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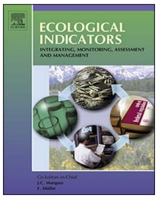

Original Articles

Thermodynamic based indicators illustrate how a run-of-river impoundment in neotropical savanna attracts invasive species and alters the benthic macroinvertebrate assemblages' complexity

Marden Seabra Linares[a,*], Marcos Callisto[a], João Carlos Marques[b]

[a] *Laboratório de Ecologia de Bentos, Departamento de Biologia Geral, Instituto de Ciências Biológicas, Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6627, CP 486, CEP: 31270-901, Brazil*

[b] *MARE-Marine and Environmental Sciences Centre, DCV, Faculty of Sciences and Technology, University of Coimbra, Portugal*

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ABSTRACT

Hydropower dams are widespread sources of anthropogenic alteration on lotic ecosystems, found in most hydrological basins system in the world. Our objective was to assess how such a run-of-river dam influences benthic macroinvertebrate assemblages in a neotropical river under a deactivated run of river dam. For that we tested four hypotheses: (1) a run-of-river dam diminishes the local diversity of the benthic macroinvertebrate assemblages; (2) the presence of the dam results in a more propitious habitat to the establishment of invasive species; (3) the presence of the dam results in a lower complexity of local benthic macroinvertebrate assemblages; (4) the ecological impacts are restricted to the sites directly affected by the dam. While the presence of the dam lowers the benthic macroinvertebrate assemblages' diversity in its reservoir, the diversity downstream next to the dam actually increases. The habitats directly affected by the dam also supported much higher biomass proportion of invasive species. By using eco-exergy and specific eco-exergy indicators, we were able to assess the complexity of benthic macroinvertebrate assemblages and the assemblages in the reservoir appeared to be enhanced by the presence of invasive species. These results illustrate that deactivated run-of-river dams still alter significantly the structure of lotic benthic macroinvertebrate assemblagesand that is advisable a management intervention for decommissioning of the dam. Finally, our results show that exergy based indicators may improve our comprehension of ecological systems' functioning in regards of ecological impacts of small dams, supporting environmental sustainable practices.

1. Introduction

Hydropower dams are widespread sources of anthropogenic alteration on lotic ecosystems, found in almost every river system in the planet (Bednarek, 2001). Hydropower is the most common renewable energy source in the world, accounting for 16% of worldwide total electricity generation(Anderson et al., 2015) and for more than 64% of Brazilian electricity production (EPE, 2016).

Due to a crescent demand for renewable energy sources and to most of the areas suitable for large scale hydropower dams already occupied by existing dams, construction of small run-of-river hydroelectric dams have increased globally in the last decades (Abbasi and Abbasi, 2011; Fearnside, 2014). Brazil has followed this trend, installing many small run-of-river dams through its river systems in the last decades, due to lower costs and easier licensing (Almeida et al., 2009), for a total of 431 installed small hydropower dams which respond for 3.21% of the national power generation, plus 27 small hydropower dams in construction (ANEEL, 2017).

Run-of-river hydropower dams are those that use in-stream flow to operate and therefore need little or no water storage (Wang et al., 2016). Despite small run-of-river dams being common in most river systems around the world, most studies focus on large dams (e.g. Agostinho et al., 2008; Horsák et al., 2009; Martins et al., 2015), there is little information about the ecological impacts of run-of-river dams (Anderson et al., 2017; Mbaka and Wanjiru Mwaniki, 2015; Wang et al., 2016).

Due to their smaller size, many of these small dams end up outliving their economic usefulness, ending their operations (Hastings et al., 2016). Dam removal have been used in the last decades as a tool to reestablish natural hydrological conditions in Europe and North

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[*] Corresponding author.
E-mail address: mslx@hotmail.com (M.S. Linares).
URL: http://lebufmg.wixsite.com/bentos (M.S. Linares).

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America (Bednarek, 2001). Characterizing the effects of run-of-river dams over lotic ecosystems is essential in terms of their management, to predict and mitigate potential ecological impacts, and for future dam removal initiatives (Hastings et al., 2016).

