JEAP
Journal of Environmental Analysis and Progress
ISSN: 2525-815X

Seasonal effects on hyporheic meiofauna structuring in sites with low and high urbanization in a South American tropical river

Suelen Nascimento dos Santos[a], Matheus Assis de Oliveira[a], Nykon Jefferson de Albuquerque Craveiro[a], Fernando Cartaxo Rolim Neto[b]

[a] Universidade Federal de Pernambuco-UFPE, Departamento de Oceanografia. Av. da Arquitetura, s/ n, Cidade Universitária, Recife, Pernambuco, Brasil. CEP: 50740-550. E-mail: suelen.nascimento@ufpe.br, matheus.assis@ufpe.br, nykon.craveiro@ufpe.br.
[b] Universidade Federal Rural de Pernambuco-UFRPE, Departamento de Tecnologia Rural. Rua Dom Manuel de Medeiros, s/n, Dois Irmãos, Recife, Pernambuco, Brasil. CEP: 52171-900. E-mail: fernandocartaxo@yahoo.com.br.

ARTICLE INFO

Received 30 Aug 2024
Accepted 03 Feb 2025
Published 10 Feb 2025

ABSTRACT

Studies on meiofauna diversity and taxonomy are fundamental for a better understanding of their community structure. Hyporheic meiofauna has not been studied, as has the beach, marine, and estuarine meiofauna. The study aimed to characterize the Beberibe River meiofauna community at two points: one with high urbanization (HU) and the other with low urbanization (LU), both located in the Recife Metropolitan Region (RMR), Pernambuco, Brazil. Meiofaunistic responses to urbanization and seasonal effects were studied regarding distribution, abundance, richness, and diversity. These benthic organisms were collected in two different seasons (dry and wet seasons 2023) at depths of 0 to 5 cm and 5 to 10 cm at two different sampling points in a hyporheic environment. At the LU point, there is a remnant from the Atlantic Forest. The HU point is urbanized, suffering considerable domestic discharge of organic and solid waste. Grain size characterization, pH, temperature, and salinity were obtained in each sample point and season. The Hill numbers of integrated indices were used to quantify and ascertain taxonomic diversity. Nonparametric analyses were also carried out through Similarity Analysis (ANOSIM), Principal Component Analysis (PCA), and Permutational Analysis (PERMANOVA). The confidence interval adopted was 95%. 269 meiofauna individuals were found, with the highest abundance distributed in the wet season. There were significant differences in the distributions of the organisms at both points ($p < 0.05$) and between two sampling seasons ($p<0.05$). No significant difference was found for the depth stratification ($p>0.05$).

Keywords: Ecology, hill numbers, Beberibe River, meiobenthos, hyporheos.

Introduction

Hyporheic meiofauna organisms (also known as hyporheos) are a group of little invertebrates associated with both the groundwater and seepage spring water, composing a unique ecotone, dwelling in an enigmatic habitat in a sediment layer between the surface and the groundwater, playing a fundamental role (alongside with biogeochemical cycles) in the environment well-functioning (Freitas et al., 2022). This group provides various ecosystemic services, such as energy carriage in different sediment depths, biomineralization, water permeabilization, and pollutant filtering.

Despite a slight upward trend in surveys, the hyporheos is not well understood, especially in tropical riverine environments, where anthropogenic impacts on the hyporheos community and the hyporheic zone are significant little, highlighting some authors who observed the impact of anthropic influence on the hyporheos was observed in the study of (Veras et al., 2018; Freitas et al., 2022).

Meiofaunistic importance to environments is approached in several surveys, as seen in Souza et al. (2020), who noted that these organisms have an expressive influence on different ecosystem interactions and functioning, especially in coastal environments. The meiofauna is currently being investigated for different purposes, such as molecular characterization studies (Castro et al., 2021), taxonomy (Schmidt-Rhaesa, 2020), and spatial-temporal composition, for example (Souza et al., 2020). Studies comprising meiofaunistic diversity have increased all over the world. However, such research is restricted to the marine and estuarine environments, as Iburg et al. (2021), who studied the composition of sediment-associated benthic communities, and Majdi et al. (2020), who analyzed the diversity and abundance of meiofauna individuals. Yusal et al. (2019) highlighted using meiofauna as a bioindicator of water quality; punctuating robust analyses of their community structuring is crucial. Historically, hyporheic meiofauna has not been widely studied compared to the beach and estuarine meiofauna, especially in Brazil. Despite this, some occasional studies, including freshwater meiofauna as essential organisms to the ecosystem, are noted, such as Palmer (1990), Brinke et al. (2011), and Monteiro et al. (2019), who used these organisms to investigate the effects of environmental pollutants. The most recent studies on meiofauna are based on statistical relationships with collected data on species distribution and environmental parameters (Schratzberger & Somerfield, 2020). Even though meiofauna is constantly being studied in some way, it is apparent how incomplete the knowledge about such a vast, diverse, and interactive group is (Cerca, Purschke & Struck, 2018). Diversity indices have become increasingly explored to relate benthic community structures to environmental factors (Semprucci et al., 2019). These indices applied to the spatial and temporal distribution of meiofauna to better represent the structure of benthic communities have been used on a large scale (Lampadariou et al., 2020; Chau et al., 2021). Classical diversity indices (e.g., Shannon and Simpson indices) are fully utilized to measure "diversity", but these indices do not follow most of the mathematical axioms to measure diversity (Laxton, 1978; Chao et al., 2020). These are symmetry, continuity, uniformity, monotonicity, and replication. Furthermore, Simpson and Shannon's indices are not comparable, as they measure different parameters. Hill numbers of integrated indices are the only diversity index that follows all the comparable axioms and can be used to adopt Chao et al. (2020) stepwise adaptation to Hill numbers to conclude the real and effective taxonomic diversity in an environment. More studies aimed at diversity surveys for benthic and hyporheic organisms in the world to fill the gaps in meiofauna ecology are of fundamental importance. In Brazil, most studies are concentrated in the South and Southeast regions, with limited research in the Northeast region of Brazil. The lack of studies on hyporheic communities is significant, requiring more and more guiding research to explain these organisms' structure and composition. Although the freshwater environments occur widely in Brazil, mainly in the Northeastern region, the Beberibe River has been increasingly explored only in the last decade for benthic organisms and the river dynamics (Albuquerque, Cabral & Paiva, 2015; Veras et al., 2017; Veras et al., 2018; Santos et al., 2021; Carvalho-Filho et al., 2024). Nevertheless, none of the studies focuses on the hyporheos ecological aspects, such as diversity, species richness, and the seasonal and anthropic impact on the community structuring. Thus, this study aimed to characterize the meiofauna community structuring spatiotemporally in two urbanely contrasted points and their seasonal variation in the tropical Beberibe River, located in the Recife Metropolitan Region, State of Pernambuco, Brazil, showing how the organisms are distributed throughout the sediment matrix, highlighting abundance, richness and diversity variations.

Material and Methods

Study area

The Beberibe river basin, located in the municipalities of Recife, Olinda, and Camaragibe, is part of the Water Planning Unit UP14, which corresponds to the Group of small coastal river basins 1 (GL1), located on the northern coast of the state of Pernambuco (APAC, 2025). This River is in the Recife Metropolitan Region (RMR), on the Pernambuco State northern coast, 7.587°S and 8.063°S, and 34.813°W and 35.1925°W (Figure 1).

