegetable crops, laundry	Medium sands, clays, silts	
S3	CDHC	12°5'53.094''N 15°2'54.114"E	Fishing, vegetable crops, navigation	Coarse sands, clays, silts	
S4	BRTEX	12°7'23.424''N 15°0'31.986"E	Fishing, dumping of waste from breweries	Pebbles, gravel, coarse sand	*Eichhornia crassipes*
S5	ABEX	12°7'2.808''N 14°59'38.592"E	Dumping of waste from slaughterhouses, fishing, laundry, and navigation	Pebbles, gravel, sand	*Eichhornia crassipes*
S6	S N'DJAV	12°6'13.68''N 14°58'43.014"E	Vegetable crops	Medium sands, clays	*Eichhornia crassipes*

2.3. Methods

2.3.1 Measurement of abiotic parameters

The fieldwork was carried out monthly at the six stations, between 7 a.m. and 11 a.m. Physicochemical parameters were measured both in the field and in the laboratory, following the recommendations of Rodier *et al.* (2009) and American Public Health Association *et al.* (2017). Water Temperature (°C), pH, Dissolved Oxygen (% saturation), and Electric Conductivity (µS/cm) were measured *in situ* using a HACH HQ11d pH meter (accurate to 0.1 UC), a HACH HQ14d oximeter, and a HACH HQ14d conductivity meter (accurate to 0.1 µS/cm). For laboratory analyses, water samples were collected using 1000 mL double-closure polyethylene bottles, which had been washed in concentrated HCl and rinsed with distilled water. In the laboratory, the turbidity (FTU) and colour (Pt-Co) of the water were measured by colorimetry using a Photometer DR/7100 according to the methods of Rodier et al. (2009) and American Public Health Association et al. (2017). The water contents in orthophosphates and various forms of nitrogen in mg/L (NH_4^+, $NO_2^{-,}$ and NO_3^-) were measured with appropriate Phosver, Nessler, Nitriver, and Nitraver reagents by the Photometer DR7100, respectively, at wavelengths of 530 nm; 507 nm, 520 nm and 570 nm, after setting the zero point using a blank sample.

2.3.2 Benthic Macroinvertebrates sampling

Benthic MacroInvertebrates (BMI) were collected using a 30 cm x 30 cm, 500 µm mesh and 50 cm in depth. At each station, 20 kick net hauls were made in different micro-habitats according to Stark *et al.* (2001). Each shot consisted of pulling the net over a distance of approximately 1 m in the opposite direction to the water flow. The bottom substrate was meticulously scraped to a depth of 2 to 3 cm. The organisms collected in the sampling net were rinsed through a 500 µm sieve, and all the benthic macroinvertebrates were sorted *in situ* and preserved in a plastic bottle containing 10% formalin to quickly preserve in the field, ensuring that tissues are preserved for identification without distorting delicate structures. In the laboratory, the specimens were rinsed under tap water and then preserved in 80% alcohol, as it fixes the tissues, prevents decomposition, and preserves the integrity of the specimens for identification. Identification and counting of preserved organisms were carried out under a binocular microscope, Wild M5, using the appropriate identification keys and books (Poisson, 1929; Durand and Levêque, 1980, 1981; Dethier, 1981; Stals and de Moor, 2007; Moisan, 2010; Tachet *et al.*, 2010).

2.3.3. Data analysis

The data collected on physicochemical parameters and benthic macroinvertebrates were entered and organised in Excel 2013. The taxonomic richness, taxonomic abundances, and frequencies of occurrence of taxa were used to describe the BMI communities. Abundance and taxon richness were presented in a graphical form using Graphpad Prism 8 and Canoco for Windows.

The Organic Pollution Index (OPI) is based on the method developed by (2001) and assesses water quality by classifying four parameters (BOD_5, phosphates, ammonium, nitrites) on a scale of 1 to 5 (Table

2). The average of these class numbers gives the final index. The lower the index (closer to 1), the better the quality; the higher the index (closer to 5), the greater the pollution. The principle involves dividing pollutant values into five classes, then, based on the measurements taken, determining the corresponding class number for each parameter and calculating the average. The IPO was calculated using three parameters. Still, the others, which are already in mineral form, can be considered to result directly from the mineralisation of organic matter and thus accurately reflect this type of pollution.

To assess the degree of pollution in each zone, the Organic Pollution Index (IPO) was calculated according to the recommendations of Leclercq (2001). Kruskall-Wallis and Mann Whitney tests were used to check for significant differences between the values of the variables analysed.

Table 2: Class of Organic Pollution Index (OPI) and levels of pollution

Class	NH_4^+ (mg/L)	NO_2^- (µg/L)	PO_4^{3-} (µg/L)	Limits of class	Level of pollution
5	< 0,1	≤ 5	≤ 15	5,0 – 4,6	Nothing
4	0,1 - 0,9	6-10	16 – 75	4,5 – 4,0	Low
3	1 - 2,4	11-50	76 – 250	3,9 – 3,0	Moderate
2	2,5 – 6	51 - 150	251 -900	2,9 – 2,0	Strong
1	> 6	> 150	> 900	1,9 – 1,0	Very strong

The frequency of occurrence (F), expressed as a percentage, provides information on the constancy of a species or taxon in a given habitat without any indication of its quantitative importance (Dajoz, 2003). It permits to distinguish ubiquitous species, which appear in all the surveys (F = 100%); regular species (75 ≤ F ≤ 100%); constant species(50 ≤ F ≤ 75%); accessory species (25 ≤ F ≤ 50%) and rare species present in 0 ≤ F ≤ 25% of the surveys (Dufrêne and Legendre, 1997). This index is based on the presence/absence matrix and is calculated according to the relationship (1), where Pt is the total number of samples and Pi is the number of samples where the species is present:

$$F = \frac{P_i \times 100}{P_t} \qquad (1)$$

The Shannon-Weaver, Simpson, and Pielou indices were performed by CANOCO for Windows to estimate the diversity of benthic macroinvertebrates at the stations sampled. The Shannon-Weaver index, which is used to assess the heterogeneity of biodiversity in an environment, was calculated as follows: the formula below with Pi = relative abundance of taxon i (pi = ni / N) (Shannon and Weaver, 1948):

$$H^{'} = -\sum_{i=0}^{n} \mathrm{Pi} \log_2 \mathrm{Pi}\, H' = -\sum_{i=0}^{n} Pi \log_2 Pi \qquad (2)$$

Simpson's index was used to calculate the probability that two randomly selected individuals in a given environment are of the same species (Keylock, 2005). It was determined using the following formula, where Pi = ni / N, is the relative abundance of species i of the sample S, Ni = number of individuals of species i, and N is the number of individuals of the whole community; S = specific richness:

$$1 - D = 1 - \sum_{i=0}^{n} p^2 i \tag{3}$$

The Pielou equitability index was used to identify the evenness of macroinvertebrates (Pielou, 1966). J is between 0 and 1, and it was calculated using the following formula, where S: number of species observed:

$$J = \frac{H\prime}{\log_2 S} \tag{4}$$

Sörensen's coefficient of similarity (β) was used to determine the level of similarity between the populations of BMI collected at the different sampling stations (Marcon, 2010). This index is calculated using the formula with *S* = similarity coefficient, a = number of taxa present at the 1st station, b = number of taxa present at the 2nd station, and C = number of taxa common to the two stations:

$$S = \frac{2C}{(a+b)} \times 100 \tag{5}$$

Friedman's non-parametric test was used to compare the values of physicochemical parameters, taxonomic richness, and abundances of the organisms studied between the sampling stations. To study the relationships between environmental variables and the abundance dynamics of benthic macroinvertebrates, a rank correlation analysis (Spearman coefficient) and a Canonical Correspondence Analysis (CCA) were carried out using two databases, the taxa abundance and the physicochemical parameter matrix, using Excel 2013 and CANOCO for Windows 4.5 (Braak, 1986).

The method for identifying indicator species (IndVal) was applied (Dufrêne and Legendre, 1997). It has the advantage of combining both frequency and abundance or coverage to assess the indicator status of species. It is based on the same approach to classifying surveys in order to identify the species that are indicative of them. A species is considered indicative of a given group of surveys if it is characteristic of that group, i.e., typical (= absent or relatively less frequent in other groups of surveys), and if it is present in all surveys within that group. For each species i in each survey group j, the indicator value (IndValij) of species i in survey group j is calculated as follows:

$$Indvalij = Aij \times Bij \times 100 \tag{6}$$

where Aij = Nindividuals ij / Nindividuals j and Bij = Nsites ij / Nsites j

Aij represents the average abundance of species i within the surveys in survey group j, relative to all groups = a measure of specificity, and Bij represents the number of surveys occupied by species i among those in group j = a measure of constancy or fidelity.

