

# Taxonomic Diversity and Spatial Variation of Benthic Macroinvertebrates in the Loutété River, Republic of the Congo

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## Abstract

This study inventories benthic macroinvertebrates at five stations along the Loutété River over four sampling campaigns across two years and relates community patterns to measured environmental variables. The authors report 15,336 specimens distributed across 4 classes, 12 orders, and 36 families, with Hydropsychidae as the dominant family. The main conclusion is that community structure varies among sites and is associated chiefly with sand and stream width.

## Keywords

Ecology, Surber Sampler, Benthic Macrofauna, Loutété River

## 1. Introduction

Waterways are among the most complex and dynamic ecosystems [1]. They are highly productive environments that support a wide variety of life forms (invertebrates, fish, amphibians, birds, mammals, reptiles, algae, and macrophytes) [2]. Unfortunately, this great biological richness is among the most threatened by the expansion of human activities and climate change, which has been and will continue to be in the future one of the major causes of long-term changes in aquatic biodiversity [3]. Consequently, for the sustainable management of disturbances in aquatic environments, systems for monitoring ecological integrity are developed using aquatic organisms [4]. These biological indicators are reliable and suitable

for monitoring aquatic ecosystems [5] [6]. The groups of organisms most commonly used as bioindicators are macrobenthic organisms [7]-[10]. Their diversity, spatio-temporal dynamics, and composition and abundance reflect the integrity of habitats and water quality. Despite their very important role in monitoring aquatic ecosystems, the benthic macroinvertebrates inhabiting the waterways of the Congo in general and the Loutété River in particular are virtually unknown, despite a few isolated studies conducted in the waterways around Mayoko [11], the Djoumouna River [12], in the waterways of the Loukoula Basin [13], and recently in the Loutété River [14] all conducted over a very short period and exclusively during the dry season. Knowledge of benthic macroinvertebrates and their functioning will therefore lead to better sustainable management of aquatic ecosystems.

In light of this, to contribute to our understanding of the macroinvertebrate fauna, an inventory of these organisms was conducted in the Loutété River, a tributary on the left bank of the Kouilou-Niari. The environment of this river is currently under the influence of human activities, particularly the mining industry recently established in the vicinity of Mfouati, one of the most important cities in this area. The aim of this study is to expand knowledge of the macrobenthic communities in this basin, specifically along the entire length of the river at stations representative of the different sections of the river (upper, middle, and lower reaches).

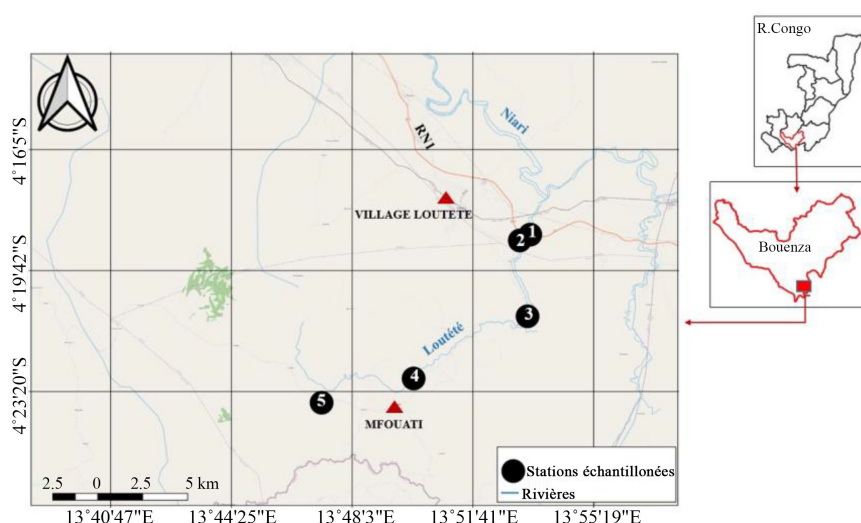
## 2. Materials and Methods

### 2.1. Environment and Sampling Sites

The Loutété River, a left-bank tributary of the Kouilou-Niari, originates on the edge of the Cataractes Plateau [15] at an elevation of approximately 413 m. It is a river that flows through savanna in the Bouenza department and empties into the Niari River. The Loutété River is one of the many tributaries that feed the Niari River on its left bank. The hydrographic network associated with the Loutété is dendritic in nature, reflecting a natural organization without strict structural control, often observed in areas with homogeneous substrate and moderately undulating terrain. The watercourses of the basin exhibit spatial and temporal variation in their hydrological parameters [16] discharge, width, and depth which are strongly influenced by the seasonal rainfall regime. This dynamic causes some rivers to become locally intermittent during the dry season, thereby exacerbating the water vulnerability of local populations. The Loutété region is subject to a transitional equatorial climate referred to by Aubreville (1449) as “Lower Congolese” or “Sudan-Guinean” [17]. It is characterized by a long, cool dry season, with temperatures ranging between 22°C and 31°C. The rainy season lasts 7 to 8 months, from October to May, interrupted by a lull or short dry season from January to February (Figure 1). Average rainfall is 1200 mm, with fluctuations ranging from less than 800 mm to just over 1400 mm [17]. However, the dry season lasts 4 to 5 months (mid-May to mid-October). As for the terrain, it consists of plains, valleys, hills,

