Hydrobiologia
https://doi.org/10.1007/s10750-024-05720-1

EMERGENT ISSUES ON NEOTROPICAL WATERS

Small hydropower dam alters the functional structure of macroinvertebrate assemblages in a Neotropical savanna river

Pedro Henrique Monteiro do Amaral · Diego Marcel Parreira de Castro · Marden Seabra Linares · Robert M. Hughes · Eduardo van den Berg · Marcos Callisto

Received: 14 December 2023 / Revised: 9 September 2024 / Accepted: 15 October 2024

Abstract Hydropower dams and their reservoirs are major disturbances affecting riverine ecosystems worldwide. However, most existing knowledge comes from large hydropower systems. We evaluated the upstream and downstream effects of a small run-of-river hydropower dam on the functional structure of benthic macroinvertebrate assemblages in a Neotropical savanna river. We found that functional originality and divergence were significantly higher near the dam site. In contrast, functional dispersion was higher at free-flowing sites upstream and downstream of the dam. Sites near the dam had greater proportions of univoltine organisms with spherical and low-flexibility bodies. On the other hand, free-flowing sites had increased proportions of multivoltine organisms with flattened bodies and flexible. The macroinvertebrate assemblages at all sites were mainly homogeneous and composed functionally generalist taxa. This study enhances our understanding of the environmental effects of small run-of-river dams on benthic macroinvertebrates, emphasizing the usefulness of functional characteristics for those assessments.

Guest editors: André M. Amado, Roberto J. P. Dias, Sthefane D´Ávila & Simone J. Cardoso / Emergent Issues of Neotropical Aquatic Ecosystems in the Anthropocene

P. H. M. do Amaral (✉) · D. M. P. de Castro · M. Callisto
Departamento de Genética, Ecologia e Evolução, Laboratório de Ecologia de Bentos, Universidade Federal de Minas Gerais, Instituto de Ciências Biológicas, CP 486, Av. Antônio Carlos 6627, Pampulha, Belo Horizonte, MG CEP 31270-901, Brazil
e-mail: pedrobio2009@gmail.com

P. H. M. do Amaral · D. M. P. de Castro · E. van den Berg
Departamento de Ecologia Aplicada, Universidade Federal de Lavras, Instituto de Ciências Naturais, Avenida Doutor Sylvio Menicucci, 3037, Lavras, MG CEP 37200-900, Brazil

M. S. Linares
Departamento de Botânica e Ecologia, Universidade Federal Do Mato Grosso, Instituto de Ciências Biológicas, Av. Fernando Correa da Costa, 237, Cuiabá, MT CEP 78060-900, Brazil

M. S. Linares
Programa de Pós-Graduação em Ciências Ambientais, Instituto de Ciências Naturais, Humanas E Sociais, Universidade Federal Do Mato Grosso, Avenida Alexandre Ferronato, 1200, Sinop, MT CEP 78550-728, Brazil

R. M. Hughes
Department of Fisheries, Wildlife, and Conservation Sciences, Oregon State University, Corvallis, OR, USA

R. M. Hughes
Amnis Opes Institute, Corvallis, OR, USA

Published online: 06 November 2024

Keywords Freshwater conservation · Dam decommissioning · Environmental filter · Functional diversity · Bioindicators

Introduction

The environmental effects of hydropower dams and reservoirs are well-documented worldwide (Ruhi et al., 2018; Arantes et al., 2019; Flecker et al., 2022). However, most of the existing knowledge comes from large hydropower systems (> 30 MW, ANEEL, 2020), with high flow regulation and extended water residence times (Zhang et al., 2010; Chaudhari & Pokhrel, 2022; Ruhi et al., 2022). On the other hand, small hydropower dams (≤ 30 MW, ANEEL, 2020) represent approximately 90% of the global hydropower facilities (Couto & Olden, 2018). In most cases, those facilities are run-of-river systems, considered less environmentally harmful (Anderson et al., 2015; Singh et al., 2015).

Brazilian environmental law defines small hydropower dams as having generating capacities of up to 30,000 MW and reservoir areas of up to 13 km^2 (ANEEL, 2017). Because most sites suitable for the construction of large hydroelectric dams are already occupied by existing dams, and small hydropower dams have lower construction costs and are easier to license, small dams have been the focus of construction projects in recent decades (Almeida et al., 2009; Fearnside, 2014). Identifying the traits that respond to the environmental impacts caused by the presence of small hydropower dams is essential because traits are less constrained by biogeographic and evolutionary patterns and thus can be more widely and consistently applied and compared to other rivers similarly affected (Martins et al., 2021a). This is especially important for neotropical rivers, because most data on the subject derived from temperate ecosystems (Cortés-Guzmán et al., 2021).

Hydropower dams, even small ones, change the natural flows of water, sediments, wood, and nutrients (Thomson et al., 2005; Ticiani et al., 2022) and cause substantial changes in the structure and dynamics of aquatic habitats, both upstream and downstream of the dams (Xiaocheng et al., 2008; Wang et al., 2022). These changes negatively affect the taxonomic and functional diversity of benthic macroinvertebrates (Petrin et al., 2013; Wang et al., 2023). Furthermore, dam-altered habitats often favor the establishment of non-native species (Karatayev et al., 2010; Linares et al., 2018; Jovem-Azevêdo et al., 2021), resulting in local functional changes (Wang et al., 2023). Thus, changes in the natural characteristics of a river impose new environmental restrictions, filtering out taxa not adapted to the new conditions and facilitating colonization by invasive species (Ruhi et al., 2018).

Different environmental factors act as filters, selecting functional traits that enable species to survive under specific local conditions (Statzner et al., 2004; Wong et al., 2019). Calapez et al. (2018) found that the respiratory mode responded to low flow and reduced dissolved oxygen, resulting in an increase in the drift of gill breathers, whereas active dispersal (e.g., flying) was affected by the combination of both stressors. The homogenization of the aquatic habitat resulting from land use (e.g., agriculture, pasture, and urbanization) resulted in the loss of macroinvertebrate characteristics with low body flexibility and a univoltine reproductive cycle (Castro et al., 2018). Thus, to characterize the functional composition of benthic assemblages, analyses based on multiple functional traits have recently been used widely (Dedieu et al., 2015; Liu et al., 2021; Roux & Clinton, 2023). Key traits include feeding mode, respiration, voltinism, locomotion, and body flexibility and shape (Luiza-Andrade et al., 2017; Erasmus et al., 2021; Paz et al., 2022).

Although studies have characterized the effects of small hydropower systems on the taxonomic structure of benthic macroinvertebrate assemblages (e.g., Linares et al., 2019; Ferreira et al., 2022; Couto et al., 2023), there is still a knowledge gap on how the functional structure and composition are affected. As part of a large, joint, scientific assessment of the ecological effects of a run-of-river dam in the Pandeiros River basin in Brazil, we aimed to develop methodologies to support decision-making regarding a possible decommissioning of the Pandeiros dam, which, if realized, will be the first in South America. Previous studies in this effort have found significant correlation between the presence of the small hydropower dam and changes in taxonomic structure (Linares et al., 2019), as well as facilitating the establishment of invasive species (Linares et al., 2018, 2022).

This multiyear river study can add to studies by providing temporal data for the planned dam decommissioning. Because benthic macroinvertebrate assemblages have high turnover rates (Datry et al., 2016; Libório & Tanaka, 2016), multiyear studies can give important insights on how small hydropower dams affect the structure and functioning of benthic macroinvertebrate assemblages. Thus, our data will play a crucial role in assessing the biological effects of dam removal. Therefore, our objective was to understand how a small hydropower dam changed the functional structure of benthic macroinvertebrate assemblages in a Neotropical savanna river. To achieve our objective, we tested two hypotheses. (1) The macroinvertebrate functional traits in sites near the dam differ from those in free-flowing sites. (2) Sites near the dam support a distinct functional diversity and have assemblages with lower specialization compared to free-flowing sites. We predicted that the functional diversity indices (functional richness, functional evenness, functional divergence, functional dispersion, and functional originality) would have lower values, and the assemblages would be more generalist in sites close to the dam (Fig. 1).

Methods

Study area

Our sites were in the 145-km-long Pandeiros River, Minas Gerais State, southeastern Brazil (Fig. 2). The Pandeiros River drainage is a priority conservation area in the Neotropical savanna (Cerrado) (Drummond et al., 2005), being protected by State Law No. 11.901, which established the Environmental Preservation Area (EPA) Pandeiros (Minas Gerais, 1995). The Pandeiros River EPA is 380,000 ha and is formed by a mosaic of phytophysiognomies in the Cerrado biome. The region's semiarid climate is characterized by average temperatures between 26 °C and 29 °C (IGAM, 2014). During the dry and rainy periods studied, average precipitation varied from 14 to 270 mm, respectively (INMET, 2024).