Alvares et al. (2013) state that the Beberibe River basin is in a warm and humid climate (As'-Köppen) with two distinct seasons: wet and dry. The annual average precipitation is around 2,450.7 mm, and the wet season lasts from April to August, while the dry season lasts from September to March. The annual temperature average is approximately 25.5ºC, with July being the coldest month and January being the hottest month.

Samples were collected from a sample area delimited in the RMR (Figure 1) by the coordinates 7.97°S, 34.92°W for the high urbanization point (HU) and Latitude 7.98°S and 34.95°W for the low urbanization point (LU) (Figure 1). HU is situated among houses and commerce with domestic, chemical, solid, and organic waste. At the same time, LU is downstream, with some remnants of the Atlantic Forest and almost no urbanized surroundings or anthropogenic waste.

Data was collected on-site with a portable multiparameter Hanna meter ® that measures pH, salinity, and temperature.

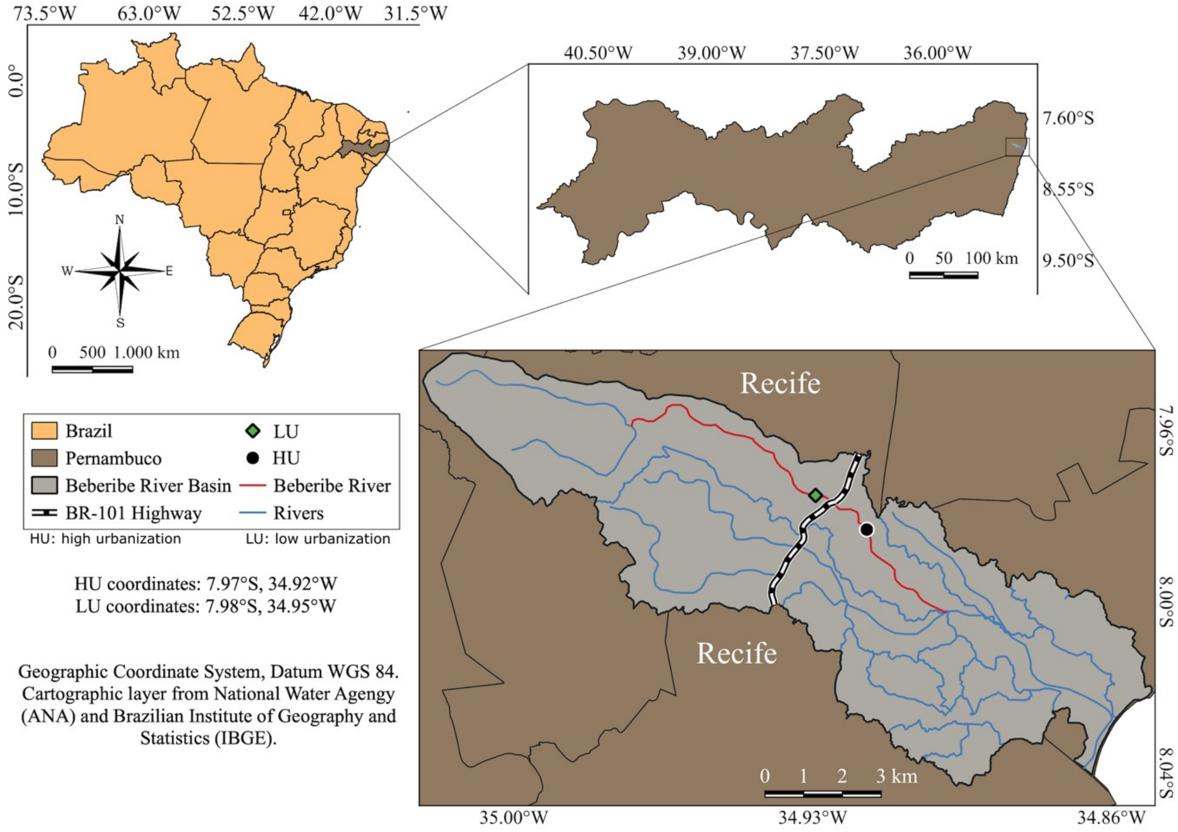

Figure 1. Location of the Beberibe River Basin and the sampled area in the municipalities of Recife, Pernambuco State, Brazil. Font: Santos et al. (2024).

Meiofauna analysis

Considering the meiofauna analyses, sediment samples were collected using a corer in an acrylic tube with 10 cm height (marked by 5 cm interval) and diameter. The collections were subdivided into the first 0-5 cm and the subsequent 5-10 cm, and three replicates were collected at each point in the two seasons of the year: dry (November) and wet (May) of 2023. Soil samples for particle size analysis were also collected with the same cylindrical sampler, thus obtaining stratified soil samples at 0-5 cm and 5-10 cm. The collected sediment material was stored in plastic bags in Styrofoam boxes and refrigerated (below 10°C) for sample preservation and preparation. After being collected, meiofauna samples were packed in plastic containers, preserved in 10% formalin, and separated, identified, and counted at the laboratory under a stereoscope. Before identification to the lowest taxonomic level possible, samples underwent the elutriation process using geological sieves with mesh sizes of 300 µm and 45 µm. Specialists checked identifications when necessary to analyze morphological characters of taxonomic importance. The identifications were conducted to the lowest taxonomic level achieved, except for Nematoda, where the phylum level was maintained. Meiofauna densities were expressed as the total number of individuals per 10 cm² of sediment. The identified specimens were preserved in 70% alcohol and deposited at the Laboratory of Benthos (LABEN) in the Oceanography Department of the Universidade Federal de Pernambuco (UFPE), Recife, Brazil.

Grain size and TOM analysis

The core sampler used for the meiofauna collections, and the same sample used for the granulometric analysis were also used to determine the total organic matter (TOM) content. The samples were dried in an oven at 60°C for 24 hours. They were then divided into two aliquots: one of 30 g to obtain the total organic matter content and, subsequently, the granulometric composition. A 10% hydrogen peroxide (H_2O_2) solution is added to burn the organic matter in the first aliquot. The samples are placed in a hood until the organic matter burns entirely. After this, the TOM content was obtained by comparing the dry weight after the samples were placed in the solution (Carver, 1971). Grain size analyses were carried out according to Suguio's method (1973) and were managed at the Laboratory of Geological Oceanography (LABOGEO), Department of Oceanography/UFPE.