While many taxa are used as bioindicators to assess ecological impacts, benthic macroinvertebrates are among the most ubiquitous and widely used, due to their ability to respond predicatively to modifications in lotic environments (Bonada et al., 2006; Castro et al., 2017; Klemm et al., 2003; Macedo et al., 2016). Usually the structure of benthic macroinvertebrate assemblages is assessed trough taxonomic based indicators, such as richness and diversity indices (Friberg, 2014). However, the taxonomic structure may vary geographically due to differences in the evolutive history of the local environment, thus limiting taxonomic indicators' capacity for generalization (Karr, 1999). Thermodynamic oriented indicators are not subjected to these limitations, as they are rooted in universal concepts, thus providing an unified language to compare different organisms and systems (Ludovisi et al., 2005). Among thermodynamic oriented indicators, eco-exergy and specific eco-exergy have been successfully used in different ecosystems in the last decades, namely in estuaries (Marques et al., 2003, 1997; Veríssimo et al., 2016), lakes (Silow et al., 2011; Xu, 1997; Xu et al., 2001), streams (Linares et al., 2018) and reservoirs (Linares et al., 2017; Molozzi et al., 2013).

Eco-exergy and specific eco-exergy were adapted from exergy, a concept originated in physics, that represents the useful energy contained within a system (Jørgensen, 2007a; Jørgensen and Fath, 2004; Jørgensen and Mejer, 1977). Eco-exergy is assumed to express the complexity of an ecological system and provide information about its stability (Li et al., 2016; Marques et al., 2003, 1997, Xu et al., 2011, 1999). Specific eco-exergy is defined as the total eco-exergy divided by the total biomass, which is assumed to take into account how well it uses the available resources, independently from the amount of resources, measuring the ability of the ecosystem to use external energy flows and reflecting the degree of complexity and development of the system (Molozzi et al., 2013; Patrício et al., 2009; Patrício and Marques, 2006; Silow and Mokry, 2010).

Eco-exergy and specific eco-exergy can be used as environmental indicators and should be used in combination (Marques et al., 2003). Higher values of these parameters are indicative of greater diversity, greater functional redundancy and greater resilience, characteristics of more complex systems (Salas et al., 2005). This can be interpreted as a consequence of the tendency of the ecosystem to maximize its eco-exergy storage capacity, stabilizing in the condition that leaves the system farther from the thermodynamic equilibrium (Jørgensen, 2007b). Thus, a perturbed ecosystem is expected to exhibit lower eco-exergy and specific eco-exergy when compared to a poorly disturbed environment, since disturbances would increase ecosystem entropy (Jørgensen, 2007c). In this theoretical context, the use of exergy based indicators represents a good holistic tool to assess the ecological impacts of run-of-river dams, the first of its kind to be realized in the neotropical savanna.

Our objective was to assess how a run-of-river dam influences benthic macroinvertebrate assemblages in a large river in the Neotropical savanna. For that we tested four hypotheses: (1) the presence of the dam diminishes local diversity of the benthic macroinvertebrate assemblages compared to the free-flowing stretch of the river, which will result in lower values of diversity indices; (2) the presence of the dam result in a more propitious habitat to the establishment of invasive species, which will result in a dominance of these species in the benthic macroinvertebrate assemblages; (3) the presence of the dam lowers the local benthic macroinvertebrate assemblages complexity (in terms of information embedded in the organisms' biomass), which will be expressed by lower eco-exergy and specific eco-exergy values; (4) the ecological impacts will be restricted to the river stretches directly affected by the dam, meaning that the downstream floodplain stretch will show for all tested indicators values were not significantly different from those of the free-flowing stretch.

This study is part of a larger project aiming to evaluate the ecological impacts of the dam over the Pandeiros river and to provide a baseline for a future decommission of the dam, which is the first in South America. As far as we know, this study presents a unique opportunity to assess the ecological impacts of a small run-of-river hydropower dam in Brazil using thermodynamic ecological indicators, providing useful data for its ecological management and for the possible dam removal.

2. Material and methods

2.1. Study area

This study was conducted in the Pandeiros river, located in Minas Gerais state, Brazil. The Pandeiros river is an important tributary of the left bank of the São Francisco river, with an approximate extension of 145 km. The floodplains of the Pandeiros river are among the top priority areas for conservation in the neotropical savannah, considered by state law to be of "Special Biological Importance", due to their unique nature and high diversity (Drummond et al., 2005). This Area of Environmental Protection (AEP) encompasses almost 400,000 ha, the largest unit for sustainable use in Minas Gerais state, and covers the entire basin of the Pandeiros River in the municipalities of Januária, Bonito de Minas, and Cônego Marinho (Lopes et al., 2010). The objective of the AEP-Pandeiros is to protect the Pandeiros Wetland and the biological diversity in the surrounding area for development and reproduction of native fish species, as the Pandeiros Wetland is considered to be the nursery of most migratory fishes of the São Francisco river Basin (Santos et al., 2015).