The small hydropower plant (SHP Pandeiros), located in the middle course of the river, was installed in 1957, and its reservoir has an area of 280 ha, with a free crest dam height of 10.3 m (Fonseca et al., 2008). When operational, its turbines produced up to

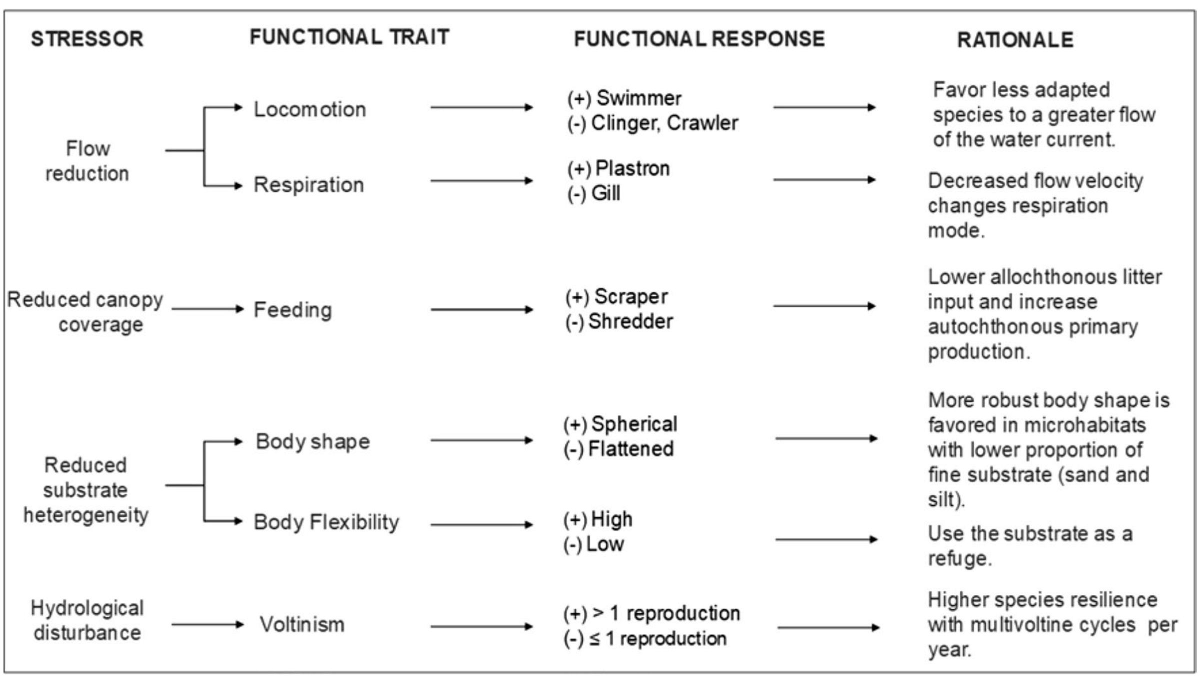


Fig. 1 Predictions for trait category responses to the hydroelectric system. Signs (+) and (−) indicate, respectively, a potential increase or potential decrease in the abundance of a given trait category (Statzner & Bêche, 2010; Feio & Dolédec, 2012; Castro et al., 2018; Firmiano et al., 2021)

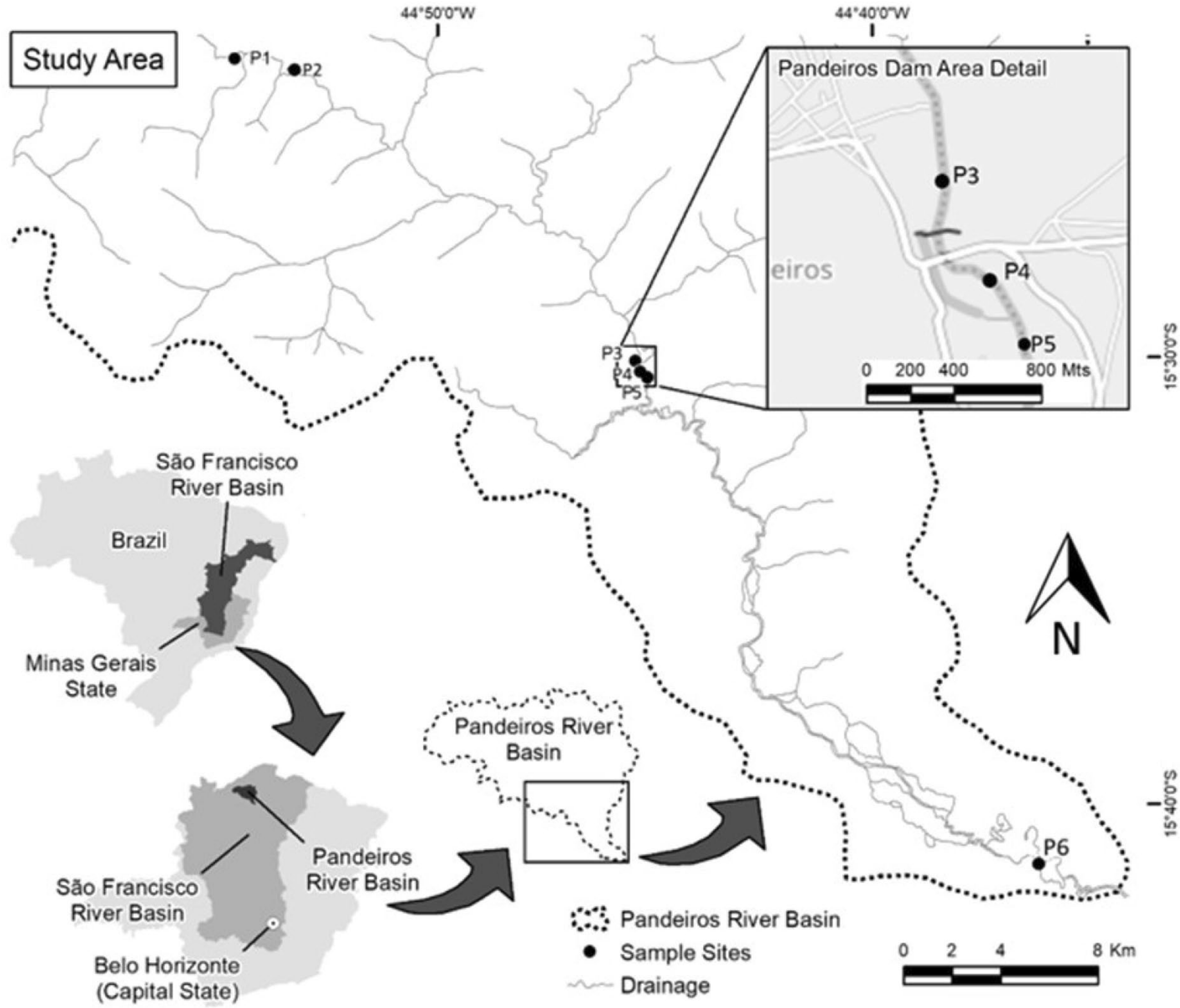


Fig. 2 Site and study area locations

4.2 MW (Fonseca et al., 2008), but its powerhouse was deactivated in 2007. Since then, the Pandeiros River and its tributaries have been studied (Santos et al., 2015; Martins et al., 2021b; Junqueira et al., 2022) to provide data for decommissioning (Linares et al., 2019)

Site selection

We selected six sites (Table 1) to represent the variation of environmental conditions related to the dam and reservoir (Fig. 2). At each site, we measured water temperature (°C) and dissolved oxygen (mg/L) with a YSI model ProSolo meter, pH with a Digimed DM-2P meter, turbidity (NTU) with a Digimed DM-TU meter, and conductivity (μS/cm) and total dissolved solids (TDS) with a Digimed DM-3P meter. In addition, we determined total alkalinity by the Gran method (Carmouze, 1994) with titration of 0.01 N sulfuric acid (Supplementary Material, S1).

Fauna collection and identification

We sampled macroinvertebrate assemblages ten times over five years at each site to assess seasonal and annual differences. Dry season samples were taken in September 2014, April and June 2015, May and August 2019. Rainy season sampling

Table 1 Site locations and descriptions

Site	Geographic coordinates	Dam Proximity	Site description
P1	15°23.364″ S 44°54.662″ W	Free-flow site upstream of the dam, about 20 km	Wide channel (> 5 m), shallow water depth (< 1 m), and has natural riparian vegetation and a sandy bottom substrate
P2	15°26.454″ S 44°49.240″ W	Free-flow site upstream of the dam, about 12 km	Wide channel (> 5 m), shallow water depth (< 1 m), and has natural riparian vegetation and a sandy bottom substrate
P3	15°29.921″ S 44°45.465″ W	Directly affected by the dam, 500 m upstream	Wide channel (> 10 m), low depth (< 2 m), sandy bottom substrate and alternation between areas with natural riparian vegetation and without vegetation along its banks
P4	15°30.289″ S and 44°45.442″ W	Directly affected by the dam, 50 m downstream	Narrow channel (< 5 m), a deeper water column (> 3 m), sandy sediment in a rocky matrix and natural riparian vegetation on its banks
P5	15°30.773″ S 44°45.222″ W	Located 500 m downstream from the dam	Wide channel (> 5 m), low water depth (< 1 m), sandy sediment and alternation of natural riparian vegetation with deforested areas
P6	15°41.669″ S 44°35.390″ W	Located 30 km downstream from the dam	Wide channel (> 5 m), a deeper water column (> 2 m), sandy sediment with a soft bottom and alternation of natural riparian vegetation and pasture on its banks

occurred in December and January 2014, February 2015, November 2019, and February 2020. We collected four substrate samples at each site using a kick-net sampler (30 cm aperture, 250 µm mesh, and 0.09 m^2 area) along a 15 m transect. The substrates were stored in plastic bags filled with 70% alcohol. We took the samples to the Laboratory of Benthos Ecology at the Universidade Federal de Minas Gerais, where we washed them through a 250-µm mesh sieve. All macroinvertebrates were identified under a stereoscopic microscope (32×) by using the taxonomic keys Merritt & Cummins (1996), Mugnai et al. (2010), Hamada et al. (2014). We identified Ephemeroptera, Plecoptera, and Trichoptera to genus (Olifiers et al., 2004; Pes et al., 2005; Salles, 2006), other macroinvertebrates to family, and Annelida to subclass because of limited taxonomic knowledge for the neotropical region. All macroinvertebrates were deposited in the Reference Collection of Benthic Macroinvertebrates, Instituto de Ciências Biológicas, Universidade Federal de Minas Gerais.