Statistical analysis

Before any statistical test was performed in this study, the Shapiro-Wilk test was used to test the normality of the data. Abundance was standardized to the unit individuals per 10 cm². No normality was obtained for the data, and no attempt at normalization parameterized the data. Therefore, only non-parametric statistical analyses were utilized. All permutational analyses were applied with 20,000 permutations. Divisive hierarchical clustering was performed using the Bray-Curtis distance and Ward linkage method to dry and wet seasons and the two sample points to identify any clustering tendencies. The non-parametric Similarity Analysis Test (ANOSIM) was used to quantify the clustering strength and significant variations. Principal Component Analysis (PCA) was executed, considering the contribution of each environmental variable on a scale from low to high, exhibiting clusters of climatic seasons and points collected and the key environmental variables that structured the hyporheic community. Permutation Multivariate Analysis of Variance (PERMANOVA) was applied with Bray-Curtis's distance using abundance as the response variable to quantify the clustering tendency in a non-hierarchical order. One-way PERMANOVA for the environmental variables (pH, temperature, salinity, granulometry, and dissolved organic matter), two-way PERMANOVA for the factors (Season and sample points), and a three-way PERMANOVA, considering environmental variables x-factors. Boxplots were plotted for the environmental variables and their respective values for seasons and sample points to represent the data graphically. Chao et al. (2020) stipulate that diversity should never be interpreted as just a decreasing or increasing number but as a conclusion of various trends in ecological parameters. Higher and lower diversity conclusions were made, considering the behavior of the accumulation curves and their trends when interpolated and extrapolated, as well as the asymptotic, empirical, and equitability trends. The R statistical programming language® (R Core Team, 2021), version 4.2, in the RStudio software® IDE, was used for the statistical analyses. The *p-value* adopted for the statistical analyses was 0.05, thus a confidence level of 95%.

Results

Only seasons and sample points showed significant values and tendencies. Depth stratification presented no clustering trend or statistical significance in any analyses and was, thus, omitted. 269 meiofauna individuals were found, 259 concentrated in the wet season (38 in LU and 221 in HU) and 10 in the dry season (2 in LU and 8 in HU). Figure 2 shows clear grouping trends for both seasons and sample points; a strong clustering for seasons (dry and wet) and ANOSIM (R=0.707, p<0.001) confirmed the cluster formation trend. Also, they presented a significant variation in taxonomic trends, exhibiting a turnover pattern relative to seasons. A moderate clustering strength was noticed regarding sample points (LU and HU), showing R=0.392 and p<0.001 values. It is also seen that HU is strongly influenced by the seasons, as it showed very far apart in the dendrogram extremes.

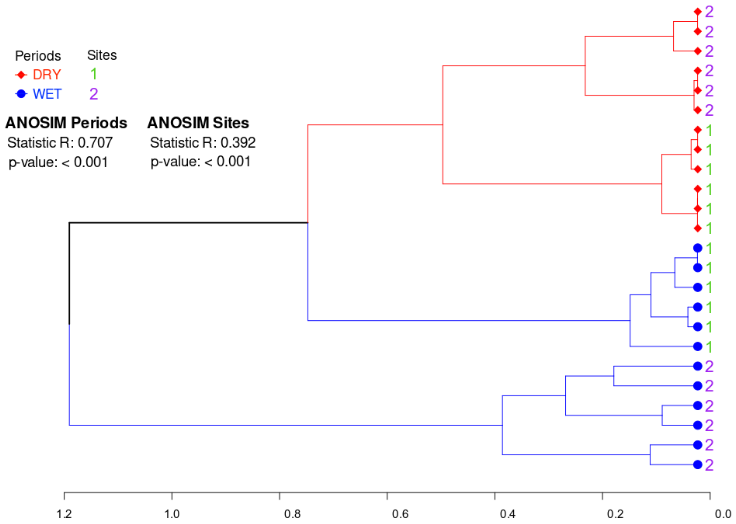

Figure 2. Dendrogram expressing groupings of the climatic seasons and sites (point 1 and point 2) collected. The distance used was Bray-Curtis with the divisive method and linkage by Ward's method. ANOSIM represented the factors tested. Font: Santos et al. (2024).

Principal Component Analysis (PCA), as shown in Figure 3, presented a strong clustering tendency of both seasons and points. Considering the contributions of variables, pH, temperature, salinity, clay, and oxygen explained most clustering trends in both factors. The one-way PERMANOVA (Table 1) corroborated the PCA results, showing a significant *p*-value for the most contributing variables. Two-way PERMANOVA (Table 1) was also similar to PCA results because the factors were statistically significant: season, point, and season x point. The relationship between environmental variables and factors (PERMANOVA three-way) showed that oxygen x season, temperature x season, pH x point, salinity x season x point, and temperature x season x point were significant (Table 1), showing that these variables (mainly salinity and temperature) have a significant influence on species abundance and turnover trends. The relationship between environmental variables and factors (PERMANOVA three-way) showed that oxygen x season, temperature x season, pH x point, salinity x season x point, and temperature x season x point were significant (Table 1), showing that these variables (mainly salinity and temperature) have a significant influence on species abundance and turnover trends.

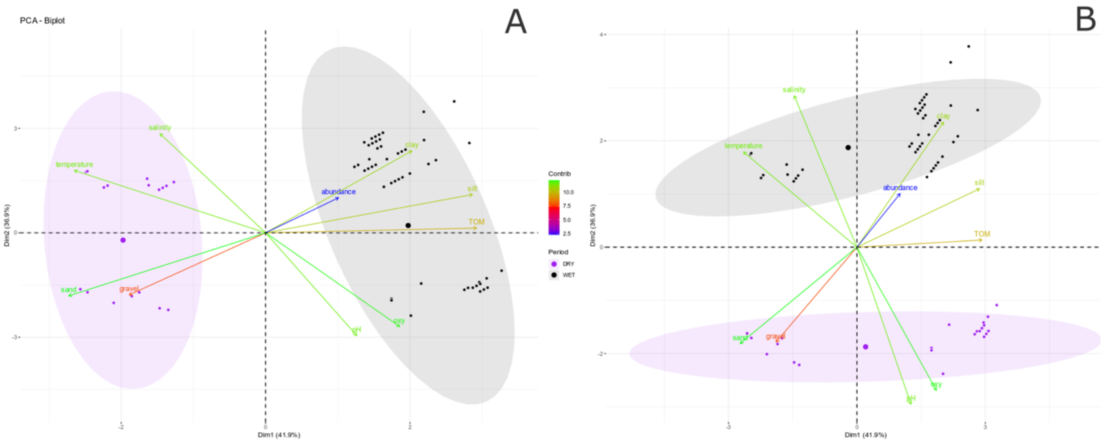

Figure 3. Principal Component Analysis (PCA). A. Climatic seasons cluster with variables and their respective contributions; B. Clustering of the points regarding the variables and respective contributions. Font: Santos et al. (2024).

Table 1. Permutation Multivariate Analysis of Variance (PERMANOVA) of the influence of environmental factors on meiofauna abundance. Non-significant variables and interactions were omitted. Font: Santos et al. (2024).