and mountain ranges. The vegetation of the Niari Valley is characterized by a shrubby savanna surrounded by higher, wetter forested areas (the Chaillu and Mayombe Forests) [18].

To conduct and complete this study, five stations were selected along the Loutété River from downstream to upstream during both the rainy and dry seasons. These are: Loutété at the bridge on the RN1 (LRN1), Loutété village Moukanda at the bridge (LVMP), Loutété at Saint Michel (LSM), Loutété village Ntadi Hubuka (LVNH), and Loutété past the village of Mfouati (LVMF). These stations were selected based on the following criteria: accessibility of the site and water depth. The sampling campaigns spanned two years, with two campaigns per year (April-May 2022, August-September 2022, and April-May 2023, August-September 2023), one during the rainy season and one during the dry season.



**Figure 1.** Study area and sampling stations. **Caption:** LRN1 (1); LVMP (2); LSM (3); LVNH (4); LVMF (5).

## 2.2. Macroinvertebrate Sampling

For each sampling campaign, benthic macroinvertebrates from the Loutété River were captured using a very practical tool, the Surber sampler, consisting of two metal frames welded at right angles. The horizontal frame, placed on the substrate, defined an area of  $33 \times 33$  cm, or  $0.109 \text{ m}^2$ . The net, made of sieving silk, had a mesh size of 0.3 mm. Sampling was conducted during four campaigns spanning two years: April-May 2022 and August-September 2022; April-May 2023 and August-September 2023, corresponding respectively to a rainy season and a dry season. Sampling was conducted during the day between 7:00 a.m. and 4:00 p.m. At each station and during each sampling campaign, five overnet sweeps were conducted to collect macroinvertebrates. The taxa from the five samples were combined to form a composite sample representative of that station for the sampling campaign in question.

After sampling, a preliminary visual sorting was performed in the field to re-

move plant debris and large stones in order to reduce the sample size and prevent damage to the macroinvertebrates during transport. Finally, the remainder of the sample was stored in a plastic bag (Ziplock) containing 10% formalin and a label including: the station name, its geographic coordinates (Elevation, Longitude, Latitude), and the collecting date.

In the laboratory, the sample from each station was rinsed with water on a sieve to remove fine sediments and as much formalin as possible. After rinsing, the contents of the sieve were placed in a Petri dish to separate the macroinvertebrates from the remaining sediments under a Carl Zeiss binocular microscope, with magnification ranging from 80× to 320×. The macroinvertebrates thus sorted were then stored in pill boxes containing 95% ethanol (to prevent any deterioration) pending identification. A label bearing the name of the river, the station, and the geographic coordinates (latitude, longitude, and elevation) was placed in each pill box. Specimen identification was carried out at the Oceanography and Environment Laboratory of the National Institute for Research in Exact and Natural Sciences (IRSEN) using the identification keys proposed by: [19]-[26]. Identification was performed for the most part down to the family level. This level of identification is appropriate for biological assessment programs [27]-[29] to determine the state of integrity of aquatic environments.

### 2.3. Environmental Variables

During each campaign and at each sampling station, physicochemical variables were recorded. Physicochemical water parameters such as pH, temperature, total dissolved solids (TDS), and conductivity were measured in situ using an AM-STRAT multi-parameter probe to characterize the habitat of benthic macroinvertebrates. Water depth (in centimeters, measured using a 10-meter tape), current velocity (estimated at the surface by timing a float released between two fixed points 10 m apart, then converted to m/s), shading type (%), and substrate type were also taken into account. The following substrate categories were identified: sand, gravel, pebbles, mud, dead leaves, small stones, rock, and bedrock. In addition to these habitat-specific variables, two non-quantifiable variables related to the site were considered: the presence or absence of agricultural activities and dwellings in the vicinity of the site.