Functional trait characterization

We used a database of six traits distributed in 23 categories to characterize the functional structure of macroinvertebrate assemblages (Table 2). We chose traits to reflect the organisms' ability to deal with multiple environmental changes, for example, food resources, oxygen availability, and life cycle (Mondy & Usseglio-Polatera, 2014; Paz et al., 2022). In addition, we included morphological and mobility adaptations linked to flow restrictions, such as body flexibility, body shape, and locomotion. Although some studied macroinvertebrates, such as Oligochaeta and Corbiculidae, lack an aerial stage in their life cycle, most sampled taxa, including certain Coleoptera and Hemiptera, have a flying stage. Because flying dispersal ability can alter their resilience to disturbances (Ding et al., 2017; Oliveira et al., 2024), such as those caused by dams, we assigned significant weight to this trait in the fuzzy coding approach. Most data used to compile the functional traits were obtained from studies of neotropical organisms (Tomanova &

Table 2 Functional traits and categories for freshwater macroinvertebrates

Type	Trait	Categories	Code
Life history	Voltinism	≤ 1 reproduction/y	Univoltine
		> 1 reproduction/y	Multivoltine
Mobility	Locomotion/Habitat	Burrower	Burrower
		Crawler	Crawler
		Clinger	Clinger
		Swimmer	Swimmer
		Flyer	Flyer
Morphology	Respiration	Integument	Integument
		Gill	Gill
		Plastron	Plastron
		Spiracle	Spiracle
	Body flexibility	< 10°	Low
		> 10–45°	Average
		> 45°	High
	Body shape	Streamlined	Streamlined
		Flattened	Flattened
		Cylindrical	Cylindrical
		Spherical	Spherical
Foraging	Feeding mode	Gathering-collector	Gatherer
		Shredder	Shredder
		Scraper	Scraper
		Filtering-collector	Filterer
		Predator	Predator

Usseglio-Polatera, 2007; Castro et al., 2017; Jovem-Azevêdo et al., ; Amaral et al., 2021; Firmiano et al., 2021; Martins et al., 2021a; Linares et al., 2022). When information from neotropical taxa was unavailable, we compiled research from North America (Pilière et al., 2016; Poff et al., 2006).

We determined the affinity of each taxon for each trait category by using a fuzzy coding approach (Chevenet et al., 1994). We assigned a score to each taxon describing its affinity to each trait category, ranging from 0 (no affinity) to 3 (maximum affinity) (Chevenet et al., 1994; Tomanova & Usseglio-Polatera, 2007). For each 'taxon × trait', the affinity scores were then transformed into a relative usage frequency distribution by dividing the taxon affinity scores by the categories of a fuzzy coding trait by their sum. Affinity scores were standardized so that their sums were equal to 1, ensuring the same weight for each taxon and each trait in subsequent analyses. Assemblage trait profiles were obtained by multiplying the frequency of each trait category by the abundance of each species (Gayraud & Philippe, 2001). A trait-by-site matrix was created, containing the frequency of each trait at each location, for subsequent analysis

Functional diversity

We calculated five complementary functional diversity indices: functional richness (FRic), functional evenness (FEve), functional divergence (FDiv) (Villéger et al., 2008), functional dispersion (FDis) (Laliberté & Legendre, 2010), and functional originality (FOri) (Mouillot et al., 2013). These components of functional diversity reflect different aspects of species in functional space (Mason et al., 2005; Rojas et al., 2021). FRic is defined as the volume of the functional space (volume of the convex hull) occupied by the species of an assemblage, regardless of their abundance (Villéger et al., 2008). FEve measures the regularity with which the functional space is occupied by the abundance of species in an assemblage (Villéger et al., 2008). FDiv quantifies the total proportion of abundance supported by the species of an assemblage within the functional trait space (Villéger et al., 2008). FDis represents the mean distance of species from the centroid in the resulting multivariate space, weighted by the relative abundance of the corresponding species (Laliberté & Legendre, 2010). Finally, FOri is the weighted average distance between a species and the closest species in the functional space (Mouillot et al., 2013).

To obtain the five functional diversity indices, we used the *alpha.fd.multidim* function of the mFD package (Magneville et al., 2022) in R (R Development Core Team, 2016). We used Gower's dissimilarity (Gower, 1966) to create a distance matrix with the functional traits table, from which we extracted independent axes via Principal Coordinate Analysis (PCoA). We used those axes and the taxa abundance matrix to calculate functional diversity indices (Schleuter et al., 2010). We maintained the first six PCoA axes after testing the functional space quality (Magneville et al., 2022; Supplementary Material, S2).

Functional specialization

We evaluated the functional specialization of the assemblages by using indices proposed by Mondy & Usseglio-Polatera (2014). A Taxon Specialization Index (TSI) was calculated for each taxon and each trait. A maximum TSI value (i.e., 1.00) corresponds to a truly specialist taxon (i.e., using only one trait category), whereas a true generalist taxon (i.e., using all trait categories uniformly) exhibits a lower TSI value. The community specialization index (CSI), which estimates the functional homogenization associated with each feature and each site, was calculated by averaging the individual staggered TSIs of all taxa weighted by their respective log-transformed abundances. Finally, we calculated each site's global specialization index by averaging each feature's CSI. Lower CSI values mean more generalist communities. Thus, for a given characteristic, such as feeding habits, a taxon that is 100% predator is categorized as a specialist, whereas a taxon that is 50% gathering collector and 50% filtering collector is considered a generalist. Scripts for TSI and CSI indices are available in Mondy & Usseglio-Polatera (2014).

Data analyses

Temporal analyses

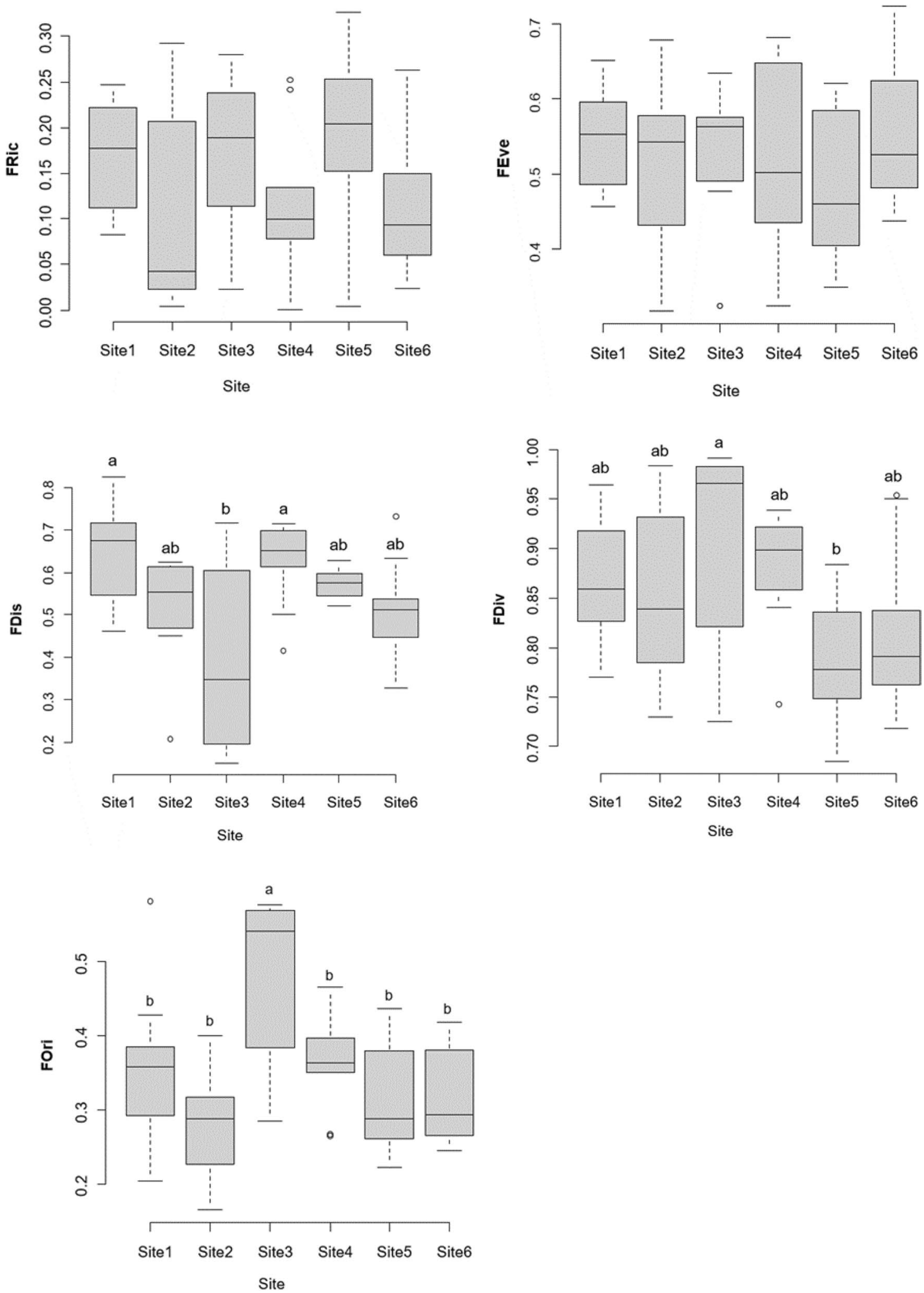
To verify possible seasonal differences, we ran a generalized linear model (GLM) with a Gaussian error structure for each functional diversity index (FRic, FEve, FDiv, FDis, and FOri). The assumptions of linearity, independence, and homoscedasticity were met. Then, we tested model significances using a variance analysis (*F* test). We did not observe significant differences between the dry and rainy seasons, nor between the different sampling years, and, therefore, grouped all six campaigns as replicas for each location.

Functional diversity and assemblage specialization

To test whether the functional diversity indices of macroinvertebrate assemblages in dam-affected sites showed a different profile from those in free-flowing sites, we performed a one-way analysis of variance (ANOVA). We then performed a post hoc Tukey HSD (Honest Significant Difference) test to identify significant differences ($P < 0.05$) between sites. Data normality and homoscedasticity were analyzed and confirmed by running Shapiro–Wilk and Bartlett tests, respectively.