3. Results

3.1. Physicochemical parameters

During the study period, the temperature was cold and varied from 22.6 °C at S2 to 30.12 °C at S6 with an average of 26 .66 ± 2.12 °C (Table 3). These temperature values generally increased from February to July at all stations. The pH values oscillated between 5.48 at S5 and 8.10 at S6 with an average of 7.37 ± 0.67. Water was low mineralised, and the conductivity oscillated between 86 µS/cm at S5 and 240 µS/cm at S6, with an average of 124.42 ± 40.53. Water was well oxygenated, and the saturation of oxygen varied between 54 % at S4 and 95.20 % at S6, with an average of 79.25 ± 11.42 %. The turbidity and color values evolved between 14 FTU at S1 – 72 FTU at S3, and 130 Pt-Co at S1 – 570 Pt-Co at S3, respectively, with respective averages of 38.94 ±15.83 Pt-Co and 341.08 ±107.96 Pt-Co. These values evolved synchronously during the study period. Orthophosphates varied between 0.1 mg/L at S2 and 3.7 mg/L at S4 with an average of 0.86 ± 0.87 mg/L. The different forms of nitrogen were low overall (Table 2).

Table 3: Minimum, Maximum, and Mean with Standard deviation (SD) of physicochemical parameters of water during the study

Variables	Minimum	Maximum	Mean	SD
Temperature (°C)	22.60	30.12	26.66	2.12
pH (UC)	5.48	8.10	7.38	0.67
Electrical conductivity (µS/cm)	86.00	240.10	124.42	40.53
Saturation on oxygen (% sat)	54.00	95.20	79.26	11.42
Turbidity (FTU)	14.00	72.00	38.94	15.83
Color (Pt-Co)	130.00	570.00	341.08	107.96
Orthophosphates (mg/l PO_4^{3-})	0.10	3.70	0.86	0.87
Nitrates (mg/l NO_3^-)	1.92	3.45	2.57	0.47
Nitrites (mg/l NO_2^-)	0.01	0.22	0.11	0.05
Ammonia (mg/l NH_4^+)	0.00	1.11	0.22	0.29

The Organic Pollution Index (OPI) calculated shows values ranging from 2.5 at station S3 to 3.33 at station S3 with an average of 2.81 ± 0.22 There were not significant difference (p>0.05) between stations. These values are lower than those recorded in the Upper Ouémé Valley (Mahugnon *et al.,* 2026) and along the Nosivolo River (Ramiandrivelo *et al.,* 2021). However, they are slightly higher than those recorded in some watercourses in the Awae agricultural zone (Nsangou Moundignigni *et al*., 2024).

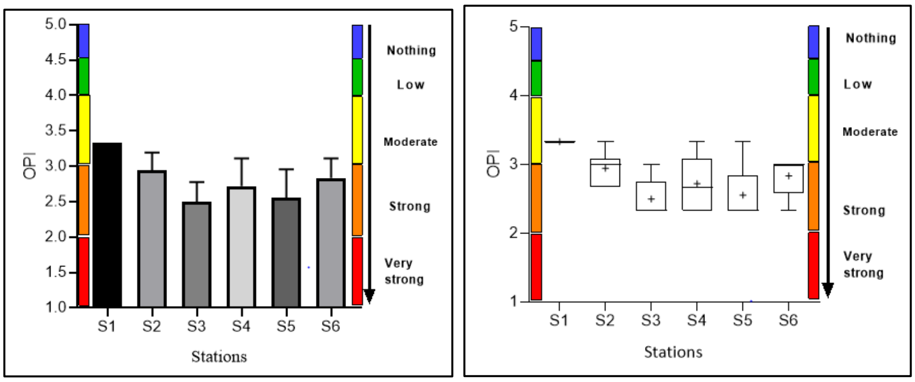

Figure 2: Variation of values of Organic Pollution Index

3.2. Biological analysis

Taxonomic composition

During the study period, a total of 28 benthic macroinvertebrate (BMI) taxa were sampled. These organisms belong to 2 phyla (Arthropoda, Mollusca), 5 classes (Gastropods, Bivalves, Hexapods, Crustaceans, and Arachnids), 12 orders, and 21 families. With 92.15 % of total abundance, Mollusca represented the major taxon. Of the 586 BMI collected, the Gastropod was more represented with 518 individuals, or 88.40% of the collections. It was followed by Hexapoda, then Bivalvia with 26 (4.44 %) and 22 individuals (3.75 %) (Figure 3a). Crustacea were represented by 18 individuals (3.07 %). Arachnida, with 0.34 % of the collection (i.e., 2 individuals), were the weakest represented (Fig. 3a). Among the Gastropods, the Thiaridae family was strongly represented with a total of 482 individuals or 82.25% of the total abundance. It is followed by the Bithyniidae (5.92%) and the Atyidae (3.07%) (Figure 3b).

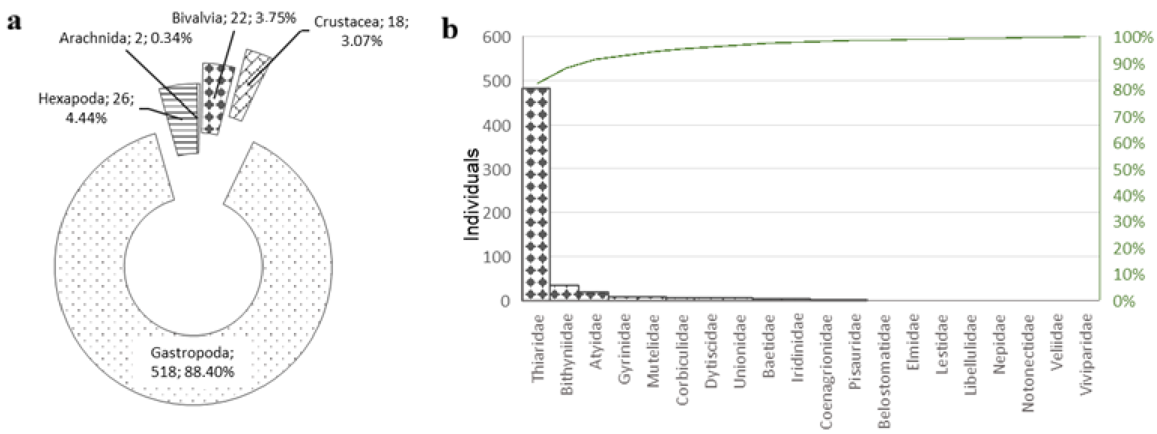

Figure 3: Distribution of abundance of benthic macroinvertebrates in class (a) and in order (b)

Spatial distribution

The analysis of taxonomic lists during the study period shows the omnipresent (*****), regular (****), constant (***), accessory (**), and rare (*) species. The ubiquitous species were the least represented, with a frequency of occurrence of 7.14%. They were followed by accessory species (10.71%) and constant species (17.85%). The rare species were the most represented, accounting for 78.26% of the total. The ubiquitous species were *Melanoides nodicincta* and *Melanoides tuberculata* (see Table 4).

Table 4: Frequency of occurrence F of Dajoz (2003) showing the rare, passive, constant, regular, and omnipresent species during the study

Taxa	S1	S2	S3	S4	S5	S6
Melanoides nodicincta	***	***	*	***	*	*
Melanoides tuberculata	***	****	*****	****	****	**
Aspatharia senegalensis	*	*	*	*	*	*
Aspatharia chaiziana	*	*	*	*	*	*
Gabbiella tchadiensis	*	***	***	**	*	**
Gabbiella spiralis	*	*	*	*	*	*
Caelatura aegyptiaca	*	*	*	*	*	*
Caelatura teretiuscula	*	*	*	*	*	*
Mutela dubia	*	*	*	*	*	*
Bellamya unicolor	*	*	*	*	*	*
Brachysthemis leucosticta	*	*	*	*	*	*
Caridina africana	*	*	*	*	*	*
Omotonus sp.	*	*	*	*	*	*
Hyphydrus sp.	*	*	*	*	*	*
Pseudagrion sp.	*	*	*	*	*	**
Ranatra linearis	*	*	*	*	*	*
Orectogyrus sp.	*	*	*	*	*	*
Baetis sp.	*	*	*	*	*	*
Methles sp.	*	*	*	*	*	*
Guignoyus sp.	*	*	*	*	*	*
Lestes sp.	*	*	*	*	*	*
Laccophilus sp.	*	*	*	*	*	*
Corbicula africana	**	*	*	*	*	*
Anisops sp.	*	*	*	*	*	*
Pisauridae sp.1	*	*	*	*	*	*
Pisauridae sp.2	**	*	*	*	*	*
Rhagovelia sp.	*	*	*	*	*	*
Diplonychus sp.	**	*	*	*	*	*

Omnipresent = *****, Regular = ****, Constant = ***, Accessory = ** and Rare=*

Station S6 had the largest number of taxa (13 taxa). This richness was 6 at stations S5 and S4. At stations S3, S2, and S1, the number of taxa was 9, 8, and 7, respectively (see Figure 4a). The Friedman test showed no significant difference in taxonomic richness between the stations (p = 0.0849). However, richness varied from 1 to 7 taxa (S1, S4, S5, and S6) and was generally low throughout the study.