### 2.4. Data Analysis

Based on the non-significant seasonal differences ( $P > 0.05$ ) found in more than 94.74% of the environmental variables recorded (**Table 1**), as determined by Student's t-test using STATISTICA version 8 software, the analyses were conducted without accounting for the seasonal effect. This analysis, which did not account for seasonal effects, provided a comprehensive and synthetic estimate of the taxonomic richness and diversity of the environment. Two approaches were used: one 1) based on synthetic indices commonly used in ecology (specific richness, "S", the Shannon index "H", Pielou's evenness index "R", Simpson's diversity in-

dex “D”, the Hill index, and Frequency of Occurrence and Constancy (FO%), which in this study apply to taxa; and the other 2) based on multivariate analyses (Principal Component Analysis “PCA” and Canonical Redundancy Analysis “CRA”). The simultaneous use of these two approaches is justified by the fact that studying biodiversity through synthetic indices amounts to studying an ecosystem through indicators that reflect the state of diversity of its biocoenosis [30]-[33].

Specific richness (S): Corresponds to the number of taxa present in the environment;

Shannon diversity index  $H'$  [34]: The Shannon diversity index is used to assess a population within a biotope [35]. It is calculated using the following formula:

$$H' = -\sum_{i=1}^S P_i \ln P_i \quad (1)$$

where  $P_i = n_i/N$ ;  $H'$ : is the diversity index (in bits);  $P_i$ : is the relative frequency of individuals in taxon  $i$ ;  $n_i$ : is the number of individuals in taxon  $i$ ;  $N$ : is the total number of individuals across all taxa;  $S$ : the total number of taxa present.

Pielou’s Evenness Index  $R$  [36]

Pielou’s  $R$  index measures the distribution of individuals within taxa, regardless of taxonomic richness.

$$R = H'/H_{\max} \text{ where } H'_{\max} = \ln(S) \quad (2)$$

$H'$ : is the diversity;  $H_{\max}$ : is the maximum diversity expressed in terms of taxonomic richness

Its value ranges from 0 (dominance of a single taxon) to 1 (equal distribution of individuals across taxa).

Simpson’s diversity index  $D$  [37]

The Simpson index measures the probability that two individuals selected at random from a collection of  $S$  taxa and  $N$  individuals belong to the same taxon. This index is a widely used measure of dominance, weighted according to the abundance of the most common taxa and with low sensitivity to sample size [38]. It is given by the following formula:

$$D = 1 - \sum_{i=1}^S \left( \frac{n_i}{N} \right)^2 \quad (3)$$

The Hill diversity index:

$$\text{Hill} = (N^2)/(N_1) = (1/\lambda)/e^{H'} \quad (4)$$

Its value ranges from 0 (strong dominance of one of the taxa and low evenness) to 1 (even distribution of individuals across taxa and high evenness).

Frequency of Occurrence and Constancy (FO%):

The Frequency of Occurrence (FO) is the ratio, expressed as a percentage, of the number of samples ( $P_a$ ) from a station where the taxon is present to the total number of samples ( $P$ ).

$$\text{FO} (\%) = P_a/P \times 100 \quad (5)$$

Three groups can thus be defined: the first comprises “very common” taxa with

$F \geq 50\%$ ; the second group consists of “common” taxa with  $25\% \leq F < 50\%$ ; and rare taxa form the third group with  $F < 25\%$ . A fourth group is also defined: this consists of absent individuals with  $F = 0\%$  [39].

To identify the relationships between the stations, the benthic macroinvertebrate communities, and various environmental variables, multivariate analyses were conducted [40]. They were used to determine the correlation between taxonomic richness and environmental variables that influence habitat conditions, using CANOCO 4.5 software for Windows [41]. Matrices, taxon abundance data, and environmental variables were used. The data were normalized prior to ordination (ACCD); taxon abundances were transformed as  $\log(x + 1)$ , while environmental variables were transformed as  $\ln(x + 1)$  or  $\arcsin\sqrt{x}$  for percentage data [42]-[45]. Principal Component Analysis (PCA) was chosen, on the one hand with a gradient length ( $3 < LG < 4$ ) for the distribution of stations based on taxon abundances; on the other hand with  $LG < 3$  for the distribution of sites based on environmental variables. To identify the relationships between the stations, the benthic macroinvertebrate communities, and various environmental variables, multivariate analyses were conducted [40]. They were used to determine the correlation between taxonomic richness and environmental variables that influence habitat conditions, using CANOCO 4.5 software for Windows [41]. Matrices, taxon abundance data, and environmental variables were used. The data were normalized prior to ordination (ACCD); taxon abundances were transformed as  $\log(x + 1)$ , while environmental variables were transformed as  $\ln(x + 1)$  or  $\arcsin\sqrt{x}$  for percentage data [42]-[45]. Principal Component Analysis (PCA) was chosen, on the one hand with a gradient length ( $3 < LG < 4$ ) for the distribution of stations based on taxon abundances; on the other hand with  $LG < 3$  for the distribution of sites based on environmental variables [46]. The Monte Carlo test (999 permutations,  $P < 0.05$ ) was performed with variable selection to identify those that best explain the variations in the benthic macroinvertebrate data. Only one variable (5.26%) out of 19 was significant at the 0.05 probability threshold.