Trait responses to environmental variables

To identify the bivariate association between traits and environmental variables, we performed both RLQ and fourth-corner methods (Dray et al., 2014; Dray & Legendre, 2008). RLQ analysis maximizes the covariance between traits and environmental variables mediated by species abundance (Dolédec et al., 1996). In contrast, the fourth-corner method facilitates quantifying and testing all positive and negative bivariate correlations between each trait category and each environmental variable (Dray et al., 2014). The Monte Carlo permutation test (9999 unrestricted permutations, $P < 0.05$) was used to test the global significance of model 2 (H1: assumes no relationship between R and L) and model 4 (H2: assumes no relationship between L and Q) (Dolédec et al., 1996). Fourth-corner analysis was then used to identify the relationship between trait categories and environmental variables based on the outcome of RLQ ordination


FRic
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Site1
Site2
Site3
Site4
Site5
Site6
Site
FEve
0.4
0.5
0.6
0.7
Site1
Site2
Site3
Site4
Site5
Site6
Site
FDis
0.2
0.3
0.4
0.5
0.6
0.7
0.8
a
ab
b
a
ab
ab
Site1
Site2
Site3
Site4
Site5
Site6
Site
FDiv
0.70
0.75
0.80
0.85
0.90
0.95
1.00
ab
ab
a
ab
b
ab
Site1
Site2
Site3
Site4
Site5
Site6
Site
FOri
0.2
0.3
0.4
0.5
b
b
a
b
b
b
Site1
Site2
Site3
Site4
Site5
Site6
Site

◂**Fig. 3** Differences in functional richness (FRic), functional evenness (FEve), functional divergence (FDiv), functional dispersion (FDis), and functional originality (FOri) of macroinvertebrates. Horizontal lines are medians, and the ends of boxes are quartiles. Vertical lines are confidence intervals, and circles represent outliers from six site visits. Different letters indicate significant differences ($P < 0.05$) between disturbance categories. Post hoc Tukey HSD (Honest Significant Difference) tests were used for pairwise comparisons

(Pallottini et al., 2017). The false discovery rate method adjusted the *P*-values for the fourth-corner analysis (Dray et al., 2014).

A community-weighted means of trait values (CWM) analysis determined individual trait category differences among the sites. CWM is a mean trait value weighted by the relative abundance (Díaz et al., 2007) and represents the expected functional value of a random assemblage sample. We explored the differences in the weighted averages of the assemblage of trait category values (CWM) that contributed to the differences ($P < 0.05$) between the sample sites using the Kruskal–Wallis test. Trait categories showing significant differences between sampling sites were further tested using a pairwise post hoc Dunn's test, where the multiple comparisons were adjusted by Bonferroni correction.

All statistical and graphical analyses were performed with R software (R Development Core Team, 2016), using the *vegan* (Oksanen et al., 2017), *ade4* (Chessel et al., 2004), and *FD* (Laliberté & Legendre, 2010) packages.

Results

Functional diversity and assemblage specialization

We found a total of 46,711 individuals comprised of 86 different taxa. Functional richness ($F_{5,54} = 2.22$, $P = 0.06$) and functional evenness ($F_{5,54} = 0.62$, $P = 0.68$) did not differ significantly among the sampling sites (Fig. 3). On the other hand, functional divergence ($F_{5,54} = 3.58$, $P = 0.01$), functional dispersion ($F_{5,54} = 4.60$, $P = 0.001$), and functional originality ($F_{5,54} = 7.16$, $P \leq 0.001$), differed significantly among the sites (Fig. 3) (Table S1, Supplementary Material). Site 3 had the highest functional originality (0.47 ± 0.03) which differed significantly from all the other sites, as well as a significantly higher functional divergence than site 5, but did not differ significantly from the other sites at a $P < 0.05$. Site 3 also had a significantly lower functional dispersion in relation to sites 1 and 4 (Fig. 3). Furthermore, the community specialization index (CSI) was not different between sampling locations ($F_{5,54} = 1.85$, $P = 0.12$, Fig. 4). The low CSI values, indicated generalist macroinvertebrate assemblages at all sites.

Trait responses to environmental variables

The RLQ and fourth-corner analyses revealed no significant relationship between the abundance of taxa and environmental variables (model 2, $P = 0.91$), nor the abundance of taxa and functional traits (model 4, $P = 0.10$) (Table 3). However, the composition of individual traits varied among sampling sites. We found significant differences ($P < 0.05$) among sample sites for 18 CWM trait categories (Table 4). Voltinism, body shape, and flexibility were the most affected functional traits, showing significant differences at a $P < 0.05$ for all trait categories (Table 4). Univoltism, spherical shape, and low body flexibility were found more often in the dam sites 3 and 4 (Fig. 5). However, multivoltism, flat body shape, and high body flexibility were associated with sites more distant from the dam (Fig. 5).

Discussion

Trait responses to water quality variables

No water quality variable influenced the trait composition of macroinvertebrate assemblages among the sampling sites. However, the first RLQ axis was responsible for the largest fraction of the explained variation. Previous studies have shown a relationship between environmental parameters and the functional structure of macroinvertebrates affected by small hydropower systems (Mueller et al., 2011; Tupinambás et al., 2014), whereas others have not (e.g., Principe, 2010; Scotti et al., 2022). Land use degrades water quality and assemblage composition (Moya et al., 2011; Castro et al., 2017), but the Pandeiros River drains an Environmental Preservation Area (Minas Gerais, 1995). Its basin lacks intensive economic activities and has low population density (IGAM, 2014) to maintain its water

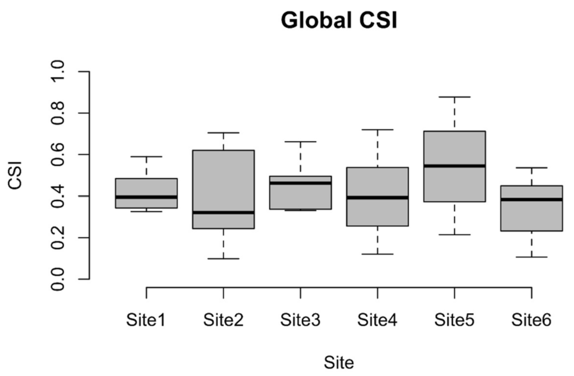


Fig. 4 General Community Specialization Index (CSI) for macroinvertebrate assemblages at each sampling site. Horizontal lines are medians, and the ends of boxes are quartiles. The vertical lines are confidence intervals the six site visits

Table 3 Multivariate analysis with (A) separate analysis showing eigenvalues and percentages of variance that represent the first axis of each analysis, and (B) RLQ analysis showing eigenvalues and percentage of total variance that accounted for the first RLQ axis

	Axis 1	
	Eigenvalue	% of variance
(A) Separate analysis		
Environment (PCA)	3.61	51.6
Abundance (COA)	0.23	26.9
Trait (FCA)	0.23	33.9
(B) RLQ analysis		
Eigenvalue	0.002	48.5
Covariance	0.043	
Correlation	0.096	
R/RLQ	2.225	61.5
L/RLQ	0.096	20
Q/RLQ	0.091	39.4

quality. However, assemblage traits may have been associated with measurements of physical habitat structure (Moya et al., 2011; Martins et al., 2021b; Kaufmann et al., 2022). Dams form reservoirs, which alter flow regimes, accumulate sediments, and increase widths and depths (Xiaocheng et al., 2008). Although the SHP Pandeiros is a small dam with short water residence time (Fonseca et al., 2008), the differences in trait composition probably resulted from physical changes in the sites influenced by the dam and reservoir.

Table 4 Kruskal–Wallis results concerning the differences among sampling sites for each trait category. Significant *P*-values ($P < 0.05$) are in bold

Trait	Category	Chi-Square	*P*
Respiration	Integument	21.776	**< 0.001**
	Gill	16.273	**< 0.001**
	Plastron	19.166	**< 0.001**
	Spiracle	10.806	0.055
Voltinism	Univoltine	26.448	**< 0.001**
	Multivoltine	26.448	**< 0.001**
Locomotion	Burrower	9.795	0.081
	Crawler	20.923	**< 0.001**
	Clinger	8.086	0.151
	Swimmer	15.071	**0.010**
	Flyer	16.97	**0.004**
Body flexibility	Low	28.942	**< 0.001**
	Average	13.187	**0.021**
	High	22.642	**< 0.001**
Body shape	Streamlined	14.403	**0.013**
	Flattened	21.684	**< 0.001**
	Cylindrical	23.028	**< 0.001**
	Spherical	27.719	**< 0.001**
Feeding mode	Gatherer	18.361	**0.002**
	Shredder	12.727	**0.026**
	Scraper	4.437	0.488
	Filterer	25.704	**< 0.001**
	Predator	5.943	0.311

Functional diversity and assemblage specialization

Our first hypothesis, that sites near the dam would support a distinct functional diversity and have less-specialized assemblages than free-flowing sites, was partially corroborated. Sites close to the dam supported a distinct functional diversity. Specifically, site 3 (reservoir), directly upriver from the dam, exhibited higher functional originality (FOri) compared to the other sites and had significantly higher functional divergence (FDiv) than site 5. The increase in FOri and FDiv is an indicator of niche differentiation, suggesting that the reservoir is composed of taxa sharing few functional characteristics with nearby taxa (Mouillot et al., 2013; Rojas et al., 2021). This result is related to the lower FDis observed at site 3 compared to the free-flowing sites 1 and 4, revealing a prevalence of taxa with uniform functional attributes in the reservoir. An increased functional dispersion indicates that taxa exhibited higher functional dissimilarity (Cooke et al., 2019), suggesting that functional traits are better distributed in free-flowing sites along the Pandeiros River. However, out of the five functional diversity metrics, the dam and reservoir affected three (FOri, FDiv, and FDis). Furthermore, the dam and reservoir did not change the specialization of macroinvertebrate assemblages. When a community has a low CSI (Community Specialization Index), the specialization of taxa within that community is reduced. This may indicate that the taxa present in the assemblages had a wide range of ecological preferences, being able to adapt to different environmental conditions. In other words, a low CSI suggests that the community is composed of generalist species, which are not strongly specialized in resource or habitat use (Mondy & Usseglio-Polatera, 2014).

Linares et al. (2019) studied macroinvertebrate assemblages in the Pandeiros River. They pointed out a change in the functional feeding groups, with an increased abundance of filterer taxa at the dam site compared to free-flowing sites. In addition, they found that the reservoir favored an increase in non-native invasive taxa. The persistence of non-native species overlaps with native species in the functional space, resulting in an increase in FDiv and FOri (Rojas et al., 2021). These increases resulting from the presence of non-native species may be related to negative effects on the ecosystem, such as niche displacement and loss of native species (Carboni et al., 2021; Haubrock et al., 2021).