The small hydropower dam Pandeiros was installed in 1957. Its reservoir presents an area of 280 hectares and its dam, with free crest, and possesses a maximum height of 10.30 m. Its powerhouse is located about 400 meters downstream from the dam and, when operational, had a power output of 4.2 MW (Fonseca et al., 2008). The powerhouse was deactivated in 2007 and since then all economical activities in the dam have ceased, allowing the reservoir to be filled by sediment.

For this study four sampling sites were chosen in the main channel of the Pandeiros river (Fig. 1) aiming to represent the diversity of environmental conditions in the Pandeiros river main channel related to the presence of the dam. P1is a free-flowing stretch 12 km upstream of the dam, characterized by soft bottom sandy sediment, wide channel, shallow water column (less than 1 m) and natural riparian vegetation. P2 is a stretch in the mouth of the reservoir circa 500 m from the dam, characterized by soft bottom sandy sediment, shallow water column (less than 2 m) wider channel and no riparian vegetation in one of its margins, as it is next to a human settlement. P3 is a stretch localized downstream/next to the dam circa 50 m to the dam, characterized by sandy sediment in a rocky matrix, deeper water column (more than 3 m), narrower channel and natural riparian vegetation on its margins. P4 is a stretch located 30 km downstream, in the Pandeiros river floodplains, characterized by soft bottom sandy sediment, deeper water column (more than 2 m), wide channel and a mix of natural riparian vegetation and pasture on its margins. To further characterize the physical habitat of the chosen sampling sites, physical and chemical variables of the water column and sediment of each site were measured. At each site temperature, turbidity, pH, conductivity and total dissolved solids (TDS) were measured in situ by a portable multiprobe model YSI 6600. Water samples were taken to measure in laboratory the water contents of phosphate, total nitrogen, nitrate and nitrites. Substrate samples were taken to estimate granulometry of the sediment.

2.2. Benthic macroinvertebrate sampling

The macroinvertebrate communities were sampled in a total of six sampling campaigns. These campaigns were chosen to contemplate both the dry and rainy seasons of the region, resulting in three

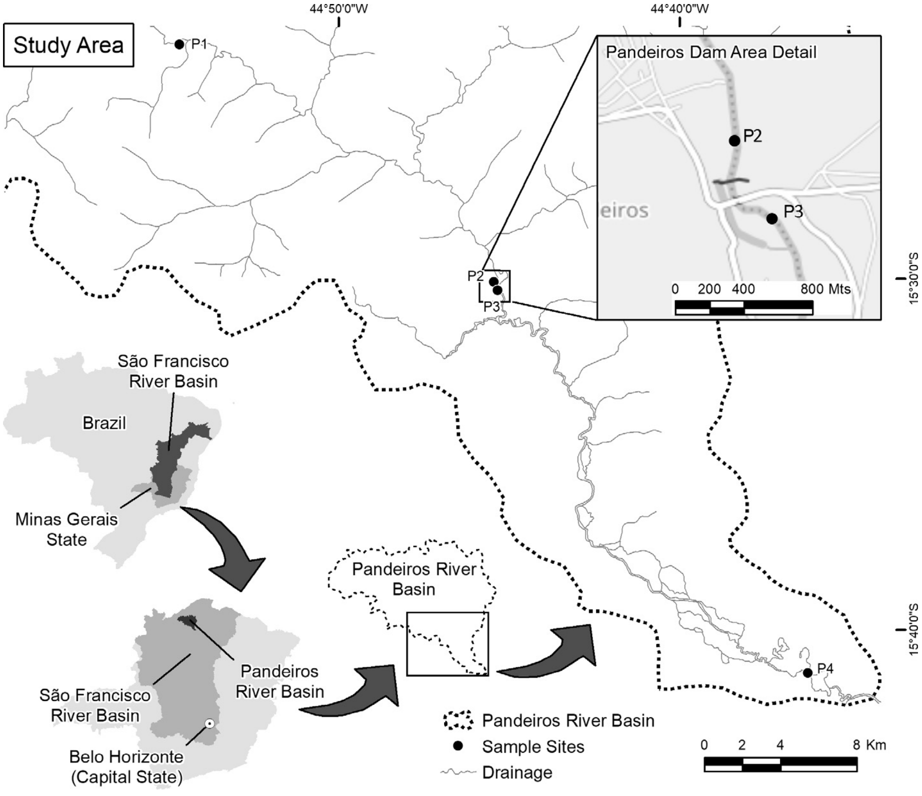

Fig. 1. Location of the sampling sites in the Pandeiros river basin.