**Table 1.** Comparison of environmental variables at stations along the Loutété River. Significant differences ( $P < 0.05$ ) are shown in red. DS: Dry season; RS: Rainy season; P: Probability.

| Variables        | Season | Stations |       |       |        |        | Test de t |           |
|------------------|--------|----------|-------|-------|--------|--------|-----------|-----------|
|                  | SP/SS  | LRN1     | LVMF  | LVNH  | LSM    | LVMP   | t-value   | P         |
| Temperature (°C) | SP     | 28.35    | 24.45 | 28.18 | 29.43  | 29.38  | 1.859548  | 0.0321681 |
|                  | SS     | 26.35    | 21.5  | 25.8  | 25.9   | 26.3   |           |           |
| pH               | SP     | 7.17     | 7.52  | 8.61  | 7      | 9.9    | 2.0150484 | 0.0822319 |
|                  | SS     | 7.23     | 6.35  | 7.59  | 7.12   | 7.18   |           |           |
| TDS (PPM)        | SP     | 160      | 22.5  | 130   | 154.75 | 193.25 | 1.859548  | 0.1227643 |
|                  | SS     | 239      | 47    | 198   | 229    | 242    |           |           |

**Continued**

|                           |    |      |      |      |       |      |           |           |
|---------------------------|----|------|------|------|-------|------|-----------|-----------|
| Conductivity<br>(μS/cm)   | SP | 358  | 51   | 289  | 344.5 | 385  | 1.859548  | 0.4995261 |
|                           | SS | 358  | 72   | 296  | 343   | 358  |           |           |
| Depth(cm)                 | SP | 25   | 25   | 22.5 | 25    | 30   | 2.0150484 | 0.4120581 |
|                           | SS | 30   | 18   | 15   | 40    | 30   |           |           |
| speed(m/s)                | SP | 0.21 | 0.3  | 0.25 | 0.59  | 0.32 | 1.859548  | 0.0634827 |
|                           | SS | 0.12 | 0.11 | 0.24 | 0.15  | 0.36 |           |           |
| Width of the river<br>(m) | SP | 15   | 5    | 10   | 10    | 7.5  | 1.859548  | 0.5       |
|                           | SS | 15   | 5    | 10   | 10    | 7.5  |           |           |
| Width of the river (%)    |    |      |      |      |       |      |           |           |
| Canopyclosure             | SP | 0    | 50   | 0    | 0     | 50   | 1.859548  | 0.5       |
|                           | SS | 0    | 50   | 0    | 0     | 50   |           |           |
| Agriculture               | SP | 1    | 1    | 1    | 1     | 1    | —         | —         |
|                           | SS | 1    | 1    | 1    | 1     | 1    |           |           |
| Village                   | SP | 0    | 0    | 1    | 0     | 1    | 1.859548  | 0.5       |
|                           | SS | 0    | 0    | 1    | 0     | 1    |           |           |
| Sand                      | SP | 7.5  | 0    | 0    | 0     | 0    | 1.859548  | 0.1047944 |
|                           | SS | 10   | 0    | 20   | 5     | 0    |           |           |
| Gravel                    | SP | 32.5 | 10   | 45   | 37.5  | 60   | 1.859548  | 0.4674917 |
|                           | SS | 30   | 10   | 40   | 50    | 60   |           |           |
| Pebbles                   | SP | 15   | 10   | 45   | 62.5  | 0    | 1.859548  | 0.3021102 |
|                           | SS | 20   | 10   | 20   | 45    | 0    |           |           |
| Bedrock                   | SP | 40   | 0    | 0    | 0     | 40   | 1.859548  | 0.5       |
|                           | SS | 40   | 0    | 0    | 0     | 40   |           |           |
| Dead wood                 | SP | 0    | 0    | 0    | 0     | 0    | 0.1869505 | 2.1318468 |
|                           | SS | 0    | 0    | 10   | 0     | 0    |           |           |
| Rocks                     | SP | 0    | 80   | 0    | 0     | 0    | 1.859548  | 0.5       |
|                           | SS | 0    | 70   | 10   | 0     | 0    |           |           |
| Small stones              | SP | 0    | 0    | 10   | 0     | 0    | 0.1869505 | 2.1318468 |
|                           | SS | 0    | 0    | 0    | 0     | 0    |           |           |
| Fallen leaves             | SP | 2.5  | 0    | 0    | 0     | 0    | 1.859548  | 0.2437998 |
|                           | SS | 0    | 10   | 0    | 0     | 0    |           |           |
| Mud                       | SP | 2.5  | 0    | 0    | 0     | 0    | 0.1869505 | 2.1318468 |
|                           | SS | 0    | 0    | 0    | 0     | 0    |           |           |

Note: 0 = Absent; 1 = Present.