Environmental variables	**pseudo-F**	**R^2**	**p-value**
pH	10.246	0.0211	< 0.001
Oxygen	22.641	0.0467	< 0.001
Salinity	5.276	0.0109	0.013
Temperature	35.293	0.0728	< 0.001
%Gravel	35.360	0.0730	< 0.001
%Silt	16.006	0.03302	< 0.001
%Clay	12.821	0.02645	< 0.001
TOM	9.841	0.00065	< 0.001
Factors (Spatial x Temporal)	**pseudo-F**	**R^2**	**p-value**
Period	51.496	0.12674	< 0.001
Point	26.563	0.06538	< 0.001
Period x Point	20.252	0.04984	< 0.001
Environmental variables x Factors	**pseudo-F**	**R^2**	**p-value**
Oxygen x Period	9.074	0.01872	< 0.001
Temperature x Period	7.279	0.01502	0.003
pH x Point	3.718	0.00767	0.040

Salinity x Period x Point	5.446	0.01124	0.011
Temperature x Period x Point	14.826	0.03059	< 0.001

Boxplots (Figure 4) show that oxygen concentration has wildly fluctuated throughout seasons and points with no "overlapping" values in the Boxplot for any factors. The pH varied expressively regarding the sample points, but slightly between the seasons, more alkaline pH was found at LU and more acid at HU. Salinity maximum values were found at HU, and the minimum values at LU. Temperature showed expressive variation between both seasons and points. The relative percentage of gravel was homogeneous at LU and very heterogeneous at HU, showing a poorly selected substratum. The sand percentage was heterogeneous for all factors. Silt and clay also showed similar patterns, but clay appeared to be somewhat influenced by seasons. Total Organic Matter (TOM) showed higher values in the wet season due to rain leaching and lower values in the dry season due to scarce rains. Abundance followed the same pattern as the TOM, seeming to be related. In Figure 5 and Table 2, the dry season shows higher species dominance and lower species richness. Otherwise, the wet season shows a higher richness and better species distribution. LU shows a lower richness than HU but a higher relative abundance distribution quality. The genera *Pristina* sp., Tubificinae, and *Enchytraeidae* sp. were the most abundant, followed by insect larvae, Nematoda, Tanaidacea, Acari, and Chironomidae (Figure 5). Among identified organisms, only the genus *Enchytraeidae* sp., the class Insecta, and the order Tanaidaceae occurred in the dry season (Figure 5 and Table 2).

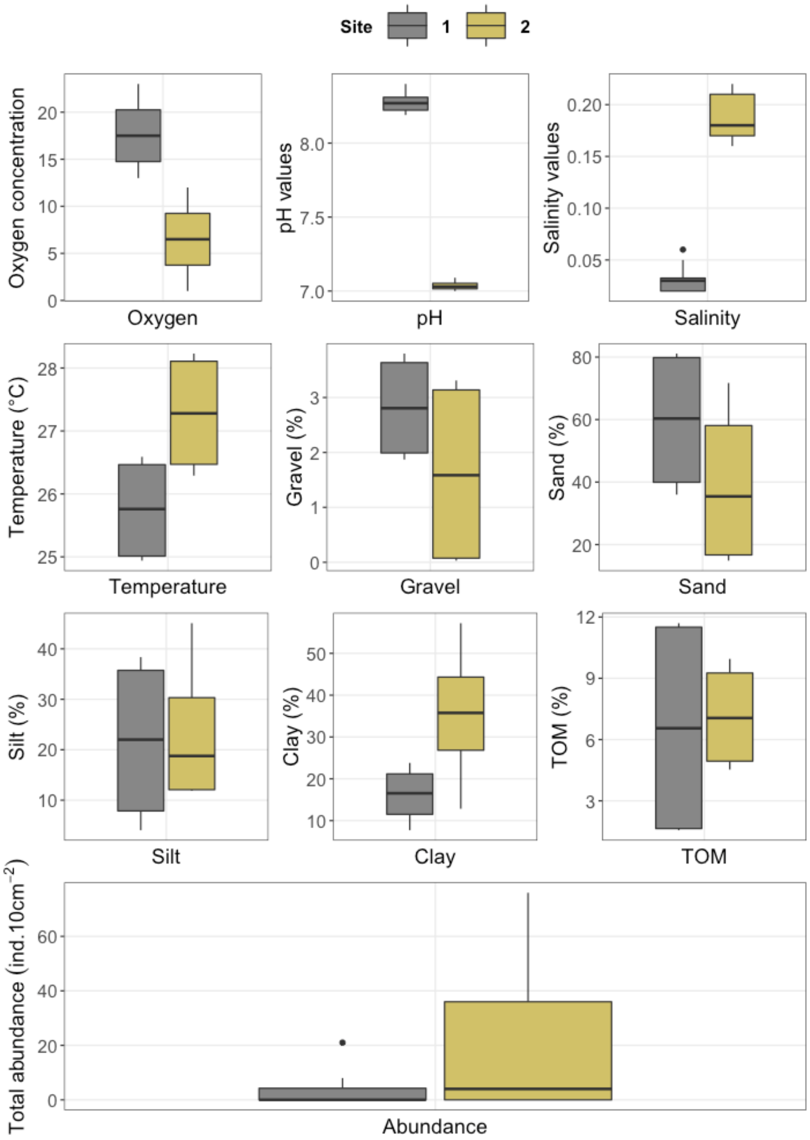

Figure 4. Boxplots of observed values using season and sample points factors. Font: Santos et al. (2024).

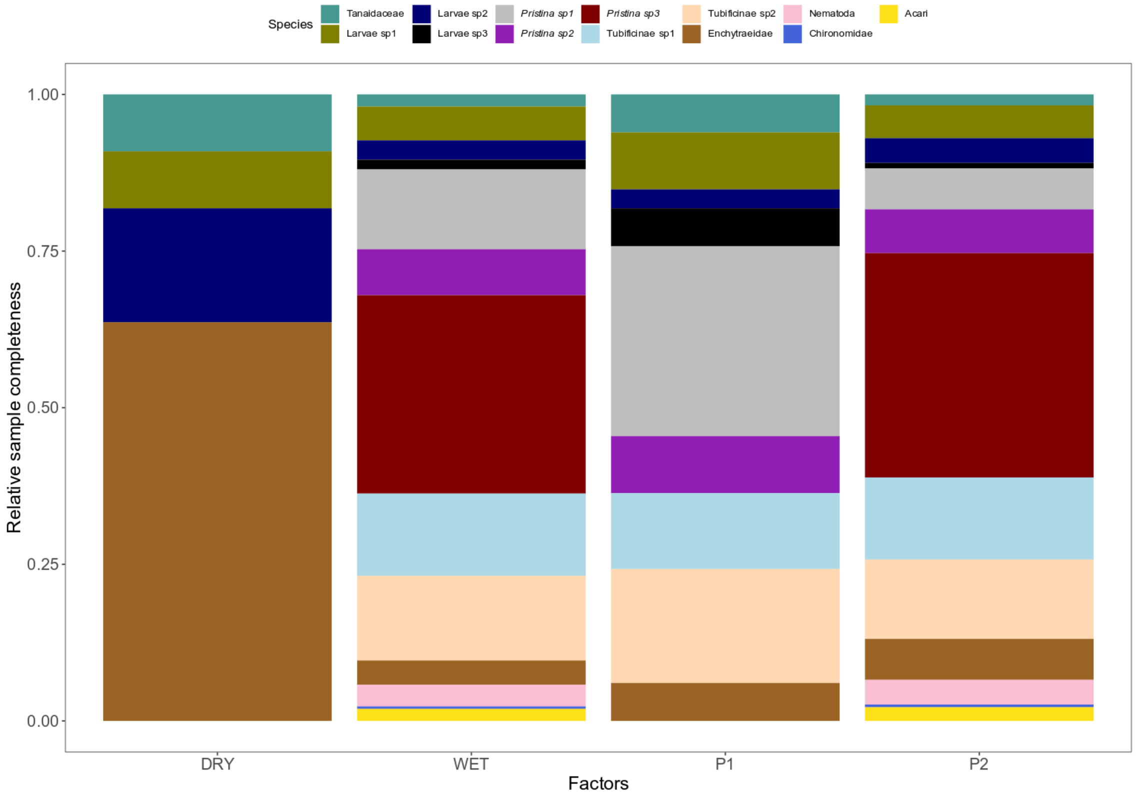

Figure 5. Barplot shows the relative contribution of the species to each factor's climate periods. Font: Santos et al. (2024).