Biological indices

Spatial abundances were greater at stations S2 and S3, with 154 or 26.27% and 117 individuals or 19.96%. They are followed respectively by stations S4, S5, S1, and S6 with respective abundances of 82 (14%), 79 (13.48%), 78 (13.31%), and 76 (12.96%) individuals (Figure 4b). The difference in BMI abundances between the different stations is not significant (p = 0.3758), although varying between 1 individual (S1 and S2) and 42 individuals (S1).

The Shannon and Weaver diversity index varied from 0 (S1) to 1.42 (S6) bits/ind. (Figure 4c). A significant difference was noted at the 5% between the H' diversity of stations (p = 0.0445). Indeed, this diversity varied significantly between station S5 (0.235 ± 0.196 bits/ind.) and S6 (0.878 ± 0.487) for p = 0.0393. Globally, the Chari-Logone River complex was poorly diversified. The J index oscillated from 0 to 0.92 (Figure 4d). The Friedman test showed no significant variation in the J index between the stations studied (p = 0.0657). The benthic macroinvertebrates collected were fairly evenly distributed across the explored stations.

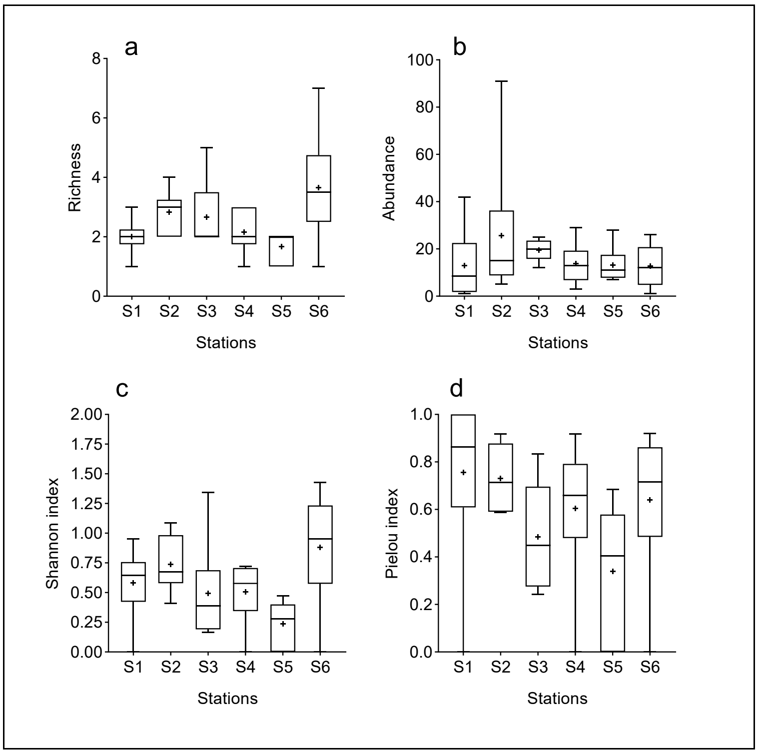

Figure 4: Graphical representation of specific richness (a), abundance (b), Shannon (c) and Pielou (d) index in the Chari-Logone River complex

Overall, the similarity indices presented many low values. Nevertheless, these similarities were considerable between stations S2-S3, S2-S4, S3-S4 and S4-S6 (Table 5).

Table 5: Sörensen similarity coefficient between the different sampled stations

Stations	S1	S2	S3	S4	S5
S2	26.66				
S3	25	70.58			
S4	42.85	66.66	75		
S5	30.76	42.85	40	30.76	
S6	25	48	46.15	50	17.39

3.3. Effects of abiotic factors on biological abundance

Canonical Correspondence Analysis (CCA) was carried out to establish relationships between physicochemical parameters and BMI collected during the period of study. The first two axes (axis 1 = 24.4% and axis 2 = 17.1%) showed 41.5% of information (Figure 5). Three groups of inertia were distinguished based on the connections between benthic macroinvertebrates and physicochemical parameters. Group I is made up of species that prefer water that contains much organic matter (ammonia, nitrites). These species are among others *Corbicula africana*, *Mutela dubia*, *Aspatharia senegalensis*, *Aspatharia chaiziana, Melanoides tuberculata,* and *Caelatura aegyptiaca* (Unionida)*, and Gabbiella chadiensis* (Littorinimorpha). Group II is made up of species preferring an oxygen-rich environment. These species include *Hyphydrus* sp., *Omotonus* sp. (Coleoptera), *Ranatra linearis, Anisops* sp. (Heteroptera), *Baetis* sp. (Ephemeroptera), and *Caridina africana* (Decapoda). Group III consists of species such as *Pseudagrion* sp., *Lestes* sp. (Odonata), *Laccophilus* sp., *Orectogyrus* sp., *Methles* sp., *Guignoyus* sp. (Coleoptera), and *Gabbiella spiralis* (Littorinimorpha). The distribution of these species is considerably influenced by pH and temperature.

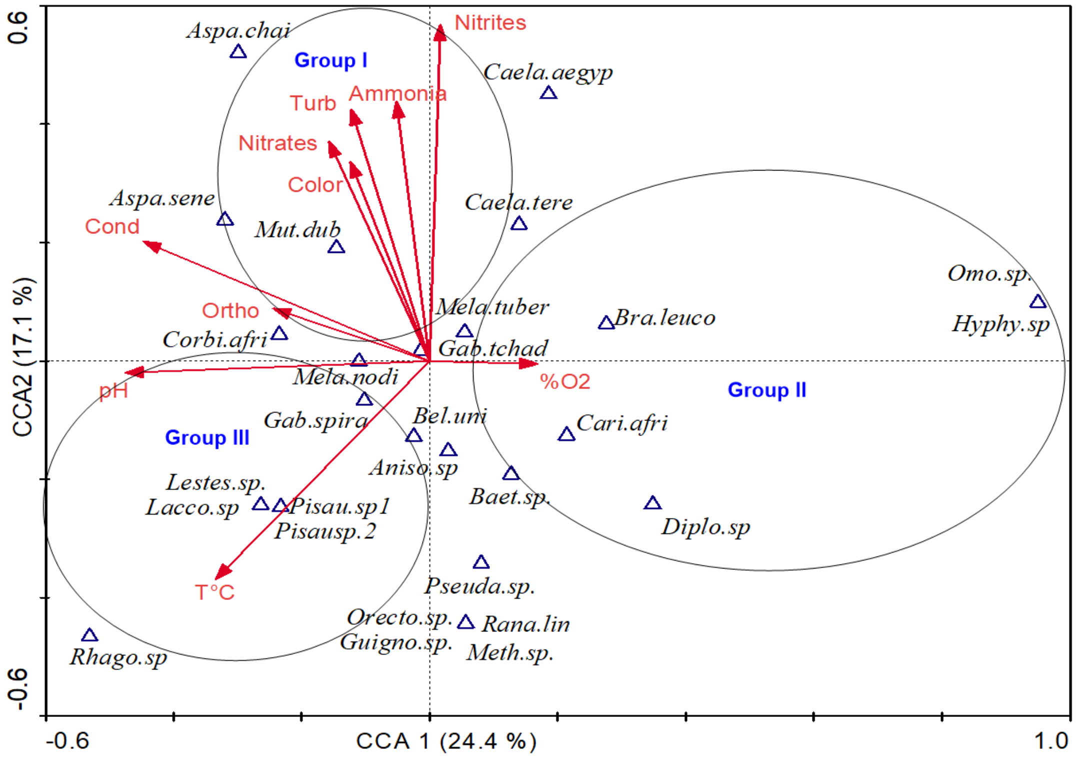

Figure 5: Canonical correspondence analysis biplot showing gathering of benthic macroinvertebrates in response to environmental variables. T°C = water temperature, pH= potential Hydrogen, Ortho= orthophosphates, %O_2= percentage of dissolved oxygen, Cond= conductivity. *Mela.nodi* = *Melanoides nodicincta*, *Mela.tuber* = *Melanoides tuberculate*, *Aspa.sene* = *Aspatharia senegalensis*, *Aspa.chai* = *Aspatharia chaiziana*, *Gab.tchad* = *Gabbiella tchadiensis*, *Gab.spira* = *Gabbiella spiralis*, *Caela.aegyp* = *Caelatura aegyptiaca*, *Caela.tere* = *Caelatura teretiuscula*, *Mut. dub* = *Mutela dubia*, *Bel.uni* = *Bellamya unicolor*, *Bra.leuco* = *Brachysthemis leucosticte*, *Cari.afri*= *Caridina Africana*, *Omo.*sp.= *Omotonus* sp., *Hyphy.*sp.= *Hyphydrus* sp., *Pseuda.*sp.= *Pseudagrion* sp., *Rana.line* = *Ranatra linearis*, *Orecto.*sp.= *Orectogyrus* sp., *Baet.*sp.= *Baetis* sp., *Meth.*sp.= *Methles* sp., *Guigno.*sp.= *Guignoyus* sp., *Lestes* sp.= *Lestes* sp., *Lacco.sp.*= *Laccophilus* sp., *Corbi.afri*= *corbicula africana*, *Aniso.*sp.= *Anisops* sp., *Pisau.*sp.*1*= *Pisauridae* sp.1, *Pisausp.*2= *Pisauridae* sp.2, *Rhago.sp.*= *Rhagovelia* sp., *Diplo.*sp.= *Diplonychus* sp.