**3. Results****3.1. Taxonomic Composition and Frequency of Occurrence**

Sampling of macroinvertebrates in the Lout  t   River yielded 15,336 specimens of

macroinvertebrates belonging to 4 classes, 12 orders, and 36 families. Among the orders recorded, Diptera, Hemiptera, Ephemeroptera, Coleoptera, Odonata, and Trichoptera proved to be the most diverse. At the family level, the Hydropsychidae was the most abundant in terms of individuals. The taxonomic composition and frequency of occurrence of benthic macroinvertebrates at the various sampling stations are presented in **Table 2**.

**Table 2.** Taxonomic composition and frequency of occurrence of benthic macroinvertebrates at the study sites.

| Class       | Order           | Family          | Taxon code | Station codes |      |      |     |      |
|-------------|-----------------|-----------------|------------|---------------|------|------|-----|------|
|             |                 |                 |            | LRN1          | LVMF | LVNH | LSM | LVMP |
| Oligochaeta | Haplotaxida     |                 | Olig       | –             | ++   | –    | ++  | +    |
| Gastropoda  | Neotaenioglossa | Thiaridae       | Thia       | –             | –    | +++  | –   | –    |
|             | Basommatophora  | Lymnaeidae      | Lymn       | –             | +    | +++  | –   | –    |
| Turbellaria | Tricladida      | Planariidae     | Plan       | +             | +++  | +    | +   | +    |
| Insect      | Coleoptera      | Elmidae         | Elmi       | +             | ++   | +    | ++  | +    |
|             |                 | Psephenidae     | Psep       | –             | +++  | +    | –   | –    |
|             |                 | Gyrinidae       | Gyri       | +++           | +    | +    | +   | –    |
|             |                 | Dytiscidae      | Dyti       | –             | –    | –    | +++ | –    |
|             | Diptera         | Limoniidae      | Limo       | +             | ++   | +    | ++  | +    |
|             |                 | Ceratopogonidae | Cera       | ++            | +    | +    | ++  | +    |
|             |                 | Simuliidae      | Simu       | ++            | +    | +    | ++  | +    |
|             |                 | Chironomidae    | Chiro      | ++            | +    | ++   | +   | +    |
|             |                 | Empididae       | Empi       | –             | +++  | +++  | –   | –    |
|             |                 | Dolichopodidae  | Doli       | +++           | –    | –    | –   | –    |
|             |                 | Tipulidae       | Tipu       | –             | +    | +    | +++ | +    |
|             |                 | Tabanidae       | Taba       | –             | –    | –    | +++ | +    |
|             |                 | Dixidae         | Dixi       | –             | –    | +++  | –   | –    |
|             | Ephemeroptera   | Leptophlebiidae | Leptop     | ++            | +++  | +    | +   | +    |
|             |                 | Baetidae        | Baet       | ++            | +    | +    | +   | +    |
|             |                 | Heptageniidae   | Hept       | –             | +++  | +    | –   | –    |
|             |                 | Caenidae        | Caen       | –             | ++   | ++   | ++  | +    |
|             |                 | Leptohyphidae   | Leptoh     | –             | +++  | +    | –   | –    |
|             | Hemiptera       | Corixidae       | Cori       | –             | +++  | –    | ++  | –    |
|             |                 | Naucoridae      | Nauc       | –             | ++   | +++  | –   | –    |
|             |                 | Gerridae        | Gerr       | –             | +++  | –    | –   | –    |
|             |                 | Veliidae        | Veli       | –             | +++  | –    | –   | –    |
|             | Lepidoptera     | Pyralidae       | Pyra       | –             | –    | +++  | –   | –    |
|             | Odonata         | Libellulidae    | Libe       | +             | +    | +++  | +   | –    |
|             |                 | Caloptérygidae  | Calo       | –             | –    | –    | +++ | –    |
|             |                 | Chlorocyphidae  | Chlo       | –             | +++  | –    | –   | –    |
|             |                 | Gomphidae       | Gomp       | –             | +    | +    | ++  | +    |

## Continued

|  | Plecoptera  | Perlidae       | Perl    | +   | +++ | +   | +  | –  |
|--|-------------|----------------|---------|-----|-----|-----|----|----|
|  |             | Hydropsychidae | Hydrops | +++ | +   | +   | +  | +  |
|  |             | Philopotamidae | Phil    | +   | +   | +++ | ++ | +  |
|  | Trichoptera | Hydroptilidae  | Hydropt | –   | +   | ++  | +  | ++ |
|  |             | Leptoceridae   | Leptoc  | –   | +++ | ++  | –  | –  |
|  |             | Molannidae     | Mola    | –   | +++ | –   | –  | –  |

–: F = 0% (taxa absent); +: F ≠ 0% and less than 25% (rare taxa); ++: 25% ≤ F < 50% (common taxa); +++: F ≥ 50% (very common taxa).