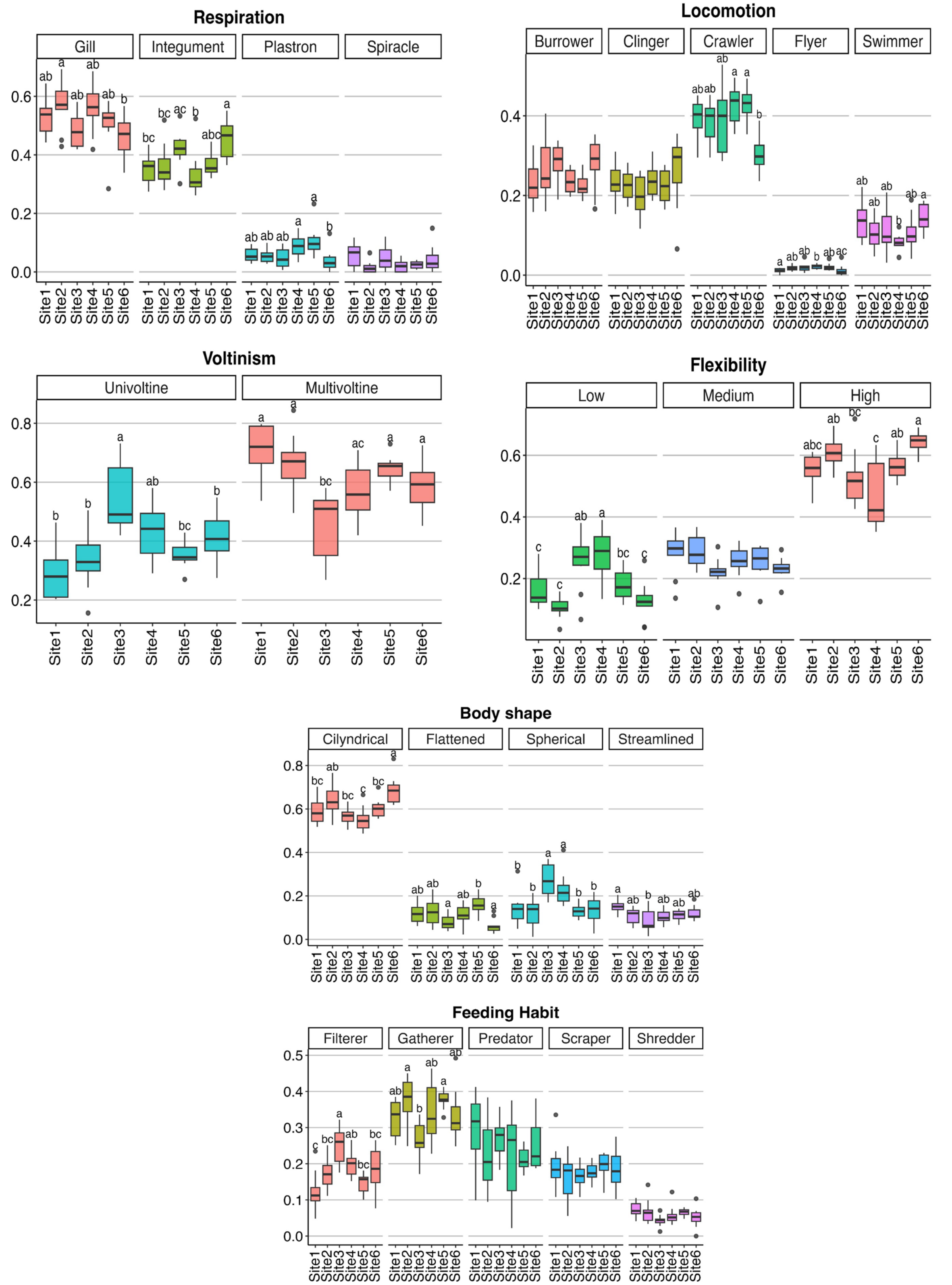
The hypothesis that the dam and reservoir would result in reduced functional complexity of local benthic macroinvertebrate assemblages was not corroborated. The macroinvertebrate assemblages at our sites were primarily composed of generalist taxa, suggesting the sampling sites were functionally more homogeneous, although the reservoir caused significant changes in functional diversity indices. The Pandeiros River substrate is predominantly sand and homogeneous throughout its course (Linares et al., 2018; Martins et al., 2021b) and this low substrate heterogeneity reduces habitat complexity, directly affecting the functional specialization of benthic macrofauna (Castro et al., 2018; Firmiano et al., 2021). This is because specialized taxa occupy restricted and highly suitable habitats, whereas generalists can occupy many habitats (Clavel et al., 2011; Mazzucco et al., 2015).

Our second hypothesis, that the composition of macroinvertebrate functional traits in dam and reservoir sites would differ from free-flowing sites, was corroborated. We found that the composition of individual traits varied significantly among sampling sites despite finding no significant relationships between environmental metrics and functional traits. The trait composition responded to the dam and reservoir, locally favoring certain assemblage traits. Body shape is linked to resistance or resilience to substrate sedimentation (Dolédec et al., 2011). Organisms that live in areas with fine sediment accumulations generally have a cylindrical shape, capable of penetrating the fine sediment (Ding et al., 2017), which explains the predominance of this body shape in the reservoir site (site 3). In contrast, the streamlined body shape was predominant in the free-flowing site (site 1). The faster flows mean fewer fine sediments, which select organisms with more hydrodynamic bodies (Ding et al., 2017). Other studies have also reported that body shape confers adaptations to changes in flow and the relationship of the organism with the substrate (Edegbene et al., 2021; Silva et al., 2021). Thus, different traits are selected as the hydrological disturbance gradient changes (Feio & Dolédec, 2012).

For the site nearest the dam (site 4), the retention of fine sediments by the dam and the presence of rocky outcrops (Linares et al., 2019) favored taxa with low body flexibility (e.g., Naucoridae). Coarse substrates offer advantages to taxa with this characteristic, facilitating the occupation of the interstices of the rock as protection (Yao et al., 2017) and reducing the possibility of being carried away by the current. Therefore, we observed that under coarse substrate conditions, faster current can be a limiting factor for lotic taxa, resulting in a more hydrodynamic body shape and low body flexibility.

On the other hand, organisms with multivoltine reproductive cycles were associated with the reservoir site (site 3), contrary to our predictions. Changes in the number of reproductive cycles are consistently related to environmental disturbances, with a higher frequency of multivoltine individuals in the most disturbed locations, which facilitates rapid recolonization of disturbed aquatic environments (Díaz et al., 2007; Castro et al., 2018).

The observed functional structure in the macroinvertebrate assemblages indicated that the small hydropower dam and reservoir acted as a local



Respiration
Gill
Integument
Plastron
Spiracle
Locomotion
Burrower
Clinger
Crawler
Flyer
Swimmer
Voltinism
Univoltine
Multivoltine
Flexibility
Low
Medium
High
Body shape
Cilyndrical
Flattened
Spherical
Streamlined
Feeding Habit
Filterer
Gatherer
Predator
Scraper
Shredder
Site1
Site2
Site3
Site4
Site5
Site6

◂**Fig. 5** Box plots expressing relative abundance of traits among sampling sites (Kruskal–Wallis test). Significant differences ($P < 0.05$) given by the post hoc pairwise test (Dunn's test) among sampling sites. Different letters indicate significant differences between disturbance categories

environmental filter, selecting unique traits that allow some taxa to occupy those conditions. However, some traits did not differ significantly among the dam/reservoir sites and the free-flowing sites, which can be explained by the low environmental variability and the predominance of generalist individuals. Ceneviva-Bastos et al. (2017) reported that generalist aquatic insects showed trophic plasticity and opportunistic feeding habits, leading to greater niche overlap. Therefore, the use of multiple traits improves our ability to assess the functional response of macroinvertebrate assemblages to gradients of environmental disturbance (Feio & Dolédec, 2012; Castro et al., 2017).

The absence of significant differences in functional diversity indices between the dry and rainy seasons can be attributed to at least three environmental factors specific to the Pandeiros River. (1) The river location within a protected and relatively well-preserved area contributes to its overall environmental stability, which buffers the assemblages from the typical seasonal fluctuations observed in more disturbed or heterogeneous systems. This stability could result in a reduced impact of seasonal variations on the functional structure of the assemblages (Baker et al., 2023). (2) The relative homogeneity of habitats along the river's course, predominantly characterized by sandy substrates (Linares et al., 2019), plays a crucial role in maintaining functional stability across seasons. The lack of habitat heterogeneity may limit the range of ecological niches available, leading to a more uniform assemblage structure that does not vary significantly with seasonal changes in flow or resource availability (Frainer et al., 2018). (3) The Pandeiros River rarely experiences extreme seasonal flow fluctuations because of its low annual rainfall (INMET, 2024). The absence of pronounced flood pulses, often responsible for restructuring benthic communities (O'Leary & Wantzen, 2012), facilitates more continuous and stable assemblages throughout the year. These three reasons help explain the observed consistency in functional diversity indices between the dry and rainy seasons.

Summary and conclusions

This study expands the knowledge of small hydropower system effects on selecting traits and functional diversity indices of macroinvertebrate assemblages at upstream and downstream sites. The FDis, FDiv, and FORi indices showed a strong relationship with the environmental pressures imposed by the dam, being sensitive to local hydrological conditions. Although the sampling sites showed functional homogenization, differences in reproductive cycles, body shape, and body flexibility indicate that certain traits were locally selected upstream and downstream of the dam. Additionally, the macroinvertebrate functional traits found in our study can be used for biomonitoring the decommissioning of other neotropical savanna river dams. Additional in situ studies of the functional structure of benthic macroinvertebrate assemblages should investigate the effects of riparian vegetation cover, riparian disturbance, channel morphology, habitat type, substrate quality, physical habitat complexity, and nutrient concentrations downstream and upstream of hydroelectric systems (Jimenez-Valencia et al., 2014; Silva et al., 2018; Herlihy et al., 2020; Martins et al., 2021b; Kaufmann et al., 2022).