Table 2. Presence and absence of taxa in the factor's climate periods and sample points. Font: Santos et al., (2024).

Benthic Fauna		**Dry Point 1**	**Dry Point 2**	**Wet Point 1**	**Wet Point 2**
Subclass Acari	Acari				X
Family Chironomidae	Chironomidae				X
Genus Enchytraeida	*Enchytraeida* sp.	X	X		X
Class Insecta	Larvae 1		X	X	X
Class Insecta	Larvae 2		X	X	X
Class Insecta	Larvae 3		X	X	X
Phylum Nematoda	Nematoda				X
Genus Pristina	*Pristina* sp.1			X	X
Genus Pristina	*Pristina* sp.2			X	X
Genus Pristina	*Pristina* sp.3				X
Order Tanaidacea	Tanaidacea		X	X	X
Subfamily Tubificinae	Tubificinae Genus 1			X	X
Subfamily Tubificinae	Tubificinae Genus 2			X	X

*X: presence

Figure 6A shows that although the dry season has smaller sample completeness than the wet season, these seasons did not vary significantly for any *q-orders* regarding completeness (since the Bootstrap 95% estimators overlap). Figure 6B shows each season's sample completeness (or coverage) and their difference in *q-orders* exhibiting higher richness and diversity in *q1* and *q2* to wet- than the dry season. Figure 6C shows that the asymptotic (observed) diversity did not vary significantly from the empirical (unidentified), expressing the reliability of the data. A greater proportional steep and lower values of the dry diversity curve indicate higher diversity in the wet season. Equitability confirms this fact, which shows that the wet season has higher values and less steep equitabilities than the dry season (Figure 6D).

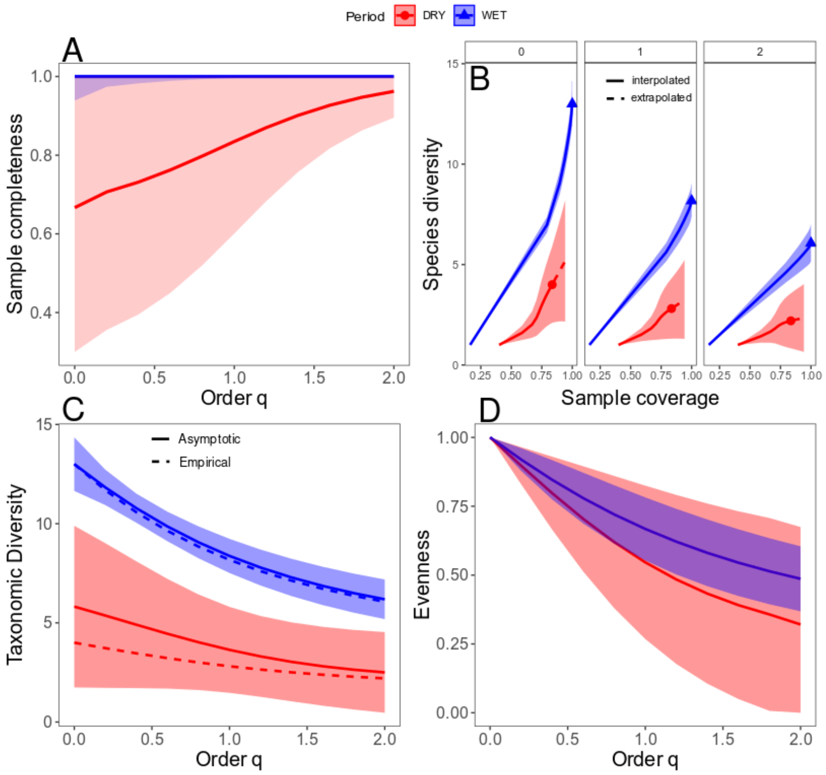

Figure 6. Diversity from the accumulation curve of the q sequence of Hill numbers for the climate seasons. A. Sample completeness by orders of q; B. Effective diversity separated by q orders over sample completeness; C. Empirical and asymptotic diversity over q orders; D. Pielou's equitability over q orders. Font: Santos et al. (2024).

Regarding points, sample completeness also did not vary significantly for *q*-orders (Figure 7A). Figure 7B shows that LU had a smaller proportional slope drop than HU but never varied significantly when sample completeness exceeded 60% for all *q-orders*. Asymptotic and empirical diversity in Figure 7C did not vary significantly between points, but HU showed greater steepness than LU. Empirical diversity did not vary significantly from asymptotic, showing the reliability of the data. Figure 7D shows that the equitability between HU and LU did not vary significantly. However, LU showed higher equitability of rare species, and according to Chao & Chiu (2016), higher equitability of rare species expresses higher diversity.

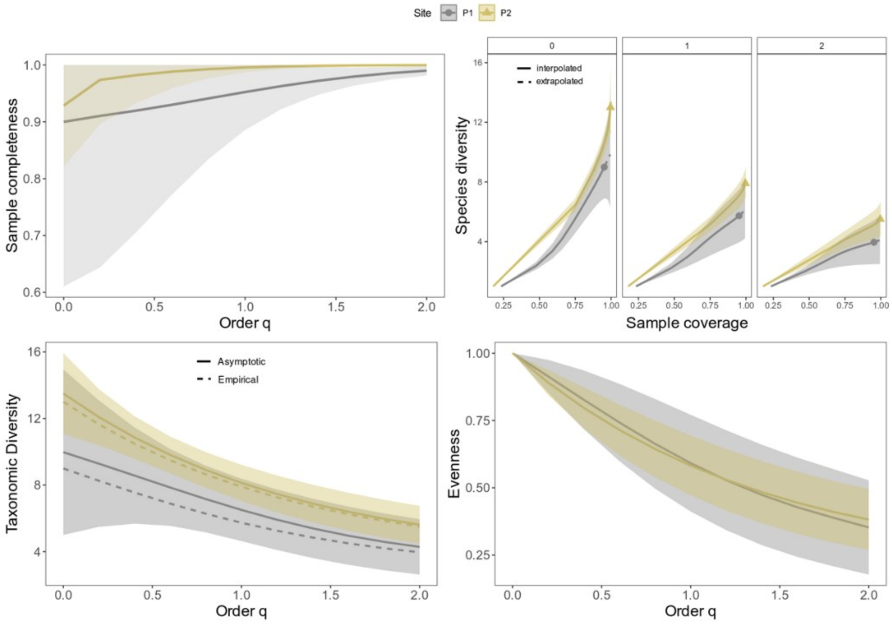

Figure 7. Diversity from the accumulation curve of the sequence q of Hill numbers for sample points. A. Sample completeness by the orders of q.; B. Effective diversity separated by q orders over sample completeness. C. Empirical and asymptotic diversity over q orders; D. Pielou's equitability over q orders. Font: Santos et al. (2024).