### 3.2. Diversity Indices

Taxonomic richness (S), the Shannon index (H'), the evenness index (R), the Simpson index (D), and the Hill index were calculated based on the numerical abundances of taxa at each site. The highest value for each index is shown in bold, and the lowest is underlined (**Table 3**).

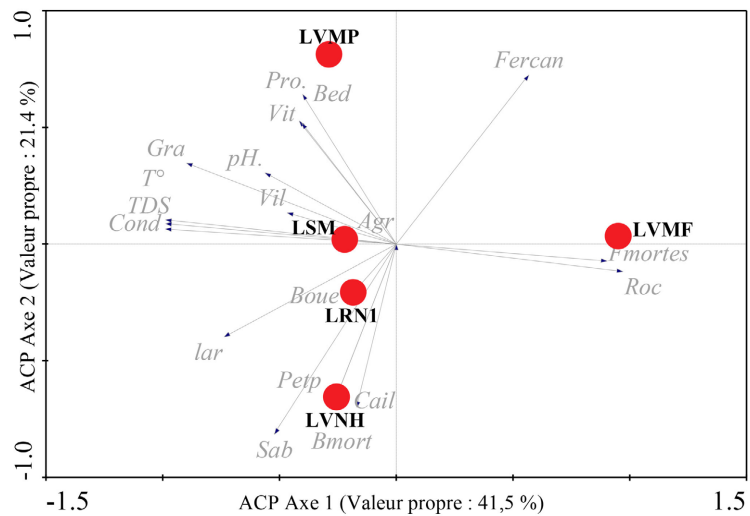
**Table 3.** Diversity indices at the sites. S: Taxonomic richness (S); N: total abundance; R: evenness; H': Shannon; Hmax; D: Simpson.

| Stations   | S           | N             | R            | H'           | Hmax        | D            | Hill         |
|------------|-------------|---------------|--------------|--------------|-------------|--------------|--------------|
| LRN1       | <u>14</u>   | <b>5858</b>   | 0.55         | <u>1.44</u>  | <u>2.64</u> | <u>0.64</u>  | <u>0.66</u>  |
| LVMF       | <b>30</b>   | <u>979</u>    | <b>0.76</b>  | <b>2.6</b>   | <b>3.4</b>  | <b>0.91</b>  | <b>0.79</b>  |
| LVNH       | 27          | 4370          | <u>0.53</u>  | 1.76         | 3.3         | 0.77         | 0.74         |
| LSM        | 22          | 2943          | 0.61         | 1.88         | 3.09        | 0.79         | 0.71         |
| LVMP       | 16          | 1186          | 0.56         | 1.55         | 2.77        | 0.73         | <b>0.79</b>  |
| <b>Min</b> | <b>14</b>   | <b>979</b>    | <b>0.53</b>  | <b>1.44</b>  | <b>2.64</b> | <b>0.64</b>  | <b>0.66</b>  |
| <b>Max</b> | <b>30</b>   | <b>5858</b>   | <b>0.76</b>  | <b>2.6</b>   | <b>3.4</b>  | <b>0.91</b>  | <b>0.79</b>  |
| <b>Moy</b> | <b>21.8</b> | <b>3067.2</b> | <b>0.602</b> | <b>1.846</b> | <b>3.04</b> | <b>0.768</b> | <b>0.738</b> |