Acknowledgements We are grateful for financial support from P&D Aneel-Cemig GT-611, the Coordenaçãoo de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)—Finance Code 001. PHMA received a postdoctoral scholarship from P&D Aneel-Cemig GT-611. DMPC received a postdoctoral scholarship from P&D Aneel-Cemig GT-611. MSL received a postdoctoral scholarship from CAPES (PDPG-AMAZONIA-LEGAL, Project: 88887.510266/2020-00). MC is a Resident Professor at the Institute of Advanced Transdisciplinary Studies (IEAT/UFMG) and was awarded CNPq research productivity grant 304060/2020-8. RMH was awarded a Fulbright-Brasil Distinguished Scholarship. Several Laboratório de Ecologia de Bentos ICB/UFMG colleagues helped with sample processing. We acknowledge SISBIO (No. 106357) and IEF-MG (No. 074/2014 e 018/2019) licenses for field samplings.

Author contributions PHMA, DMPC, MSL, and MC designed the study. PHMA and DMPC performed the statistical analyses. PHMA was involved in writing the original draft preparation. MC supervised the entire study. All authors contributed to reviewing the manuscript and approved the final version.

Funding P&D Aneel-CEMIG, CAPES, CNPq, and Fulbright-Brasil provided funding.

Data availability Part of the analyzed data set is provided as supplementary material, and another part is available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval No approval of research ethics committees was required to accomplish the goal of this study because experimental work was conducted with an unregulated invertebrate species.

References

Almeida, E. F., R. B. Oliveira, R. Mugnai, J. L. Nessimian & D. F. Baptista, 2009. Effects of small dams on the benthic community of streams in an Atlantic Forest area of Southeastern Brazil. International Review of Hydrobiology 94: 179–193. https://doi.org/10.1002/iroh.200811113

Amaral, P. H. M., C. H. B. Rocha & R. D. G. Alves, 2021. Effect of eucalyptus plantations on the taxonomic and functional structure of aquatic insect assemblages in Neotropical springs. Studies on Neotropical Fauna and Environment 58: 35–46. https://doi.org/10.1080/01650521.2021.1895512

Anderson, D., H. Moggridge, P. Warren & J. Shucksmith, 2015. The impacts of "run-of-river" hydropower on the physical and ecological condition of rivers. Water and Environment Journal 29: 268–276. https://doi.org/10.1111/wej.12101

ANEEL—Agência Nacional de Energia Elétrica, 2017. Banco de Informações de Geração.http://www2.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.cfm

ANEEL—Agência Nacional de Energia Elétrica. Resolução normativa n° 875, de 10 de março de 2020. https://www2.aneel.gov.br/cedoc/ren2020875.pdf

Arantes, C. C., D. B. Fitzgerald, D. J. Hoeinghaus & K. O. Winemiller, 2019. Impacts of hydroelectric dams on fishes and fisheries in tropical rivers through the lens of functional traits. Current Opinion in Environmental Sustainability 37: 28–40. https://doi.org/10.1016/j.cosust.2019.04.009

Baker, N. J., E. A. R. Welti, F. Pilotto, J. Jourdan, B. Beudert, K. L. Huttunen, T. Muotka, R. Paavola, E. Göthe & P. Haase, 2023. Seasonal and spatial variation of stream macroinvertebrate taxonomic and functional diversity across three boreal regions. Insect Conservation and Diversity 16: 2. https://doi.org/10.1111/icad.12623

Calapez, A. R., S. R. Q. Serra, J. M. Santos, P. Branco, T. Ferreira, T. Hein, A. G. Brito & M. J. Feio, 2018. The effect of hypoxia and flow decrease in macroinvertebrate functional responses: a trait-based approach to multiple-stressors in mesocosms. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2018.05.071

Carboni, M., S. W. Livingstone & M. E. Isaac, 2021. Invasion drives plant diversity loss through competition and ecosystem modification. Journal of Ecology. https://doi.org/10.1111/1365-2745.13739

Carmouze, J. P., 1994. O Metabolismo dos Ecossistemas Aquáticos. Fundamentos teóricos, métodos de estudo e análises químicas. São Paulo: Edgard Blücher/FAPESP 253p

Castro, D. M. P., S. Dolédec & M. Callisto, 2017. Landscape variables influence taxonomic and trait composition of insect assemblages in Neotropical savanna streams. Freshwater Biology 62: 1472–1486. https://doi.org/10.1111/fwb.12961

Castro, D. M. P., S. Dolédec & M. Callisto, 2018. Land cover disturbance homogenizes aquatic insect functional structure in neotropical savanna streams. Ecological Indicators 84: 573–582. https://doi.org/10.1016/j.ecolind.2017.09.030

Ceneviva-Bastos, M., D. B. Prates, R. M. Romero, P. C. Bispo & L. Casatti, 2017. Trophic guilds of EPT (Ephemeroptera, Plecoptera, and Trichoptera) in three basins of the Brazilian Savanna. Limnologica 63: 11–17. https://doi.org/10.1016/j.limno.2016.12.004

Chessel, D., A. B. Dufour & J. Thioulouse, 2004. The ade4 package-I-one-table methods. R News 4: 5

Chevenet, F., S. Dolédec & D. Chessel, 1994. A fuzzy coding approach for the analysis of long-term ecological data. Freshwater Biology 31: 295–309. https://doi.org/10.1111/j.1365-2427.1994.tb01742.x

Clavel, J., R. Julliard & V. Devictor, 2011. Worldwide decline of specialist species: toward a global functional homogenization? Frontiers in Ecology and the Environment 9: 222–228. https://doi.org/10.1890/080216

Chaudhari, S. & Y. Pokhrel, 2022. Alteration of river flow and flood dynamics by existing and planned hydropower dams in the Amazon River basin. Water Resources Research. https://doi.org/10.1029/2021WR030555

Cooke, R. S. C., A. E. Bates & F. Eigenbrod, 2019. Global trade-offs of functional redundancy and functional dispersion for birds and mammals. Global Ecology and Biogeography 28: 484–495. https://doi.org/10.1111/geb.12869

Cortés-Guzmán, D., J. Alcocer & K. W. Cummins, 2021. Benthic macroinvertebrates of tropical streams: functional and trophic diversity of the Lacantún River. Mexico. Limnology 22: 313–328. https://doi.org/10.1007/s10201-021-00658-y

Couto, T. B. A. & J. D. Olden, 2018. Global proliferation of small hydropower plants-science and policy. Frontiers in Ecology and the Environment 16: 91–100. https://doi.org/10.1002/fee.1746

Couto, T. B. A., R. S. Rezende, P. P. U. de Aquino, R. Costa-Pereira, G. L. de Campos, T. V. T. Occhi, J. R. R. Vitule, H. M. V. Espírito-Santo, Y. F. Soares & J. D. Olden, 2023. Effects of small hydropower dams on macroinvertebrate and fish assemblages in southern Brazil. Freshwater Biology 68: 956–971. https://doi.org/10.1111/fwb.14078

Datry, T., N. Moya, J. Zubieta & T. Oberdorff, 2016. Determinants of local and regional communities in intermittent and perennial headwaters of the Bolivian Amazon.

Freshw. Biol. 61: 1335–1349. https://doi.org/10.1111/fwb.12706

Dedieu, N., M. Rhone, R. Vigouroux & R. Céréghino, 2015. Assessing the impact of gold mining in headwater streams of Eastern Amazonia using Ephemeroptera assemblages and biological traits. Ecological Indicators 52: 332–340. https://doi.org/10.1016/j.ecolind.2014.12.012

Díaz, A. M., M. L. S. Alonso & M. R. V. A. Gutiérrez, 2007. Biological traits of stream macroinvertebrates from a semi-arid catchment: patterns along complex environmental gradients. Freshwater Biology. https://doi.org/10.1111/j.1365-2427.2007.01854.x

Ding, N., W. Yang, Y. Zhou, I. González-Bergonzoni, J. Zhang, K. Chen, N. Vidal, E. Jeppesen, Z. Liu & B. Wang, 2017. Different responses of functional traits and diversity of stream macroinvertebrates to environmental and spatial factors in the Xishuangbanna watershed of the upper Mekong River Basin, China. Science of the Total Environment 574: 288–299. https://doi.org/10.1016/j.scitotenv.2016.09.053

Dolédec, S., D. Chessel, C. J. F. Braak & S. Champely, 1996. Matching species traits to environmental variables: a new three-table ordination method. Environmental and Ecological Statistics 3: 143–166. https://doi.org/10.1007/BF02427859

Dolédec, S., N. Phillips & C. Townsend, 2011. Invertebrate community responses to land use at a broad spatial scale: trait and taxonomic measures compared in New Zealand rivers. Freshwater Biology 56: 1670–1688. https://doi.org/10.1111/j.1365-2427.2011.02597.x

Dray, S. & P. Legendre, 2008. Testing the species traits–environment relationships: the fourth-corner problem revisited. Ecology 89: 3400–3412. https://doi.org/10.1890/08-0349.1

Dray, S., P. Choler, S. Dolédec, P. R. Peres-Neto, W. Thuiller, S. Pavoine & C. J. F. ter Braak, 2014. Combining the fourth-corner and the RLQ methods for assessing trait responses to environmental variation. Ecology 95: 14–21. https://doi.org/10.1890/13-0196.1

Drummond, G. M., C. S. Martins, A. B. M. Machado, F. Sebaio & Y. Antonini, 2005. Biodiversidade em Minas Gerais: um atlas para sua conservação, Fundação Biodiversitas, Belo Horizonte:, 222

Edegbene, A. O., M. B. Adam, J. Gambo, E. C. Osimen, R. B. Ikomi, E. Ogidiaka, G. O. Omovoh & F. C. Akamagwuna, 2021. Searching for indicator macroinvertebrate traits in an Afrotropical riverine system: implication for ecosystem biomonitoring and sustainability. Environmental Monitoring and Assessment 193: 711. https://doi.org/10.1007/s10661-021-09450-y

Erasmus, J. H., A. W. Lorenz, S. Zimmermann, V. Wepener, B. Sures, N. J. Smit & W. Malherbe, 2021. A diversity and functional approach to evaluate the macroinvertebrate responses to multiple stressors in a small subtropical austral river. Ecological Indicators. https://doi.org/10.1016/j.ecolind.2021.108206

Feio, M. J. & S. Dolédec, 2012. Integration of invertebrate traits into predictive models for indirect assessment of stream functional integrity: a case study in Portugal. Ecological Indicators 15: 236–247. https://doi.org/10.1016/j.ecolind.2011.09.039