Discussion

The discrepant difference in abundance and richness between seasons shows that hyporheic meiofauna is sensitive to changes in environmental variables. As the entire wet season is rainy, salinity and temperature decrease, meanwhile the leaching TOM and fine sediments increase; those factors positively influence meiofauna sensitive/rare species occurrence and abundance (Semprucci et al., 2019; Venekey et al., 2019; Santos et al., 2021). The abundance/richness contrast in sample points is explained by the higher anthropogenic impact in HU concerning LU. The organic and solid waste in HU contributes to a massive increase in generalist species richness and abundances (providing more TOM and "habitats"), such as *Pristina* spp., Enchytraeidae, insects larvae, and Nematoda. This is due to the "enrichment paradox" (Rana et al., 2013). This paradox describes a continuous and steady increase in density/abundance of generalist organisms until the system collapses due to a lack of resources (e.g., bioavailable oxygen, Nitrate, and Phosphatic molecules, Fe, Si, Ca, and other micronutrients), leading to an abrupt decrease in abundance, richness, and diversity. HU was the taxonomically richest, covering 100% of the sample richness.

The wet season was the most abundant climatic season; this fact was confirmed by the principal component analysis (PCA), which also showed higher abundances in the HU and wet season. The PCA revealed the key environmental variables that ruled the hyporheic meiofauna structure in abundance and richness.

These were total organic matter (TOM), silt (%), clay (%), dissolved oxygen, and salinity (Figure 4), explaining the most significant proportion of the benthic community in the wet season and HU point. These most influencing variables explicitly show how fine sediments are essential to the hyporheos, as these organisms are eco-morphologically adapted to thinner interstitial habitats. Hence, thicker grains (sand and gravel) negatively influence the meiofaunal community (Huang et al., 2022).

Seasonal and spatial changes were ascertained to regulate the community structure (see Figures 2 and 3). Insofar as the invertebrate community composition and abundance in the Beberibe River is strongly clustered (in ANOSIM and PCA) and varied significantly among sample points and seasons. PERMANOVA and ANOSIM results showed that there were significant differences between points ($p<0.001$), seasons ($p<0.001$), and points x seasons ($p<0.001$). However, no significant differences were seen for depths ($p>0.05$). Seasons significantly influenced the community more than spatial variation (sample points), as seen in the dendrogram (Figure 2). This deviation occurs since seasonal variations regulate all the key environmental factors that structure the meiofauna community. Spatial differences mainly provide more habitats to generalist species (due to solid waste) and vary most in non-key variables, which weakens the relationship between points and community responses concerning seasons. However, there is a strong relationship (Figure 2).

Therefore, spatial variations are explained by the different anthropic impacts and the different pressures of urbanization in the two sample points. Thus, impacts on the HU significantly affect the hyporheic meiofauna community, which confirms that the anthropogenic pressures on HU are modifying the fast-responsive faunal composition.

These results would be a major starting point for management plans in areas under human pressure before affecting upper/larger (and slower responsive) faunal groups. Similar results were achieved by Baia, Rollnic & Venekey (2021), who found that organisms were strongly affected by both seasonal and spatial variations.

In Figure 4, it is noticeable that the variable values patterns of the wet season were more susceptible to a higher value of the total abundance, as the fine sediments, TOM, and oxygen are higher than in the dry season. Oxygen showed higher values in the wet season than in the dry season; salinity was slightly lower in the wet season; such a fact was also presented by Venekey et al. (2019) as susceptible conditions for meiofauna to proliferate. Still, in the wet season, the temperature was significantly lower concerning, the temperature was significantly lower concerning; in the wet season, the temperature was significantly lower in the dry season. The percentage of thicker sediments, such as gravel and sand, was higher in the dry season, while silt, clay, organic matter, and abundance had higher values in the wet season. PCA shows a negative relationship between grain size and meiofauna abundance.

The co-variation in the key environmental variables will always influence the abundance, and the best conditions seem to be found in the wet season, unlike the dry season. Such a fact explains the higher total abundance only in the wet season unless it is in an impacted environment with generalist species found in highly unfavorable conditions, as seen in the dry season in HU point (Capeletti, Marchese & Zilli, 2021). Regarding sample points (Figure 4), a confusing pattern was seen, where the unbalance of environmental variables resulted in higher total abundance, lower oxygen and organic matter values, and higher salinity and temperature co-vary for higher abundance values. This fact is due to the generalist-dominated environment in the HU point, which often takes advantage and is favorable to pullulate in adverse conditions. This pattern is typical of an impacted environment (as is HU), and the dominance of *Pristina* sp., the subclass Acari, and the phylum Nematoda (Figure 6) might bioindicate an impacted and unsteady environment. This evidence shows that HU is under severe anthropogenic impact, and the enrichment paradox is probably applying/occurring in this case.

The maximum effective taxonomic diversity of the meiofauna seen in the wet season (Figure 7) is probably due to the key variables influencing the total abundance of non-generalist species positively and causing better distribution of relative abundances. Given a positive abundance influence for most species, there are high equitability values with species added equitably in an almost linear fashioned curve as sample completeness accumulates, thus increasing diversity.

The influence of environmental factors is always a critical point in the estimation and discussion regarding ecological parameters because they always determine whether species are equally distributed in an ecosystem, community, or assemblage (Chao et al., 2014; Magurran, 2021). The fact that values varied significantly from one season to the other, with even higher values in the wet season, shows how the wet season provides a very susceptible environment for the meiofaunal community of abundance, richness, composition, equitability, and diversity.

Considering different weights for rare and dominant species, the higher proportional drop in effective diversity along the q-orders (Figure 7c) displays the minimum equitability in the dry season. However, although *q0* varied significantly, the order diversities *q1* and *q2* did not vary (Figures-D). This pattern of significantly different richness and similar diversities values confirms that there are more dominant/generalist species at HU than at LU. The fact also expresses greater equitability of species in LU, concluding, thus, greater diversity at the LU point. The similar equitability curve behavior in LU and HU is because generalist/dominant species often show similar abundances in impacted areas as they take advantage of degraded environments almost equally (Ricklefs, 2010; Magurran, 2021).

Variables did not have so much influence on the diversity balance of the points because the spatial influence on the increase of generalist species in HU ended up masking the variables' influences on species, having an effective diversity in *q1* and *q2* with similar values in LU and HU and a contrasted *q0* (Gotelli & Ellison, 2004; Ricklefs, 2010; Magurran, 2021). Sampled points taxonomic diversity differences are thus attributed only to differences in human impacts, which rule the meiofaunal community in every aspect - from taxonomic composition to diversity, as the HU environment has lower diversity due to dominant species. Several kinds of research aim to study if environmental variables, anthropogenic and these two mutual influences impacts are responsible for the abundance of meiofauna organisms and their variations in richness, composition, and diversity (Semprucci et al., 2015; Kim et al., 2020; Martínez et al., 2020; Schratzberger & Somerfield, 2020; Gheller & Corbisier, 2022). In this study (the first inferring the influence of urbanization on ecological aspects of hyporheos), it was statistically identified that key-environmental variables and anthropogenic impacts contribute more expressively to changes in hyporheic meiobenthos structure patterns than others. Also, spatiotemporal factors with human impacts regulate the hyporheic meiofauna's composition, community, abundance, and diversity. This paper must be an alert to species conservation because non-natural factors structuring communities should be a topic of concern to establish effective conservation plans to mitigate impacts at a community and ecosystem level.