Some significant correlations were observed in this study (Table 5). *Melanoides nodicincta* was significantly and positively correlated with pH (p = 0.021) and with ammonia (p = 0.007). Positive and significant correlations were observed between *Caelatura aegyptiaca* with nitrites (p = 0.013) and with ammonia (p = 0.025), and *Pseudagrion* sp. was positively and significantly correlated with conductivity (p = 0.037). These organisms were most abundant when these parameters increased.

Table 6: Summary of Spearman correlation between benthic macroinvertebrate abundances and physicochemical variables

Variables	T°C	pH	Cond	%O2	Turb	Color	Ortho	Nitrates	Nitrites	Ammonia
Melanoides nodicincta	0.497	0.021*	0.103	0.240	0.248	0.419	0.408	0.877	0.758	0.007*
Melanoides tuberculata	0.067	0.276	0.122	0.870	0.228	0.299	0.076	0.416	0.018*	0.210
Aspatharia senegalensis	0.383	0.840	0.360	0.162	0.977	0.991	0.156	0.624	0.760	0.384
Aspatharia chaiziana	0.472	0.826	0.198	0.623	0.324	0.695	0.647	0.061	0.049*	0.932
Gabbiella tchadiensis	0.775	0.713	0.780	0.751	0.782	0.571	0.539	0.632	0.300	0.567
Gabbiella spiralis	0.282	0.593	0.257	0.654	0.906	0.792	0.734	0.313	0.596	0.268
Caelatura aegyptiaca	0.155	0.294	0.295	0.593	0.172	0.295	0.381	0.631	0.013*	0.025*
Caelatura teretiuscula	0.366	0.887	0.317	0.317	0.232	0.125	0.506	0.124	0.812	0.136

Mutela dubia	0.963	0.366	0.670	0.233	0.392	0.125	0.813	0.850	0.416	0.091
Bellamya unicolor	0.113	0.272	0.233	0.165	0.392	0.197	0.341	0.196	0.812	0.569
Brachysthemis leucosticta	0.538	0.537	0.295	0.887	0.813	0.887	0.317	0.536	0.703	0.272
Caridina africana	0.953	0.271	0.362	0.902	0.503	0.369	0.479	0.167	0.122	0.811
Omotonus sp.	0.137	0.196	0.197	0.740	0.137	0.181	0.963	0.112	0.270	0.704
Hyphydrus sp.	0.137	0.196	0.197	0.740	0.137	0.181	0.963	0.112	0.270	0.704
Pseudagrion sp.	0.973	0.453	0.037*	0.946	0.305	0.339	0.148	0.734	0.319	0.658
Ranatra linearis	0.476	0.272	0.137	0.670	0.537	0.538	0.669	0.887	0.535	0.635
Orectogyrus sp.	0.476	0.272	0.137	0.670	0.537	0.538	0.669	0.887	0.535	0.635
Baetis sp.	0.814	0.268	0.209	0.632	0.967	0.799	0.934	0.838	0.849	0.583
Methles sp.	0.476	0.272	0.137	0.670	0.537	0.538	0.669	0.887	0.535	0.635
Guignoyus sp.	0.476	0.272	0.137	0.670	0.537	0.538	0.669	0.887	0.535	0.635
Lestes sp.	0.151	0.272	0.137	0.273	0.537	0.670	0.196	0.365	0.090	0.536
Laccophilus sp.	0.151	0.272	0.137	0.273	0.537	0.670	0.196	0.365	0.090	0.536
Corbicula africana	0.462	0.229	0.090	0.374	0.619	0.443	0.557	0.403	0.418	0.095
Anisops sp.	0.602	0.232	0.741	0.197	0.635	0.776	0.850	0.537	0.703	0.475
Pisauridae sp.1	0.962	0.887	0.538	0.420	0.273	0.366	0.150	0.180	0.812	1.000
Pisauridae sp.2	0.962	0.887	0.538	0.420	0.273	0.366	0.150	0.180	0.812	1.000
Rhagovelia sp.	0.705	0.476	0.538	0.165	0.102	0.125	0.887	0.537	0.148	0.850
Diplonychus sp.	0.317	0.317	0.366	0.602	0.341	0.181	0.670	0.232	0.148	0.569

The p-values bearing a star (*) are significant correlations at the level of p = 0.05

The analysis of indicator values by Dufrêne and Legendre (1997) reveals four indicator taxa at the 5% level, namely two taxa for site S6 and one taxon each for sites S2 and S3. No indicator taxa were observed at sites S1 and S4 (Fig. 6). Site S2 is characterised by *Gabbiella tchadiensis* (IndVal = 29.63%; p = 0.0195), and site S3 is characterised by *Melanoides tuberculata* (IndVal = 33.73%; p = 0.0051). Station S6 is therefore characterised by *Caridina africana* (IndVal = 47.22%; p = 0.0063) and *Pseudagrion* sp. (IndVal = 33.33%; p = 0.0235).

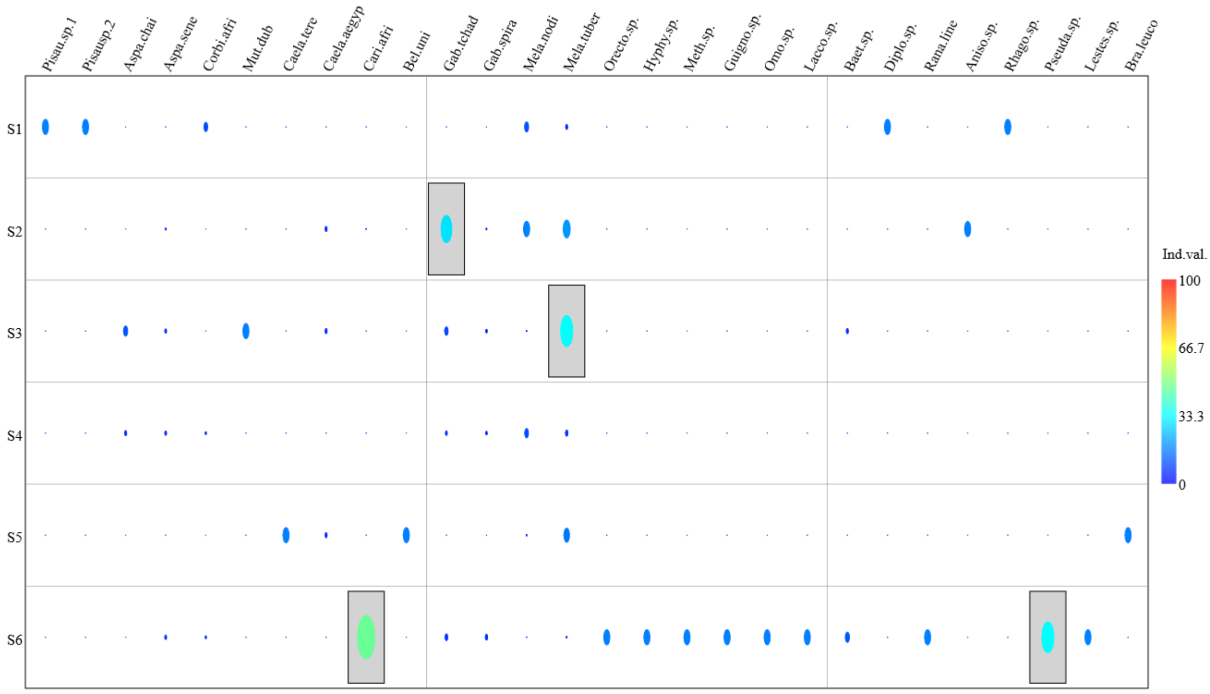

Figure 6: Map of the indicator values of benthic macroinvertebrates collected in the Chari-Logone river complex, with p < 0.05 boxed.