### 3.3. Experimental Stations and Environmental Variables

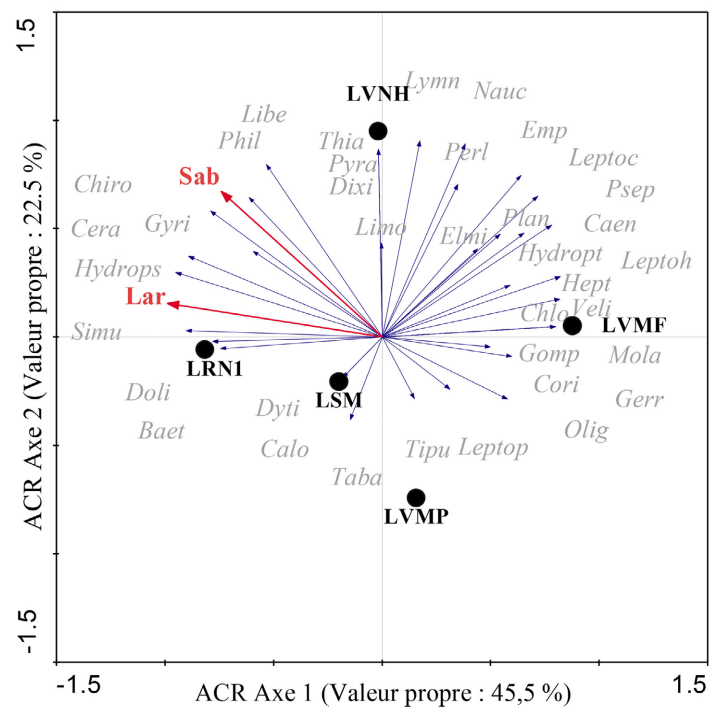
The results of the Principal Component Analysis (**Figure 2**) indicate that the first two axes (41.5% and 21.4%, respectively) account for 62.9% of the total variance in the dataset. This PCA generally highlights the formation of three distinct major groups. The first group consists solely of the LVMP station, located on the negative side of the most significant axis, axis 1 (41.5%), which is strongly correlated with depth, bedrock, and velocity. At the opposite end of this same axis lies the second group, consisting of the LVMF station, which is isolated on the positive side of the axis and correlated with canopy closure, dead leaves, and rocks. The third group, on the other hand, comprises the LSM, LRN1, and LVNH stations, which cluster around the origin. However, the LRN1 and LVNH stations are located on the negative side of axis 2, while the LSM station is positioned almost at the zero point of this axis, indicating neutrality with respect to this gradient. This

group is generally associated with conductivity, TDS, temperature, pH, gravel, mud, width, small stones, sand, dead wood, and pebbles.



**Figure 2.** PCA of stations grouped according to environmental variables in the Loutété.

### 3.4. Macroinvertebrate Communities, Sampling Sites, and Environmental Variables



**Figure 3.** Community composition of benthic macroinvertebrate populations in the Loutété.

The study of correlations between taxa, environmental variables, and all sampling stations in the Loutété River, conducted using Canonical Redundancy Analysis

(**Figure 3**), indicates that the first two axes (45.5% and 22.5%, respectively) account for 68% of the cumulative variance in the taxon data. The correlations between taxa and environmental variables for the two axes are high (0.95 and 0.98, respectively), and the Monte Carlo permutation test (999 permutations) shows that the two axes are significant ( $F = 2.13$ ;  $P = 0.04$ ). These results demonstrate that the distribution of taxa, as observed in this analysis, is not random, but rather depends on environmental variables. CRA with “forward selection” identified two environmental variables: sand (Sab) and width (Lar), which proved significant at the 0.05 probability threshold. Although these variables are significant, the majority of taxa are concentrated on the side opposite this gradient.

#### 4. Discussion

The collection of benthic macroinvertebrates in the Loutété River identified 36 families, 12 orders, and 4 classes. Six orders were found to be the most diverse: Diptera, Hemiptera, Ephemeroptera, Coleoptera, Odonata, and Trichoptera. These results have also been reported by several authors, including [20] [24] [47] [48]. Regarding the family, this result differs from the frequently observed pattern, namely a dominance of Chironomidae often found in freshwater. This difference is likely primarily linked to the contrasting characteristics of the savanna environment of the Loutété. This river features generally high current velocities (0.21 - 0.59 m/s), a coarse substrate, and better oxygenation conditions typical of rheophilic habitats colonized by Hydropsychidae, whose filter-feeding larvae require sustained currents and stable substrates for the installation of their nets [49] [50]. These results show that, although Chironomidae are often described as dominant in tropical lotic systems [51], the actual structure of the communities depends heavily on the local combination of current, substrate, oxygenation, and the nature of human activities in the surrounding area. Furthermore, analysis of the frequency of occurrence of macroinvertebrates at the five study sites reveals significant differences in terms of species richness, community structure, and potentially ecological quality. These results allow for several key observations. The LVMF station stands out for its high taxonomic richness (30 taxa present) with a predominance of common taxa (13), indicating an aquatic ecosystem in good condition, relatively stable, and minimally impacted by anthropogenic pressures. This rich and balanced faunal structure likely reflects a diverse, well-oxygenated, and minimally polluted habitat. In contrast, the LRN1 site shows very low diversity (14 taxa) and a high number of absent taxa (23), which is generally interpreted as a sign of environmental disturbance. Sand extraction in this area by companies and/or local residents could be the primary cause of this disturbance. The LVNH and LSM sites exhibit intermediate profiles. The LVNH site has relatively high species richness (27 taxa), but is marked by a high proportion of rare taxa (15), indicating moderate disturbance due to anthropogenic pressure from local communities (specifically, the population of the village of Ntadi Hubuka). The LSM station, meanwhile, has 22 taxa, including 4 very common taxa. These very com-