Among taxa found, Tanaidacea deserves greater prominence even though it is not an abundant taxon because these organisms were never recorded in hyporheic environments, being described in South America with the occurrence of only one species in freshwater habitats (Jaume & Boxhall, 2008). The most recent record of freshwater Tanaidacea was noted by Rodrigues et al. (2021) in a coastal lagoon in Rio de Janeiro - Brazil. Based on this, this fact makes the Beberibe River a remarkable case of occurrence of Tanaidacea, besides this study being the first ever conducted in benthic communities at the taxon level in Beberibe River and this being the first record of this order for the region. This fact also highlights the importance of applying more effort to studying the hyporheos because it is almost unknown to science and ecology, mainly regarding tropical hyporheic environments.

Conclusion

Significant differences in composition, abundance, richness, and diversity in HU and LU showed how the anthropogenic impact affects the hyporheos structure. Seasonality and points with contrasting organic enrichment and anthropogenic waste were determining factors for establishing the hyporheic benthic communities. The analysis and patterns of the benthic community structure obtained herein allowed a more concise evaluation of the enigmatic and poorly known hyporheos relations with different environmental factors in ecological terms, besides demonstrating the importance of anthropogenic impacts and future taxonomic studies, generating a basis for future studies in lotic systems.

Given the importance of these meiofaunal organisms, it is essential to evaluate the impact of non-natural effects to maintain the ecosystem's functional role and its services to the adjacent environments. Knowledge of the taxonomic composition, ecology, and anthropic influence on tropical hyporheic ecosystems is of fundamental importance to future research in ecology, taxonomy, hydrology, and biogeochemical cycles, for example.

There is a lack of information about the hyporheic community ecology, especially in tropical environments. The results of the ecology, distribution, and key environmental and spatial variables provide essential information that previously did not exist regarding the structure of the meiofauna community from the hyporheos of a tropical river.

Acknowledgments

This study was partially financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-Brazil (CAPES), Finance Code: 001.

References

Albuquerque, T. B. V; Cabral, J. J. S. P; Paiva, A. L. R. 2015. Interação água subterrânea-água superficial e comunidade de organismos da meiofauna do ambiente hiporreico. Águas Subterrâneas, 1, (1), 1-4. https://doi.org/10.14295/ras.v0i0.29638

Alvares, C. A.; Stape, J. L.; Sentelhas, P. C.; Gonçalves, J. D. M.; Sparovek, G. 2013. Köppen's climate classification map for Brazil. Meteorologische zeitschrift, 22, (6), 711-728. https://doi.org/10.1127/0941-2948/2013/0507

APAC. Agência Pernambucana de Águas e Climas. Bacias hidrográficas. Disponível em: http://www.apac.pe.gov.br/pagina.php?page_id=5&subpage_id=14. Acesso em: Fev. 2025.

Baia, E.; Rollnic, M.; Venekey, V. 2021. Seasonality of pluviosity and saline intrusion drive meiofauna and nematodes on an Amazon freshwater-oligohaline beach. Journal of Sea Research, 170, 102022. https://doi.org/10.1016/j.seares.2021.102022

Brinke, M.; Ristau, K.; Bergtold, M.; Höss, S.; Claus, E.; Heininger, P.; Traunspurger, W. 2011. Using meiofauna to assess pollutants in freshwater sediments: a microcosm study with cadmium. Environmental Toxicology and Chemistry, 30, (2), 427-438. https://doi.org/10.1002/etc.387

Capeletti, J.; Marchese, M. R.; Zilli, F. L. 2021. Evaluating macroinvertebrate metrics for ecological assessment of large saline rivers (Argentina). Environmental Science and Pollution Research, 28, 66464-66476. https://doi.org/10.1007/s11356-021-16559-7

Carvalho Filho, J. A. A. D.; Clemente, C. C. C.; Santos, P. J. P. D.; Cabral, J. J. D. S. P.; Paiva, A. L. R. D. 2024. Spatial and temporal characterization of sediments and hyporheic meiofauna in a section of an urban river. Revista Brasileira de Recursos Hídricos, 29, e28. https://doi.org/10.1590/2318-0331.292420240026

Carver, R. E. 1971. Procedures in Sedimentary Petrology. Publisher, John Wiley & Sons Canada, Limited. 329p.

Castro, L. R.; Meyer, R. S.; Shapiro, B.; Shirazi, S.; Cutler, S.; Lagos, A. M.; Quiroga, S. Y. 2021. Metabarcoding meiofauna biodiversity assessment in four beaches of Northern Colombia: effects of sampling protocols and primer choice. Hydrobiologia, 848, (15), 3407-3426. https://doi.org/10.1007/s10750-021-04576-z

Cerca, J.; Purschke, G.; Struck, T. H. 2018. Marine connectivity dynamics: clarifying cosmopolitan distributions of marine interstitial invertebrates and the meiofauna paradox. Marine Biology, 165, 1-21. https://doi.org/10.1007/s00227-018-3383-2

Chao, A.; Chiu, C. H. 2016. Species richness: estimation and comparison. Wiley StatsRef: statistics reference online, 1, (1), 26. https://doi.org/10.1002/9781118445112.stat03432.pub2

Chao, A.; Gotelli, N. J.; Hsieh, T. C.; Sander, E. L.; Ma, K. H.; Colwell, R. K.; Ellison, A. M. 2014. Rarefaction and extrapolation with Hill numbers: a framework for sampling and estimation in species diversity studies. Ecological Monographs, 84, (1), 45-67. https://doi.org/10.1890/13-0133.1

Chao, A.; Kubota, Y.; Zelený, D.; Chiu, C. H.; Li, C. F.; Kusumoto, B.; Colwell, R. K. 2020. Quantifying sample completeness and comparing diversities among assemblages. Ecological Research, 35, (2), 292-314. https://doi.org/10.1111/1440-1703.12102

Chau, M. K.; Vo, Q. M.; Nguyen, T. K. P.; Araki, M.; Perry, R. N.; Tran, A. D.; Toyota, K. 2021. Impacts of saltwater intrusion on soil nematodes community in alluvial and acid sulfate soils in paddy rice fields in the Vietnamese Mekong Delta. Ecological Indicators, 122, 107284. https://doi.org/10.1016/j.ecolind.2020.107284

Freitas, J. B.A.; Cabral, J. J.; Paiva, A. L.; Veras, T. B.; Barcellos, R. L.; Santos, P. J.; Gomes Junior, E. L. 2022. Evidence of protective effects on aquifer recharge from polluted tropical rivers: An analysis of hyporheic meiofauna and sediments. River Research and Applications, 38, (2), 345-357. https://doi.org/10.1002/rra.3906

Gheller, P. F.; Corbisier, T. N. 2022. Monitoring the anthropogenic impacts in Admiralty Bay using meiofauna community as indicators (King George Island, Antarctica). Anais da Academia Brasileira de Ciências, 94, Supl. 1. https://doi.org/10.1590/0001-3765202220210616

Gotelli, N. J.; Ellison, A. M. 2004. A primer of ecological statistics. Sunderland: Sinauer Associates, 640p.