4. Discussion

4.1. Physicochemical characteristics

The temperature values recorded during the study period (22.6 - 30.12 °C) varied slightly between the stations. This could be explained by the absence of the canopy in the stations and the importance of solar rays. These temperature values (26.66 ± 2.12 °C), on the one hand, are close to those obtained by Sanogo *et al.* (2021) in the Kou river (26.13 ± 1.73 °C). On the other hand, they are higher than those obtained by Koumba *et al.* (2017) in the streams of the National Park in the southwest of Gabon (22.22°C). The pH average (7.37 ± 0.67) corresponds to that of the neutral surface water (Rodier *et al.*, 2009). Indeed, pH values between 5 UC and 9 UC are considered normal for biological development (Blinda, 2007). Electrical conductivity also had values that gradually evolved over the study period. These values , which oscillated between 86 and 240 µS/cm (124.42 ± 40.53), show weak mineralisation. These values are far lower than those (39.42 -1332 µS/cm) obtained by Madomguia *et al.* (2019) in the Far-North of Cameroon.

The oxygen contents varied with an average of 79.25 ± 11.42%. These values, close to those obtained by Ngoay-Kossy *et al.* (2018) and Dzavi *et al.* (2020), respectively in the Central African Republic and North Cameroon, showed good oxygenation of the water. However, values lower than 60% recorded at stations 4 and 5 at certain sampling periods could be linked to the process of transforming waste from industrial effluents from breweries and slaughterhouses. The slightly elevated concentrations of different nitrogen forms and orthophosphates are believed to be due to anthropogenic activities, notably laundry and vegetable crops, which could result from the discharge of detergents and fertilizers. Certain values are higher than those obtained by (Biram à Ngon *et al.*, 2020) but lower than those obtained by Temgoua Zemo *et al.*, 2023). The average values of the different physicochemical parameters didn't seem to show poor quality of water, but they were limited in giving the precise water quality.

Concernig pollution, the average OPI (2.81 ± 0.22) indicates globaly hight pollution. With the exeption of Station S1, which is moderately polluated, the high levels of pollution observed at all other stations could be attribueted to a combination of pollutants from agricultural,fishing and transportation activities, as well as effluents from slaughterhouses and breweries operating in those areas.

4.2. Benthic macroinvertebrates' structure

The portion of the Chari-Logone River complex studied is a Gastropod-dominated community. The same findings are generally reported in studies carried out on urban waterways in sub-Saharan Africa (Kock and Wolmarans, 2009; Tchakonté *et al.*, 2014b; Koudenoukpo *et al.*, 2021). Generally, the dominance of gastropods is linked to their resistance to water pollution and siltation of the seabed (Dillon, 2000a; Tchakonte *et al.*, 2023). Being scrapers (Tachet *et al.*, 2010), gastropods easily find nutrients by scraping the bottoms of waterways and do better than other organisms like crustaceans and insects, which prefer heterogeneous and less polluted habitats (Mboye *et al.*, 2020; Temgoua Zemo *et al.*, 2023). Only the species *Melanoides nodicincta*, *Melanoides tuberculata,* and *Gabbiella tchadiensis* were recurrent in the Chari-Logone River complex. Unlike other rare species, these three species seem to be the most resistant and invasive (Durán-Rodríguez *et al.*, 2024). It should also be remembered that these organisms favor rivers or lentic environments with harsh conditions (Strong *et al.*, 2008; Koudenoukpo *et al.*, 2021). Whether it is the abundance of organisms or the taxonomic richness, the Chari-Logone River complex has probably lost part of its biodiversity following the urbanization and industrialization of its watershed. The richness and abundance reported in this study indicate a scarcity of organisms and low diversity (Marcon, 2010). Urbanization in Africa has notable effects on biodiversity (Munganga Kilingwa *et al.*, 2020; Koudenoukpo *et al.*, 2021; Edegbene *et al.*, 2023, 2023; Temgoua Zemo *et al.*, 2024).

The organisms were almost the same in the sections inside the city of N'Djamena. Only the up station and the down station, located respectively before and after the city, showed a dissimilarity with the other stations. The very high number of rare species is at the origin of this dissimilarity. Foto Menbohan *et al.* (2019) noted this discontinuity within the benthic macroinvertebrate community of a watercourse whose downstream portion was disturbed. They had shown that pollution was the cause of the modification of the biological composition and even the structure. We propose to follow Carraro *et al.* (2020) that an eDNA study could provide deep insight into more species of benthic macroinvertebrates that populate this Chari-Logone river system. The world is increasingly calling for river restoration (Feio *et al.*, 2021). Rare species *Caridina africana*, *Baetis* sp., *Rhagovelia* sp., *Lestes* sp., or *Ranatra linearis* are very sensitive to pollution (Andem *et al.*, 2023; Akindele *et al.*, 2024; Dzavi, 2024). It is therefore not surprising that they are rare in this study.

4.3. Abiotic variables' effects on benthic macroinvertebrates

The presence of industrial effluents probably containing heavy metals and organic matter would have positive effects on certain organisms (*Melanoides nodicincta*) and negative effects on others (*Caridina africana*, *Baetis* sp.). Koudenoukpo *et al.* (2021) have shown that certain gastropods are associated with significant organic pollution and the presence of heavy metals. Notably, *Melanoides tuberculata* grows in varied environments (rock, mud, still water, low flow) with a wide range of pH and cations (Berry and Kadri, 1973; Vogler *et al.*, 2012). Although suggested for several years as an invasive species in certain environments (Vogler *et al.*, 2012), it is the most abundant and frequent species in the Chari-Logone River complex. The less recurrent genus *Gabbiella* (*G. chadiensis* and *G. spiralis*) has already been reported in Lake Chad and sub-Saharan Africa (Dillon, 2000b). Other benthic macroinvertebrates, due to their character, had no association with abiotic variables. These observations are mentioned in the literature (Strong *et al.*, 2008; Kock and Wolmarans, 2009; Tchakonté *et al.*, 2015; Böhm *et al.*, 2020; Onana *et al.*, 2021; Dzavi *et al.*, 2022).

The results of the IndVal analysis indicate a clear ecological differentiation of communities between sites, as it combines relative abundance and occurrence fidelity to identify taxa strongly associated with specific locations (Dufrêne and Legendre, 1997). The absence of indicator taxa at S1 and S4 may suggest lower biological specificity at these sites or more uniform or disturbed environmental conditions that do not support the assembly of specialist species (Xu *et al.*, 1999; Mboye *et al.*, 2020). In contrast, the presence of indicators at S2, S3, and particularly S6 suggests more distinct ecological niches. *Gabbiella tchadiensis* at S2 and *Melanoides tuberculata* at S3 seem to serve as markers of specific local conditions. Meanwhile, *Caridina africana* and *Pseudagrion* sp. at S6 have the highest indicator values and reflect this site's particular preference for habitats suitable for these taxa. It indicated that the water quality is improving in the downstream (Tchakonté *et al.*, 2014a). *M. tuberculata* is especially notable because it is often found in permanent and varied environments, sometimes in modified habitats, which may explain its indicator role at certain sites (Kock and Wolmarans, 2009; Durán-Rodríguez *et al.*, 2024). Overall, the statistical significance of the IndVal values at the 5% threshold supports the idea that the identified taxa can serve as useful bioindicators for assessing the quality or type of the habitats studied.

5. Conclusions

This study made it possible to inventory the benthic macroinvertebrates in the Chari-Logone River complex around the N'Djamena town. These fairly well oxygenated waters still have slightly high levels of nitrogen and phosphate nutrients, and are very poorly diversified. The arthropod phylum presented the greatest abundance. Crustacea were present mainly downstream from the town, where the dominant substrate is sand, and there are no macrophytes. The main taxa in this River complex were pollution-resistant or seemed to need organic matter. The benthic macroinvertebrate community presented low taxonomic richness and diversity. The Chari-Logone River complex is disturbed and shows more pollutants and organisms, mainly Gastropod, but ecological conditions seem to be restoring downstream from the city of N'Djamena, with the appearance of Crustacea, recognised as pollution-sensitive. We propose to the Chadian authorities to protect the Chari-Logone River complex from industrial and domestic effluents, because it is of capital importance for the population. We believe that the physicochemical variables selected in this study are limited to have precise information on water quality since the organisms identified were pollutant-tolerant. In future studies, we suggest analyzing heavy metals and other active ingredients contained in the products used in vegetable crops and factories whose effluents flow into the Logone-Chari River complex. This will enable the sustainability of fish, navigation, and recreational areas for people.