mon families notably Calopterygidae, Dytiscidae, Tabanidae, and Tipulidae though abundant, are mostly tolerant of variable conditions. The Calopterygidae, which are more sensitive, may indicate a certain level of water quality, although their presence alone is not sufficient to confirm good ecological quality. Finally, the LVMP station presents the most concerning situation after the LRN1 station, with a majority of rare (15) and absent (21) taxa, and the near-total absence of common or very common taxa. This situation suggests a relatively disturbed environment due to its location in the heart of the village (Moukanda), involving domestic activities such as the washing of clothes, dishes, or bodies directly in the river by the local population, leading to organic and chemical pollution that is not conducive to the sustainable establishment of less tolerant taxa.

A comparison of the Shannon diversity index ( $H'$ ), Simpson's index  $D$ , and Hill's ratio ( $N2/N1$ ) revealed distinct ecological profiles among the five sites. The Shannon index, which is sensitive to species richness and rare taxa, ranges from 1.44 to 2.60, reaching its maximum at the LVMF site, reflecting a high and relatively homogeneous distribution of taxa. The Simpson index, which is more influenced by the dominance of abundant taxa, shows a similar trend with a maximum value of 0.91 at the LVMF site and a minimum of 0.64 at the LRN1 site, indicating that the latter is strongly dominated by a few taxa. Two families dominate in terms of abundance, including the Hydropsychidae family, which alone accounts for 57% of the total number of individuals, followed by the Baetidae family at 16%. By combining Shannon's sensitivity to rare taxa with Simpson's sensitivity to dominant taxa, Hill's index provided us with a more comprehensive measure of effective diversity. It shows that the LVMF site (0.79) has the most balanced and diverse structure, which can be explained by the fact that this site is located in an area far from human settlements and receives fresh water directly from the mountains of the Cataract Plateau, whereas the LRN1 site (0.66) exhibits both low diversity and high taxonomic dominance. The LVMP site, although low in diversity according to Shannon (1.55), has a high Hill's index (0.79), indicating that its taxa are distributed fairly evenly despite their small number. The LVNH and LSM stations occupy intermediate positions, with moderate diversity but dominance in the structure of the plant communities. Thus, the Hill index appears to be the most comprehensive measure for characterizing overall ecological diversity, reflecting both relative abundance and sensitivity across the different taxon strata. Several authors also recommend its use [52] [53]. Consequently, these results show maximum taxon diversity and a relatively homogeneous distribution, with a slightly more pronounced dominance of certain families of benthic macroinvertebrates.

The results of the PCA show that the first two principal components account for 62.9% of the total variance in the dataset, indicating that the sites are well structured according to environmental variables. However, this PCA highlights three distinct groups, demonstrating the decisive influence of hydromorphological and physicochemical factors on the spatial organization of the sites. Canonical Redundancy Analysis (CRA) was used to examine the relationship between the

structure of benthic communities and the environmental variables measured in the Loutété River. The first two axes account for 68% of the cumulative variance in the taxon data, a percentage considered high and generally sufficient to describe the ecological organization of aquatic communities [54] [55]. Among the environmental variables analyzed to determine whether the distribution of taxa was random or not, two were found to be significant according to the Monte Carlo permutation test ( $F = 2.13$ ;  $P = 0.04$ ). Despite this statistical significance of stream width and sand proportion, the majority of taxa appear clustered on the side opposite these variables on the principal axis of the PCA. This pattern could be explained by the type of substrate, which is not very conducive to the establishment of macroinvertebrates. Indeed, according to [56], sandy bottoms are often poor in biodiversity, with only a few Diptera larvae sometimes found there.

## 5. Conclusion

This study updates our understanding of the taxonomic diversity and community structure of benthic macroinvertebrates in the Loutété River and provides a baseline for their spatial distribution within this river system. The results show a non-random distribution of taxa, with six orders exhibiting particularly high diversity. The community is dominated by Hydropsychidae, contrary to the pattern generally observed in many watercourses where Chironomidae are the dominant taxa. Furthermore, certain sites exhibit disturbances linked to human activities, which are likely to alter the composition and abundance of the observed benthic communities. These changes demonstrate the impact of human pressures on the river's ecological functioning and underscore the need for regular monitoring based on benthic macroinvertebrates, in addition to the assessment of environmental variables, in order to better understand changes in the ecological quality of waterways. They also support the implementation of appropriate management and conservation measures to preserve the ecological integrity of the Loutété River. Thus, these findings contribute to our understanding of benthic communities in tropical African environments and provide a useful reference for comparative studies at the regional and international levels.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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