Huang, D.; Wang, J.; Tian, P.; Niu, W. 2022. The distribution and controlling factors of meiofaunal community in Prydz Bay, Antarctica. Deep Sea Research Part II: Topical Studies in Oceanography, 202, 105107. https://doi.org/10.1016/j.dsr2.2022.105107

Iburg, S.; Izabel-Shen, D.; Austin, Å. N.; Hansen, J. P.; Eklöf, J. S.; Nascimento, F. J. 2021. Effects of Recreational Boating on Microbial and Meiofauna Diversity in Coastal Shallow Ecosystems of the Baltic Sea. Msphere, 6, (5), 127. https://doi.org/10.1128/mSphere.00127-21

Jaume, D.; Boxshall, G. A. 2008. Global diversity of cumaceans & tanaidaceans (Crustacea: Cumacea & Tanaidacea) in freshwater. Freshwater Animal Diversity Assessment, 225-230. https://doi.org/10.1007/978-1-4020-8259-7_25

Kim, H. G.; Song, S. J.; Bae, H.; Noh, J.; Lee, C.; Kwon, B. O.; Khim, J. S. 2020. Natural and anthropogenic impacts on long-term meiobenthic communities in two contrasting nearshore habitats. Environment international, 134, 105-200. https://doi.org/10.1016/j.envint.2019.105200

Lampadariou, N.; Syranidou, E.; Sevastou, K.; Tselepides, A. 2020. Meiobenthos from biogenic structures of the abyssal time-series station in the NE Pacific (Station M). Deep Sea Research Part II: Topical Studies in Oceanography, 173, 104-720. https://doi.org/10.1016/j.dsr2.2019.104720

Laxton, R. R. 1978. The measure of diversity. Journal of theoretical biology, 70, (1), 51-67. https://doi.org/10.1016/0022-5193(78)90302-8

Magurran, A. E. 2021. Measuring biological diversity. Current Biology, 31, (19), 1174-1177. https://doi.org/10.1016/j.cub.2021.07.049

Majdi, N.; Colls, M.; Weiss, L.; Acuña, V.; Sabater, S.; Traunspurger, W. 2020. Duration and frequency of non-flow periods affect the abundance and diversity of stream meiofauna. Freshwater Biology, 65, (11), 1906-1922. https://doi.org/10.1111/fwb.13587

Martínez, A.; Eckert, E. M.; Artois, T.; Careddu, G.; Casu, M.; Curini-Galletti, M.; Fontaneto, D. 2020. Human access impacts biodiversity of microscopic animals in sandy beaches. Communications Biology, 3, (1), 175. https://doi.org/10.1038/s42003-020-0912-6

Monteiro, L.; Moens, T.; Lynen, F.; Traunspurger, W. 2019. Effects of the water-soluble fraction of a crude oil on freshwater meiofauna and Nematode Assemblages. Ecotoxicology and Environmental Safety, 176, 186-195. https://doi.org/10.1016/J.Ecoenv.2019.03.083

Palmer, M. A. 1990. Temporal and Spatial Dynamics of Meiofauna within the Hyporheic Zone of Goose Creek, Virginia. Journal of the North American Benthological Society, 9, (1), 17-25. https://doi.org/10.2307/1467930

R Core Team. (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/

Rana, S., Bhattacharya, S., Pal, J., N'Guérékata, G. M., & Chattopadhyay, J. (2013). Paradox of enrichment: A fractional differential approach with memory. Physica A: Statistical Mechanics and its Applications, 392, (17), 3610-3621. https://doi.org/10.1016/j.physa.2013.03.061

Ricklefs, R. E. 2010. A economia da natureza. Guanabara Koogan, Sixth Edition. 572p.

Rodrigues, A. J. D. S.; Fernandes, M. R.; Miyahira, I. C.; Santos, L. N. D.; Caetano, C. H. S. 2021. Benthic Macrofauna Associated to the Invasive Bivalve Mytilopsis Leucophaeata (Dreissenidae) In A Coastal Lagoon In Rio De Janeiro, Brazil. Anais da Academia Brasileira de Ciências, 93, (4), 191-221. https://doi.org/10.1590/0001-3765202120191221

Santos, S. N.; Freitas, J. B. A.; Cabral, J. J. D. S. P.; Paiva, A. L. R.; Clemente, C. C. C. 2021. Evaluation of freshwater benthic communities: a case study in an urban source in the Northeast of Brazil. Brazilian Journal of Environmental Sciences (Online), 56, (1), 28-40. https://doi.org/10.5327/z2176-947820200661

Schmidt-Rhaesa, A. 2020. Guide to the Identification of Marine Meiofauna. München: Verlag Dr. Friedrich Pfeil. 608p.

Schratzberger, M.; Somerfield, P. J. 2020. Effects Of Widespread Human Disturbances in the Marine Environment Suggest a New Agenda for Meiofauna Research Is Needed. Science of the Total Environment, 728, 138-435. https://doi.org/10.1016/J.Scitotenv.2020.138435

Semprucci, F.; Gravina, M. F.; Magni, P. 2019. Meiofaunal Dynamics and Heterogeneity Along Salinity and Trophic Gradients in a Mediterranean Transitional System. Water, 11, (7), 1488. https://doi.org/10.3390/W11071488

Semprucci, F.; Sbrocca, C.; Rocchi, M.; Balsamo, M. 2015. Temporal Changes of The Meiofaunal Assemblage as a Tool for the Assessment of the Ecological Quality Status. Journal of the Marine Biological Association of the United Kingdom, 95, (2), 247-254. https://doi.org/10.1017/S0025315414001271

Souza, M. T.; Silva, D. R.; Fortunato, W. C. P.; Santos, A. C. M.; Pereira, S. F. 2020. Composição e variabilidade espaço-temporal da meiofauna da praia do Goiabal, Calçoene–AP. Brazilian Journal of Animal and Environmental Research, 3, (3), 1755-1765. https://doi.org/10.34188/bjaerv3n3-091

Venekey, V.; Melo, T. P. G.; Rosa Filho, J. S. 2019. Effects Of Seasonal Fluctuation of Amazon River Discharge on the Spatial and Temporal Changes of Meiofauna and Nematodes in the Amazonian Coast. Estuarine, Coastal and Shelf Science, 227, 106-330. https://doi.org/10.1016/J.Ecss.2019.106330

Veras, T. B.; Cabral, J. J. D. S. P.; Paiva, A. L. R.; Barreto, A. F. S. 2017. Interação rio-aquífero e a meiofauna do ambiente hiporreico. Águas Subterrâneas, 31, (1), 20-35. https://doi.org/10.14295/ras.v31i1.28548

Veras, T. B.; Cabral, J. J.; Paiva, A. L.; Santos, P. J.; Freitas, D. A. 2018. Evaluation of Meiofauna in the Hyporheic Zone of the Beberibe River, Pernambuco, Brazil: Veras et al. Water Environment Research, 90, (8), 685-696. https://doi.org/10.2175/106143017X15054988926307

Yusal, M. S; Marfai, M. A.; Hadisusanto, S.; Khakhim, N. 2019. Abundance and diversity of meiofauna as water quality bioindicator in Losari Coast, Makassar, Indonesia. Ecology, Environment and Conservation, 25, (2), 589-598. https://doi.org/10.1016/j.ecss.2019.106330