Author Contributions: Safia Mahamat Tahir: Conceptualization, Methodology, Resources, Data curation, Writing - Original Draft, Writing - Review & Editing. **Jean Dzavi**: Contribution on Methodology, Data Curation, Formal Analysis, Writing - Original Draft, Writing-Review & Editing. **Mikail Abakar:** Data curation, Writing - Review & Editing. **Serge Hubert Zebaze Togouet**: Methodology, Identification of the BMI analysis, Writing - Review & Editing.

Funding: This research received no external funding.

Acknowledgements: The author gratefully acknowledges Bechir Assidick Mahamat, Abdelmoutalib Adam, Owona Edoa François Désiré, and Ndo Samuel for their help in data collection and treatment of biological.

Conflicts of Interest: The authors declare no competing interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Akindele EO, Adedapo AM, Akinpelu OT, Fagbohun IR, Kowobari ED, Oladeji TA, Adeniyi AV, Aliu OO. 2024. Freshwater macroinvertebrates along the Nigeria-Cameroon border enhance the conservation value of the lower Guinea forest biodiversity hotspot. *Journal of Environmental Management* 355: 120532.

Allan JD, Castillo MM, Capps KA. 2021. Rivers in the Anthropocene. In: Allan JD, Castillo MM, Capps KA, eds. Stream Ecology : Structure and Function of Running Waters, Springer International Publishing, Cham., 1–17.

American Public Health Association, American Water Works Association, Water Environment Federation. 2017. Standard methods for the examination of water and wastewater, Baird RB, Eaton AD, Rice EW, eds., American Public Health Association, 800 I Street NW, Washington, DC 20001-3710, 1546 p.

Andem AB, Odey CO, Beshel SB, Ojo OB, Etuk MC. 2023. Human-Induced Impact on the Distribution and Diversity of Benthic Macroinvertebrates and Fish Fauna in the Tropical Ikang River, Nigeria. *Croatian Journal of Fisheries* 81: 1–12.

Bagalwa M. 2006. The impact of land use on water quality of the Lwiro River, Democratic Republic of Congo, Central Africa. *African Journal of Aquatic Science* 31: 137–143.

Berry AJ, Kadri ABH. 1973. Reproduction in Malayan Freshwater Cerithiacean Gastropod Melenoides Tuberculata. *Journal of Zoology* 172: 369–381.

Biram à Ngon EB, Menbohan S, Ndjama J, Njoya Z, Mboye BR, Dzavi J, Oumar Mahamat O, Tarkang carine, Nyame Mbia D-L, Mbondo Biyong SR, Ngalamou C. 2020. Water quality assessment in a less anthropogenic forest stream in the Centre Region of Cameroon. *Haya Saudi J Life Sci* 5: 1–8.

Biram à Ngon EB, Chinche SB, Ndjama J, Dzavi J, Mbia DLN, Nwaha M, Nhiomock SRG, Mboye BR, Tchaouapi IL, Tchouta U, Ngalamou C, Menbohan SF. 2024. Inventory and Distribution of Benthic Macroinvertebrates, Indicators of Water Quality in Four Forested Watercourses in Centre Region of Cameroon. *Open Journal of Ecology* 14: 381–394.

Blinda M. 2007. Pollution tellurique du littoral nord-ouest du Maroc entre Tanger et Te'touan : Caractérisation, impact sur l'environnement et proposition de solution. [Thèse de Doctorat], Université Mohamed V, Faculté des Sciences, Maroc.

Böhm M, Dewhurst-Richman NI, Seddon M, Ledger SEH, Albrecht C, Allen D, Bogan AE, Cordeiro J, Cummings KS, Cuttelod A, Darrigran G, Darwall W, Fehér Z, Gibson C, Graf DL, Köhler F, Lopes-Lima M, Pastorino G, Perez KE, Smith K, van Damme D, Vinarski MV, von Proschwitz T, von Rintelen T, Aldridge DC, Aravind NA, Budha PB, Clavijo C, Van Tu D, Gargominy O, Ghamizi M, Haase M, Hilton-Taylor C, Johnson PD, Kebapçı Ü, Lajtner J, Lange CN, Lepitzki DAW, Martínez-Ortí A, Moorkens EA, Neubert E, Pollock CM, Prié V, Radea C, Ramirez R, Ramos MA, Santos SB, Slapnik R, Son MO, Stensgaard A-S, Collen B. 2020. The conservation status of the world's freshwater molluscs. *Hydrobiologia*.

Bouchez C, Goncalves J, Deschamps P, Vallet-Coulomb C, Hamelin B, Doumnang J-C, Sylvestre F. 2016. Hydrological, chemical, and isotopic budgets of Lake Chad: a quantitative assessment of evaporation, transpiration and infiltration fluxes. *Hydrology and Earth System Sciences* 20: 1599–1619.

Bowen KL, Currie WJS. 2021. Effect of the urbanized embayment Toronto Harbour on the composition and production of zooplankton. *Journal of Great Lakes Research* 47: 378–394.

Braak CJF ter. 1986. Canonical Correspondence Analysis: A New Eigenvector Technique for Multivariate Direct Gradient Analysis. *Ecology* 67: 1167–1179.

Carraro L, Stauffer JB, Altermatt F. 2020. How to design optimal eDNA sampling strategies for biomonitoring in river networks. *bioRxiv* 2020.05.18.102368.

Dajoz R. 2003. Précis d'écologie, Paris, 615 p.

Dethier M. 1981. Hétéroptères. Flore et faune aquatiques de l'Afrique Sahelo-Soudanienne, Office de Recherche Scientifique et Technique Outre-Mer (ORSTOM), Paris, France., 661–685.

Dillon RT. 2000a. The Ecology of Freshwater Molluscs. *Cambridge Core*. https://www.cambridge.org/core/books/ecology-of-freshwater-molluscs/1BF5BE49D95C21366E465B04BDE90753 (accessed October 19, 2024).

Dillon RT. 2000b. Biogeography. The Ecology of Freshwater Molluscs, Cambridge University Press., 326–366.

Djikoloum Beosso T, Richard Akwanjoh S, Norbert Tchamadeu N. 2024. Stream Quality and Benthic Macroinvertebrate Diversity in the Badeye Area, Logone Occidental Province, Southwestern Chad. *International Journal of Ecology* 2024: 3878910.

Dos Santos S, Adams EA, Neville G, Wada Y, de Sherbinin A, Mullin Bernhardt E, Adamo SB. 2017. Urban growth and water access in sub-Saharan Africa: Progress, challenges, and emerging research directions. *Science of The Total Environment* 607–608: 497–508.

Dufrêne M, Legendre P. 1997. Species Assemblages and Indicator Species: the Need for a Flexible Asymmetrical Approach. *Ecological Monographs* 67: 345–366.

Durand JR, Levêque C. 1980. Flore et faune aquatiques de l'Afrique Sahélo-soudanienne, Office des Recherches Scientifiques et Techniques d'Outre-Mer (ORSTOM), Paris, France, 389 p.

Durand JR, Levêque C. 1981. Flore et faune aquatiques de l'Afrique Sahélo-soudanienne, Office des Recherches Scientifiques et Techniques d'Outre-Mer (ORSTOM), Paris, France, 874 p.

Durán-Rodríguez OY, Moncayo-Estrada R, Torres-Olvera MJ, Pineda-López RF, Ramírez-Herrejón JP. 2024. Invasion stage of the exotic snail Melanoides tuberculata related to environmental and biological factors in a subtropical river drainage. *Journal of Freshwater Ecology* 39: 2403368.

Dzavi J. 2024. État écologique de quelques cours d'eau du bassin du Nyong au Cameroun: diversité des macroinvertébrés benthiques et des hyphomycètes aquatiques, décomposition de la litière et physico-chimie des eaux. [Thesis], Université de Yaoundé I, Cameroun.

Dzavi J, Kodji E, Koji E, Kalieu WAI, Dionkas J, Foto Menbohan S. 2020. An Idea on Physico-Chemical Parameters of Waters in Two Streams of Savannah Agro-Pastoral Zone, North Region of Cameroon. *International Journal of Research and Scientific Innovation* 7: 160–166.

Dzavi J, Menbohan SF, Mboye BR, Nwaha M, Ngon EBB à. 2022. Spatiotemporal Variation of Benthic Macroinvertebrates in Some Tropical Forest Streams of the Nyong Catchment (Cameroon). *Open Journal of Applied Sciences* 12: 1210–1231.

Edegbene AO, Jazuli A, Ayuba IM, Ovie TTE, Akumabor EC. 2023. Assessing the ecological health of River Ringim, Northwestern, Nigeria using macroinvertebrate-based Chanchaga Multimetric Index. *Water Science* 37.