Fearnside, P. M., 2014. Impacts of Brazil's Madeira River dams: unlearned lessons for hydroelectric development in Amazonia. Environmental Science and Policy 38: 164–172. https://doi.org/10.1016/j.envsci.2013.11.004

Ferreira, M. E., S. H. M. Nogueira, M. N. Macedo, M. Callisto, J. F. B. Neto & G. W. Fernandes, 2022. Dams Pose a Critical Threat to Rivers in Brazil's Cerrado Hotspot. Water. https://doi.org/10.3390/w14223762

Firmiano, K. R., D. M. P. Castro, M. S. Linares & M. Callisto, 2021. Functional responses of aquatic invertebrates to anthropogenic stressors in riparian zones of Neotropical savanna streams. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2020.141865

Flecker, A. S., O. Shi, R. Almeida, H. Angarita, J. M. Gomes-Selman, R. Garcia-Villacorta, S. A. Sethi, N. L. Thomas, N. L. Poff, et al., 2022. Reducing adverse impacts of Amazon hydropower expansion. Science 375: 753–769. https://doi.org/10.1126/science.abj4017

Fonseca, E.M.B., W. R. Grossi, F. A. Fiorini, N. J. S. Prado, 2008. PCH Pandeiros: uma complexa interface com a gestão ambiental regional. VI Simpósio Brasileiro sobre Pequenas e Médias Centrais Hidrelétricas

Frainer, A., L. E. Polvi, R. Jansson & B. G. McKie, 2018. Enhanced ecosystem functioning following stream restoration: the roles of habitat heterogeneity and invertebrate species traits. Journal of Applied Ecology 55: 377–385. https://doi.org/10.1111/1365-2664.12932

Gayraud, S. & M. Philippe, 2001. Does subsurface interstitial space influence general features and morphological traits of the benthic macroinvertebrate community in streams? Fundamental Applied Limnology 151: 667–686. https://doi.org/10.1127/archiv-hydrobiol/151/2001/667

Gower, J. C., 1966. Some Distance Properties of Latent Root and Vector Methods Used in Multivariate Analysis. Biometrika 53: 325. https://doi.org/10.2307/2333639

Hamada, N., J. L. Nessimian, R. B. Querino, 2014. Insetos aquáticos na Amazônia brasileira: taxonomia, biologia e ecologia. Editora do INPA: Manaus

Haubrock, P. J., F. Pilotto, G. Innocenti, S. Cianfanelli & P. Haase, 2021. Two centuries for an almost complete community turnover from native to non-native species in a riverine ecosystem. Global Change Biology 27: 606–623. https://doi.org/10.1111/gcb.15442

Herlihy, A. T., J. C. Sifneos, R. M. Hughes, D. V. Peck & R. M. Mitchell, 2020. The relation of lotic fish and benthic macroinvertebrate condition indices to environmental factors across the conterminous USA. Ecological Indicators. https://doi.org/10.1016/j.ecolind.2019.105958

IGAM—Instituto Mineiro de Gestão das Águas., 2014. Plano Diretor de Recursos Hídricos da Bacia Hidrográfica do Rio Pandeiros. Belo Horizonte, 678 p

INMET—Instituto Nacional de Meteorologia. 2024. Banco de dados meteorológicos. Available in: https://portal.inmet.gov.br/

Jimenez-Valencia, J., P. R. Kaufmann, A. Sattamini, R. Mugnai & D. F. Baptista, 2014. Assessing the ecological condition of streams in a southeastern Brazilian basin using a probabilistic monitoring design. Environ. Monitor. Assess. 186: 4685–4695

Jovem-Azevêdo, D., J. F. Bezerra-Neto, M. J. Feio, R. Fernandes, W. I. A. Gomes, S. M. Thomaz & J. Molozzi, 2021. Modelling the abundance of a non-native mollusk in tropical semi-arid reservoirs. Hydrobiologia 1: 15. https://doi.org/10.1007/s10750-021-04729-0

Junqueira, R., M. R. Viola, J. S. Amorim, C. Camargos & C. R. Mello, 2022. Hydrological modeling using remote. Journal of South American Earth Sciences. https://doi.org/10.1016/j.jsames.2022.103773

Karatayev, A. Y., L. E. Burlakova, V. A. Karatayev & D. Boltovskoy, 2010. Limnoperna fortunei Versus Dreissena polymorpha: Population Densities and Benthic Community Impacts of Two Invasive Freshwater Bivalves. Journal of Shellfish Research 29: 975–984. https://doi.org/10.2983/035.029.0432

Kaufmann, P. R., R. M. Hughes, S. G. Paulsen, D. V. Peck, C. Seeliger, T. Kincaid & R. M. Mitchell, 2022. Physical habitat in conterminous US streams and rivers, part 2: quantitative assessment of condition. Ecological Indicators. https://doi.org/10.1016/j.ecolind.2022.109047

Laliberté, E. & P. Legendre, 2010. A distance-based framework for measuring functional diversity from multiple traits. Ecology 91: 299–305. https://doi.org/10.1890/08-2244.1

Libório, R. A. & M. O. Tanaka, 2016. Does environmental disturbance also influence within-stream beta diversity of macroinvertebrate assemblages in tropical streams? Studies on Neotropical Fauna and Environment 51: 206–214. https://doi.org/10.1080/01650521.2016.1237801

Linares, M. S., M. Callisto & J. C. Marques, 2018. Thermodynamic based indicators illustrate how a run-of-river impoundment in neotropical savanna attracts invasive species and alters the benthic macroinvertebrate assemblages' complexity. Ecological Indicators 88: 181–189. https://doi.org/10.1016/j.ecolind.2018.01.040

Linares, M. S., W. Assis, R. R. C. Solar, R. P. Leitão, R. M. Hughes & M. Callisto, 2019. Small hydropower dam alters the taxonomic composition of benthic macroinvertebrate assemblages in a neotropical river. River Research and Applications. https://doi.org/10.1002/rra.3442

Linares, M. S., P. H. M. Amaral & M. Callisto, 2022. Corbicula fluminea (Corbiculidae, Bivalvia) alters the taxonomic and functional structure of benthic assemblages in neotropical hydropower reservoirs. Ecological Indicators 141: 109115. https://doi.org/10.1016/j.ecolind.2022.109115

Liu, Z., Z. Li, D. M. P. Castro, X. Tan, X. Jiang, X. Meng, Y. Ge & Z. Xie, 2021. Effects of different types of land-use on taxonomic and functional diversity of benthic macroinvertebrates in a subtropical river network. Environmental Science and Pollution Research 28: 44339–44353. https://doi.org/10.1007/s11356-021-13867-w

Luiza-Andrade, A., V. Brasil, N. L. Benone, Y. Shimano, A. P. J. Farias, L. F. Montaga, S. Dolédec & L. Juen, 2017. Influence of oil palm monoculture on the taxonomic and functional composition of aquatic insect communities in eastern Brazilian Amazonia. Ecological Indicators 82: 478–483. https://doi.org/10.1016/j.ecolind.2017.07.006

Magneville, C., N. Loiseau, C. Albouy, N. Casajus, T. Claverie, A. Escalas, F. Leprieur, E. Maire, D. Mouillot & S. Villéger, 2022. mFD: an R package to compute and illustrate the multiple facets of functional diversity. Ecography (Cop.). https://doi.org/10.1111/ecog.05904

Martins, I., D. M. P. Castro, D. R. Macedo, R. M. Hughes & M. Callisto, 2021a. Anthropogenic impacts influence the functional traits of Chironomidae (Diptera) assemblages in a neotropical savanna river basin. Aquatic Ecology 55: 1081–1095. https://doi.org/10.1007/s10452-021-09884-z

Martins, I., D. R. Macedo, R. M. Hughes & M. Callisto, 2021b. Major risks to aquatic biotic condition in a Neotropical Savanna River basin. River Research and Applications 37: 858–868. https://doi.org/10.1002/rra.3801

Mason, N. W. H., D. Mouillot, W. G. Lee & J, B. Wilson, 2005. Functional richness, functional evenness and functional divergence: the primary components of functional diversity. Oikos 111: 112–118. https://doi.org/10.1111/j.0030-1299.2005.13886.x

Mazzucco, R., T. van Nguyen, D. H. Kim, T. S. Chon & U. Dieckmann, 2015. Adaptation of aquatic insects to the current flow in streams. Ecological Modelling 310: 143–152. https://doi.org/10.1016/j.ecolmodel.2015.04.019

Merritt, R. W. & K. W. Cummins, 1996. An Introduction to the Aquatic Insects of North America, 3rd ed. Kendall/Hunt Publishing, Dubuque, Iowa:

Minas Gerais—Lei Estadual Nº 11.901., 1995. Declara de Proteção Ambiental as áreas de interesse ecológico situadas na Bacia Hidrográfica do Rio Pandeiros

Mondy, C. P. & P. Usseglio-Polatera, 2014. Using fuzzy-coded traits to elucidate the non-random role of anthropogenic stress in the functional homogenisation of invertebrate assemblages. Freshwater Biology 59: 584–600. https://doi.org/10.1111/fwb.12289

Mouillot, D., N. J. Graham, S. Villéger, N. W. H. Mason & D. R. Bellwood, 2013. A functional approach reveals community responses to disturbances. Trends in Ecology & Evolution 28: 167–177. https://doi.org/10.1016/j.tree.2012.10.004

Moya, N., R. M. Hughes, E. Domínguez, F. M. Gibon, E. Goitia & T. Oberdorff, 2011. Macroinvertebrate-based multimetric predictive models for evaluating the human impact on biotic condition of Bolivian streams. Ecological Indicators 11: 840–847. https://doi.org/10.1016/j.ecolind.2010.10.012

Mueller, M., J. Pander & J. Geist, 2011. The effects of weirs on structural stream habitat and biological communities. Journal of Applied Ecology 48: 1450–1461. https://doi.org/10.1111/j.1365-2664.2011.02035.x

Mugnai, R., J. L. Nessimian & D. F. Baptista, 2010. Manual de identificação de macroinvertebrados aquáticos do estado do Rio de Janeiro, Technical Books Editora, Rio de Janeiro:

Oksanen, J., F. G. Blanchet, M. Friendly, R. Kindt, P. Legendre, D. McGlinn, P. R. Minchin, R. B. O'Hara, G. L. Simpson, P. Solymos, M. H. H. Stevens, E. Szoecs, H. Wagner, 2017. Vegan: Community Ecology Package. R Package Version 2

O'Leary, S. J. & K. M. Wantzen, 2012. Flood pulse effects on benthic invertebrate assemblages in the hypolacustric interstitial zone of Lake Constance. Ann. Limnol. Int. J. Lim. 48: 267–277. https://doi.org/10.1051/limn/2012008

Olifiers, M. H., L. F. M. J. L. Dorvillé, H. N. Nessimian, 2004. A key to Brazilian genera of Plecoptera (insecta) based on nynphs. Zootaxa 65: p.1–15. https://doi.org/10.11646/zootaxa.651.1.1

Oliveira, J. S., R. M. Hughes & B. F. Terra, 2024. Fish and macroinvertebrate assemblages respond differently to flow cessation in intermittent Brazilian streams. Austral Ecology. https://doi.org/10.1111/aec.13558

Pallottini, M., D. Cappelletti, A. Fabrizi, E. Gaino, E. Goretti, R. Selvaggi & R. Céréghino, 2017. Macroinvertebrate Functional Trait Responses to Chemical Pollution in Agricultural-Industrial Landscapes. River Research and Applications 33: 505–513. https://doi.org/10.1002/rra.3101

Paz, L. E., M. Rodriguez, B. Gullo & C. A. Rodrigues, 2022. Impacts of urban and industrial pollution on functional traits of benthic macroinvertebrates: are some traits advantageous for survival? Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2021.150650

Pes, A. M. O., N. Hamada & J. L. Nessimian, 2005. Chaves de identificacão de larvas para famílias e gêneros de Trichoptera (Insecta) da Amazônia Central. Brasil. Revista Brasileira De Entomologia 49(81–204): 2005. https://doi.org/10.1590/S0085-56262005000200002

Petrin, Z., J. E. Brittain & S. J. Saltveit, 2013. Mayfly and stonefly species traits and species composition reflect hydrological regulation: a meta-analysis. Freshwater Science. https://doi.org/10.1899/11-172.1

Pilière, A. F. H., W. C. E. P. Verberk, M. Gräwe, A. M. Breure, S. D. Dyer, L. Posthuma, D. de Zwart, M. A. J. Huijbregts & A. M. Schipper, 2016. On the importance of trait interrelationships for understanding environmental responses of stream macroinvertebrates. Freshwater Biology 61: 181–194. https://doi.org/10.1111/fwb.12690

Poff, N. L. R., J. D. Olden, N. K. M. Vieira, D. S. Finn, M. P. Simmons & B. C. Kondratieff, 2006. Functional trait niches of North American lotic insects: traits-based ecological applications in light of phylogenetic relationships. Journal of the North American Benthological Society 25: 730–755. https://doi.org/10.1899/0887-3593(2006)025[0730:FTNONA]2.0.CO;2

Principe, R. E., 2010. Ecological effects of small dams on benthic macroinvertebrate communities of mountain streams (Córdoba, Argentina). Annales De Limnologie-International Journal of Limnology 46: 77–91. https://doi.org/10.1051/limn/2010010

R Core Team, 2016. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria URL. https://www.R-project.org/

Rojas, P., S. A. Castro, I. Vila & F. M. Jaksic, 2021. Exotic species elicit decoupled responses in functional diversity components of freshwater fish assemblages in Chile. Ecological Indicator. https://doi.org/10.1016/j.ecolind.2021.108364

Roux, J. & S. M. Clinton, 2023. Evaluation of the Relationship between Stream Habitat Quality and taxa and Trait Richness and Diversity in Piedmont Streams in North Carolina Anthony. Hydrobiology 2: 363–381. https://doi.org/10.3390/hydrobiology2020024

Ruhi, A., X. Dong, C. H. McDaniel, D. P. Batzer & J. L. Sabo, 2018. Detrimental effects of a novel flow regime on the functional trajectory of an aquatic invertebrate metacommunity. Global Change Biology 24: 3749–3765. https://doi.org/10.1111/gcb.14133

Ruhi, A., J. Hwan, N. Devineni, S. Mukhopadhyay, H. Kumar, L. Comte, L. S. Worland & A. Sankarasubramanian, 2022. How Does Flow Alteration Propagate Across a Large, Highly Regulated Basin? Dam Attributes, Network Context, and Implications for Biodiversity. Earth's Future. https://doi.org/10.1029/2021EF002490

Salles, F. F. A., 2006. Ordem Ephemeroptera no Brasil (insecta): taxonomia e diversidade. Ph.D. Thesis, Universidade Federal de Viçosa 108p

Santos, U., P. C. Silva, L. C. Barros & J. A. S. Dergam, 2015. Fish fauna of the Pandeiros River, a region of environmental protection for fish species in Minas Gerais state. Brazil. Check List. https://doi.org/10.15560/11.1.1507

Schleuter, D., M. Daufresne, F. Massol & C. Argillier, 2010. A user's guide to functional diversity indices. Ecological Monographs 80: 469–484. https://doi.org/10.1890/08-2225.1

Scotti, A., D. Jacobsen & R. Bottarin, 2022. Small hydropower—Small ecological footprint? A multi-annual environmental impact analysis using aquatic macroinvertebrates as bioindicators. Part 2: effects on functional diversity. Frontiers in Environmental Science. https://doi.org/10.3389/fenvs.2022.904547

Silva, D. R. O., A. T. Herlihy, R. M. Hughes, D. R. Macedo & M. Callisto, 2018. Assessing the extent and relative risk of aquatic stressors on stream macroinvertebrate assemblages in the neotropical savanna. Science of the Total Environment 633: 179–188. https://doi.org/10.1016/j.scitotenv.2018.03.127

Silva, L. F. R., D. M. P. Castro, L. Juen, M. Callisto, R. M. Hughes & M. G. Hermes, 2021. Functional responses of Odonata larvae to human disturbances in neotropical savanna headwater streams. Ecological Indicators. https://doi.org/10.1016/j.ecolind.2021.108367

Singh, H., A. Kumar & N. Kumar, 2015. Analysis and evaluation of small hydropower plants: a bibliographical survey. Renewable and Sustainable Energy Reviews 51: 1013–1022. https://doi.org/10.1016/j.rser.2015.06.065

Statzner, B., S. Dolédec & B. Hugueny, 2004. Biological trait composition of European stream invertebrate communities: assessing the effects of various trait filter types. Ecography 27: 470–488. https://doi.org/10.1111/j.0906-7590.2004.03836.x

Statzner, B. & L. A. Bêche, 2010. Can biological invertebrate traits resolve effects of multiple stressors on running water ecosystems? Freshwater Biology 55: 80–119. https://doi.org/10.1111/j.1365-2427.2009.02369.x

Thomson, J. R., D. D. Hart, D. F. Charles, T. L. Nightengale & D. M. Winter, 2005. Effects of removal of a small dam on downstream macroinvertebrate and algal assemblages in a Pennsylvania stream. Journal of the North American Benthological Society 24: 192–207. https://doi.org/10.1899/08873593(2005)024%3c0192:EOROAS%3e2.0.CO;2

Ticiani, D., C. Larentis, D. R. Carvalho, A. C. Ribeiro & R. L. Delariva, 2022. Dam cascade in run-of-river systems promotes homogenisation of fish functional traits in a plateau river. Ecology of Freshwater Fish. https://doi.org/10.1111/eff.12675

Tomanova, S. & P. Usseglio-Polatera, 2007. Patterns of benthic community traits in neotropical streams: relationship to mesoscale spatial variability. Fundamental Applied Limnology 170: 243–255. https://doi.org/10.1127/1863-9135/2007/0170-0243

Tupinambás, T. H., R. M. V. Cortes, S. G. Varandas, S. J. Hughes, J. S. França & M. Callisto, 2014. Taxonomy, metrics or traits? Assessing macroinvertebrate community responses to daily flow peaking in a highly regulated Brazilian river system. Ecohydrology 7: 828–842. https://doi.org/10.1002/eco.1406

Villéger, S., N. W. H. Mason & D. Mouillot, 2008. New multidimensional functional diversity indices for a multifaceted framework in functional ecology. Ecology 89: 2290–2301. https://doi.org/10.1890/07-1206.1

Wang, Y., N. Wu, T. Tang, Y. Wang & Q. Cai, 2022. Small run-of-river hydropower dams and associated water regulation filter benthic diatom traits and affect functional diversity. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2021.152566

Wang, J., S. Bao, K. Zhang, J. Heino, X. Jiang, Z. Liu & J. Tao, 2023. Responses of macroinvertebrate functional trait structure to river damming: from within-river to basin-scale patterns. Environmental Research. https://doi.org/10.1016/j.envres.2023.115255

Wong, M. K. L., B. Guenard & O. T. Lewi, 2019. Trait-based ecology of terrestrial arthropods. Biological Reviews 94: 999–1022. https://doi.org/10.1111/brv.12488

Xiaocheng, F., T. Tao, J. Wanxiang, L. Fengqing, W. Naicheng, Z. Shuchan & C. Qinghua, 2008. Impacts of small hydropower plants on macroinvertebrate communities. Acta Ecologica Sinica 28: 45–52. https://doi.org/10.1016/S1872-2032(08)60019-0

Yao, J., F. Colas, A. G. Solimini, T. J. Battin, S. Gafny, M. Morais, M. Á. Puig, E. Martí, M. T. Pusch, C. Voreadou, F. Sabater, F. Julien, J. M. Sánchez-Pérez, S. Sauvage, P. Vervier & M. Gerino, 2017. Macroinvertebrate community traits and nitrate removal in stream sediments. Freshwater Biology 62: 929–944. https://doi.org/10.1111/fwb.12913

Zhang, M., S. Shao, Y. Xu & Q. Cai, 2010. Effect of hydrological regime on the macroinvertebrate community in Three-Gorges Reservoir, China. Quaternary International 226: 129–135. https://doi.org/10.1016/j.quaint.2009.12.019