Feio MJ, Hughes RM, Callisto M, Nichols SJ, Odume ON, Quintella BR, Kuemmerlen M, Aguiar FC, Almeida SFP, Alonso-EguíaLis P, Arimoro FO, Dyer FJ, Harding JS, Jang S, Kaufmann PR, Lee S, Li J, Macedo DR, Mendes A, Mercado-Silva N, Monk W, Nakamura K, Ndiritu GG, Ogden R, Peat M, Reynoldson TB, Rios-Touma B, Segurado P, Yates AG. 2021. The Biological Assessment and Rehabilitation of the World's Rivers: An Overview. *Water* 13: 371.

Foto Menbohan S, Tchakonté S, Ajeagah Aghaindum G, Zebaze Togouet SH, Bilong Bilong CF, Njiné T. 2013. Water Quality Assessment Using Benthic Macroinvertebrates in a Periurban Stream (Cameroon). *The International Journal of Biotechnology* 2: 91–104.

Foto Menbohan S, Dzavi J, Kenfack Nzongang C, Biram à Ngon EB, Ntchantcho R. 2019. Impact of the anthropogenic activities on the diversity and structure of benthic macroinvertebrates in tropical forest stream. *IJPSAT* 15: 280–292.

Ge Y, Liu Z, García-Girón J, Chen X, Yan Y, Li Z, Xie Z. 2022. Human-induced loss of functional and phylogenetic diversity is mediated by concomitant deterministic processes in subtropical aquatic insect communities. *Ecological Indicators* 136: 108600.

Hassane Hemchi M, Hallou Ahmat Mahamat, Danvide Tameon Benoit. 2021. Analyse du processus d'extension de la ville de N'Djamena au Tchad (1900 – 2018). *Geo-Eco-Trop* 45: 507–516.

INSEED. 2009. Institut National de la Statistique, des Etudes Economiques et Demographiques (INSEED): le deuxième recensement général de la population et de l'habitat (RGPH2) de 2009, Tchad, 96 p.

Kelly MG, Free G, Simaika JP, Warner S, Bruder A, Correa-Bedoya A, de Oliveira Roque F, Eriksen TE, Lento J, Macadam CR, Meissner K, Moretti MS, Penrose D, Stribling J, Poikane S. 2025. The global role of bioassessment in policy delivery and decision-making for inland waters. *Journal of Environmental Management* 393: 127099.

Kengne Tenkeu J, Mogue Kamdem GJ, Nyamsi Tchatcho NL, Mvondo N, Kalieu IA, Takam W, ZebazeTogouet SH. 2020. Phytoplankton Dynamics of Mokolo and Mopa Ponds in Bertoua City (East-Cameroon). *Open Journal of Ecology* 10: 482–496.

Keylock CJ. 2005. Simpson Diversity and the Shannon-Wiener Index as Special Cases of a Generalized Entropy. *Oikos* 109: 203–207.

Kock K de, Wolmarans CT. 2009. Distribution and habitats of Melanoides tuberculata (Müller, 1774) and M. victoriae (Dohrn, 1865)(Mollusca: Prosobranchia: Thiaridae) in South Africa. *Water SA* 35: 713–720.

Koudenoukpo ZC, Odountan OH, Agboho PA, Dalu T, Van Bocxlaer B, Janssens de Bistoven L, Chikou A, Backeljau T. 2021. Using self–organizing maps and machine learning models to assess mollusc community structure in relation to physicochemical variables in a West Africa river–estuary system. *Ecological Indicators* 126: 107706.

Koumba M, Kevin Mipounga H, Armel Koumba A, Zinga Koumba CR, Rollinat Mboye B, Félicien Liwouwou J, Daniel Mbega J, François Mavoungou J. 2017. Diversité familiale des macroinvertébrés et qualité des cours d'eau du Parc National de Moukalaba Doudou (sud-ouest du Gabon). *ef* 70: 107–120.

Lactio NL, Menbohan SF, Owona DFE, Dzavi J, Zambo BG, Temgoua MAZ, Tchouta GU. 2026. Ecological health status of some watercourses in the Mfoundi Watershed, Yaoundé (Central Cameroon): Structure of the benthic macroinvertebrate community and water quality. *Hydrobiological Research* 4: 1–13.

Leclercq L, Maquet B. 1987. Deux nouveaux indices chimique et diatomique de qualité d'eau courante. Application au Samson et à ses affluents (Bassin de la Meuse Belge). Comparaison avec d'autres indices chimiques, biocénotiques et diatomiques. *Studiedocumenten van het Koninklijk Belgisch*

Instituut voor Natuurwetenschappen - Documents de travail de l'Institut Royal des Sciences naturelles de Belgique 38: 3–112.

Leclercq L. (2001). *Les eaux courantes : caractéristiques et moyens d'étude, dans Les zones humides.* Actes des colloques organisés par le Ministère de la Région Wallonne dans le cadre de l'Année Mondiale des Zones Humides, Jambes, Région Wallonne, DGRNE. pp. 67-82.

Lemoalle J, Brami-Hourtal D. 1996. Ressources en eau du bassin conventionnel. *Atlas* 11.

Lento J, Laske SM, Culp JM, Goedkoop W, Kahlert M, Lau DCP, Lavoie I, Musetta-Lambert J, Ólafsson JS, Christoffersen KS. 2026. Harmonization of aggregated freshwater biotic data to support continental and global assessment. *PLOS Water* 5: e0000502.

Madomguia D, Togouet SHZ, Fomena A. 2016. Macro Invertebrates Functional Feeding Groups, Hilsenhoff Biotic Index, Percentage of Tolerant Taxa and Intolerant Taxa as Major Indices of Biological Assessment in Ephemeral Stream in Sudano-Sahelian Zone (Far-North, Cameroon). *IntJCurrMicrobiolAppSci* 5: 792–806.

Madomguia D, Zébazé Togouet SH, Fomena A. 2019. Biological Assessment of the Mayo Kaliao River, an Ephemeral Stream in Sudano-Sahelian Zone (Far North, Cameroon). *N Y Sci J* 12: 79–87.

Mahamat Tahir S, Otchoum BB, Ibrahim MA, Siméon T, Achuo ED, Hubert ZTS. 2020. Spatio-temporal dynamics of zooplankton communities (Rotifers, Cladocerans, Copepods) and water quality of Lake Léré (TCHAD). *International Journal of Environment, Agriculture and Biotechnology* 5.

Mahugnon Kiki Joseph, Adote Herve Gildas Akueson et Arcadius Yves Justin Akossou. 2026. Impact de la qualite des eaux de surface de la haute vallée de l'oueme supérieur sur la production. *Afrique Science* 28 (2) : 13 – 26.

Marcon E. 2010. Mesures de la biodiversité.

Mbaka JG, Aura CM. 2022. Spatio-temporal Effects of Anthropogenic Disturbances on Macroinvertebrates in Subukia River, Kenya. *East African Journal of Environment and Natural Resources* 5: 257–277.

Mboye BR, Koumba AA, Dzavi J, Tchinga G, Foto Menbohan S, Mbega JD. 2020. Abondance, diversité et valeur indicatrice des macroinvertébrés benthiques des cours d'eau forestier du bassin versant de la Mabounié au Gabon. *Afrique science* 17: 89–103.

MEPDD. 2024. Premier rapport biennal actualisé du Tchad - UNFCCC. LA CONVENTION CADRE DES NATIONS UNIES SUR LES CHANGEMENTS CLIMATIQUESMinistère de l'Environnement, de la Pêche et du Développement Durable, Tcahd.

Moisan J. 2010. Guide d'identification des principaux Macroinvertébrés benthiques d'eau douce du Québec, 2010 - surveillance volontaire des cours peu profonds, Direction du suivi de l'état de l'environnement, Ministère du Développement Durable, de l'Environnement et des Parcs, 82 p.

Munganga Kilingwa C, Kavumbu Mutanda S, Kunonga Nzadimwena L, Lusasi Swana W, Pwema Kiamfu V. 2020. Evaluation de la Qualité Écologique de la Rivière Musolo à Kinkole Basée sur les Macroinvertébrés Benthiques (Kinshasa, R.D Congo). *European Journal of Scientific Research* 155: 162–176.

Nambatingar N, Clement Y, Merle A, New Mahamat T, Lanteri P. 2017. Heavy Metal Pollution of Chari River Water during the Crossing of N'Djamena (Chad). *Toxics* 5: 26.

Ngaram N. 2011. Contribution à l'étude analytique des polluants (en particulier de type métaux lourds) dans les eaux du fleuve Chari lors de sa traversée de la ville de N'Djamena. Université Claude Bernard, Lyon 1, France.

Ngoay-Kossy JC, Zebazé Togouet SH, Wango SP, Bolevane Ouantinam SF, Tchakonté S, Piscart C. 2018. Bioindicators of running freshwaters in Central African Republic: benthic macroinvertebrates and anthropogenic stress in the Nguitto Stream. *Revue d'Ecologie (Terre et Vie)* 73: 603–616.

Nsangou Moundignigni Hénock Yves, Nonga Tang Brillant, Kengne Tenkeu Janvier, Mogue Kamdem Gwladys Joelle and Zébazé Togouet Serge Hubert. 2024. Spatio-temporal distribution of zooplankton and physico-chemistry in some rivers of the agricultural area of Awae (Centre Region-Cameroon). *International Journal of Fisheries and Aquatic Studies* 12 (3) : 34-41

Nwaha M, Ngon EBB a, Dzavi J, Mbongue SR, Epounde ACM. 2026. Distribution of Benthic Macroinvertebrates in Some Rivers of the Ntem Basin in Southern Cameroon. *Ecology and Evolutionary Biology* 11: 1–11.

Ochieng H, Gandhi WP, Magezi G, Okot-Okumu J, Odong R. 2021. Diversity of benthic macroinvertebrates in anthropogenically disturbed Aturukuku River, Eastern Uganda. *African Zoology* 56: 85–103.

Ochuka M, Ikporukpo C, Mijinyawa Y, Ogendi G. 2019. Land Use/Land Cover Dynamics and Anthropogenic Driving Factors in Lake Baringo Catchment, Rift Valley, Kenya. *Natural Resources* 10: 367–389.

Onana FM, Zébazé Togouet SH, Koji E, Nyamsi Tchatcho NL, Tchakonté S. 2016. Influence of municipal and industrial pollution on the diversity and the structure of benthic macro-invertebrates community of an urban river in Douala-Cameroon (Central-Africa). *J Bio Env Sci* 8: 120–133.

Onana FM, Tamsa AA, Tchakonte S, Koji E, Tchatcho NLN, Nfongmo YN, Togouet SHZ. 2021. Effects of Industrial Agriculture and Urbanization on Structure and Functional Organization of Macroinvertebrate of Coastal Streams in Cameroon. *Journal of Water Resource and Protection* 13: 154–171.

Pielou EC. 1966. The measurement of diversity in different types of biological collections. *Journal of Theoretical Biology* 13: 131–144.

Poisson R. 1929. Contribution à la faune du Cameroun, Hémiptères aquatiques. *Faune Colonies Françaises* 3: 135–164.

Ramiandrivelo Kotoarinosy Joel Philemon, Andriamalala Alain Mikael, Randimbiarivelo Ronald Harisson, Randriamialy Jean Dominique et Ranarijaona Hery Lisy Tiana. 2021 : mise en place d'un plan de restauration hydromorphologique de la riviere nosivolo ; 3ème édition spéciale, volume 5, Université d'été, mahajanga, Madagascar.

Rodier J, Legube B, Merlet N, Brunet R, Collaborateurs. 2009. L'analyse de l'eau, Dunod, Paris, 1579 p.

Saha F, Tchindjang M, Dzana J-G, Nguemadjita D. 2021. Dynamique des extrêmes hydrologiques du système Chari-Logone et risques naturels dans la région de l'extrême-nord du Cameroun. Proceedings of IAHS, Copernicus GmbH., 241–246.

Sanogo S, Inoussa Compaore, Issaka Senou, Somda MB, Ouedraogo RB, Ouattara B, Kabre TAT. 2021. Etude comparée de la structuration des macroinvertébrés benthiques de cours d'eau urbain et péri-urbain à l'ouest du Burkina faso. *International Journal of Development Research* 11: 43173–43184.

Shannon CE. 1948. A Mathematical Theory of Communication. *Bell System Technical Journal* 27: 379–423.

Stals R, de Moor IJ. 2007. Guides to the Freshwater Invertebrates of Southern Africa, Vol. 10: Coleoptera, WRC Report No, TT320/07, South Africa, 263 p.

Stark JD, Boothroyd I, Harding J, Maxted JR, Scarsbrook M. 2001. Protocols for Sampling Macroinvertebrates in Wadeable Streams. *New Zealand Macroinvertebrate Working Group Report No 1, Ministry for the Environment Sustainable Management Fund Contract No 5103* 65.

Strong EE, Gargominy O, Ponder WF, Bouchet P. 2008. Global diversity of gastropods (Gastropoda; Mollusca) in freshwater. In: Balian EV, Lévêque C, Segers H, Martens K, eds. Freshwater Animal Diversity Assessment, Springer Netherlands, Dordrecht., 149–166.

Tachet H, Richoux P, Bournaud M, Usseglio-Polatera P. 2010. Invertébrés d'eau douce: systématique, biologie et écologie, CNRS, Paris, 588 p.

Tchakonté S, Ajeagah Aghaindum G, Diomandé D, Camara AI, Konan Koffi M, Ngassam P. 2014a. Impact of anthropogenic activities on water quality and Freshwater Shrimps diversity and distribution in five rivers in Douala, Cameroon. *Journal of Biodiversity and Environmental Sciences* 4: 183–194.

Tchakonté S, Ajeagah GA, Diomandé D, Camara AI, Ngassam P. 2014b. Diversity, dynamic and ecology of freshwater snails related to environmental factors in urban and suburban streams in Douala–Cameroon (Central Africa). *Aquat Ecol* 48: 379–395.

Tchakonté S, Ajeagah GA, Camara AI, Diomandé D, Nyamsi Tchatcho NL, Ngassam P. 2015. Impact of urbanization on aquatic insect assemblages in the coastal zone of Cameroon: the use of biotraits and indicator taxa to assess environmental pollution. *Hydrobiologia* 755: 123–144.

Tchakonte S, Nana PA, Tamsa Arfao A, Nyamsi Tchatcho NL, Koji E, Onana FM, Ajeagah Aghaindum G. 2023. Using machine learning models to assess the population dynamic of the freshwater invasive snail Physa acuta Draparnaud, 1805 (Gastropoda: Physidae) in a tropical urban polluted streams-system. *Limnologica - Ecology and Management of Inland Waters* 99: 126049.

Temgoua Zemo MA, Menbohan SF, Atchrimi BT, Betsi WCN, Nwaha M, Dzavi J, Mavunda CA, Lactio N. 2023. Effect of Anthropogenic Pressure on the Biodiversity of Benthic Macroinvertebrates in Some Urban Rivers (Yaoundé). *Water* 15: 2383.

Temgoua Zemo MA, Foto Menbohan S, Atchrimi BT, Assou D, Biram à Ngon BE, Betsi NCW, Gwos Nhiomock S, Harissou, Lactio NL, Far Ndourwe B, Nwaha M, Mbia D l'or N, Tchouapi LY, Tchouta GU, Mboye BR, Dzavi J. 2024. Distribution Profile of Benthic Macroinvertebrates in Some Rivers of Yaoundé City and Its Surroundings Using Self Organizing Map and Indicator value methods. *Diversity* 16: 385.

Vicat J-P, Jean-Claude Doumnang Mbaigané, Edith Kadjangaba, Léontine Tekoum. 2025. Dissolved Trace Elements in the Chari–Logone Rivers from N'Djamena to the Chari Mouth (Chad Republique). An Early-2000s Baseline for Assessing Anthropogenic Impacts. *International Journal of Scientific Engineering and Science* 9: 104–112.

Vogler R, Nunez V, Gultierrez Gregoric DiegoE, Beltramino AA, Peso JG. 2012. Melanoides Tuberculuta: The History of an Invader, Nova Science publishers.

Xu F-L, Jørgensen SE, Tao S. 1999. Ecological indicators for assessing freshwater ecosystem health. *Ecological Modelling* 116: 77–106.

Yates AG, Brua RB, Culp JM, Aguiar FC, Ajayan AP, Aspin T, Bundschuh M, Calderón MR, Csabai Z, Dallas H, Datry T, Silva KD, Dzavi J, England J, Erős T, Gebler D, Goedkoop W, González-Ferreras AM, Hamilton DP, Hughes RM, Juen L, Kefford BJ, Koroiva R, Krynak EM, Lavoie I, Lento J, Ligeiro R, Martins RT, Masese FO, de Assis Montag LF, Musetta-Lambert J, Painter KJ, Poikane S, Rico A, Ruaro R, Sabater S, Michelan TS, Schoelynck J, Smucker NJ, Stanković I, Stubbington R, van Deventer H, van Niekerk L, Van den Brink PJ, Várbíró G, Wanderi EW. 2025. Charting a course for freshwater biomonitoring: The grand challenges identified by the global scientific community. *Ecological Indicators* 176: 113646.