Table 1
Exergy conversion factors for benthic communities, based on Jørgensen et al. (2005). The values in bold were used in this study.

Organisms	Energy Conversion Factor (β)
Virus	1.01
Bacteria	8.5
Algae	20
Yeast	17.4
Cnidaria	91
Platyhelminthes	**120**
Gastropoda	**312**
Bivalvia	**297**
Crustacea	232
Coleoptera	**156**
Diptera	**184**
Hymenoptera	267
Lepdoptera	**221**
Other Insecta	**167**
Fish	499

samplings in dry season (September/15, April and June/16) and three samplings in rainy season (December/15, January and February/16). As preliminary tests we ran a Generalized Linear Model (GLM) with a Gaussian error structure for Simpsom and Shannon-Wienner indices, eco-exergy, specific eco-exergy and invasive species' biomass percentage and then tested the models' significance by an Analysis of Deviance (F test). Our preliminary tests failed to detect any significant difference for any of the tested indicators between seasons in any site, and therefore we pooled all of them as temporal replicates for each site.

At each sampling site, a kick-net sampler (30 cm opening, 500 μm sieve) was used, resulting in four sub-samples in each sampling sites for a total area of 0.36 m^2 sampled per site per field campaign. Organisms from each sub-sample were stored in plastic bags, fixed in 10% formalin, and then washed in a sieve (0.5 mm mesh) in laboratory.

Macroinvertebrates were identified under a stereomicroscope, using specialized literature (Hamada et al. 2014; Merritt and Cummins 1996; Mungnai et al. 2010). The individuals of the invasive species *Corbicula fluminea* (Corbiculidae) and *Melanoides tuberculata* (Thiaridae) were identified to species level. Other taxa were identified to family (other Insecta) or subclass (Anellida), taxonomic resolution that require less laboratory time without compromising the tested indices performance (Silva et al., 2017). The specimens were fixed in 70% alcohol and deposited in the Reference Collection of Benthic Macroinvertebrates, Instituto de Ciências Biológicas, Universidade Federal de Minas Gerais.

2.3. Diversity measures calculation

To test if the presence of the dam lower the local diversity of the benthic macroinvertebrate assemblages compared to the free-flowing segments of the river, the Shannon-Wienner (Shannon, 1948) and the Simpson (1949) diversity indices were calculated for each sampling site.

2.4. Biomass estimation

Dry-mass biomass was estimated for each sampling site. Biomass was estimated using length-mass equations (Benke et al., 1999; Johnston and Cunjak, 1999; Miserendino, 2001; Smock, 1980; Stoffels et al., 2003). Each individual of each taxon, up to 100, were photographed in a stereomicroscope (model Leica M80) equipped with a digital camera (model Leica IC 80 HD). Each photographed specimen's length was measured using the software Motic Image Plus 2.0. Using the length-mass equations the dry-mass biomass (g/m2) of each sampled taxon was estimated.

To test if the presence of the dam results in a more propitious habitat to the establishment of invasive species, the proportion of the biomass of the invasive species to the total biomass of each sampling site was calculated.

2.5. Calculation of exergy based indicators

To test if the presence of the dam lowers the local benthic

Table 2
Water column physical and chemical variables for the selected sampling sites.

Sampling Sites	Temperature (°C)	pH	Conductivity (µS/cm)	TDS (mg/L)	Turbidity (UNT)	DO (mg/L)
1	24,9 ± 2,6	7,3 ± 0,3	73,9 ± 4,0	35,1 ± 18,5	9,4 ± 9,5	7,2 ± 1,4
2	23,3 ± 2,2	7,3 ± 0,7	82,7 ± 9,8	40,6 ± 18,7	6,7 ± 5,6	7,2 ± 1,6
3	25,1 ± 1,3	7,4 ± 0,3	91,6 ± 31,7	38,4 ± 14,9	7,0 ± 6,3	6,8 ± 1,6
4	25,4 ± 2,2	7,3 ± 0,2	83,6 ± 3,8	31,6 ± 4,6	18,2 ± 23,9	6,5 ± 0,9

Sampling Sites	Alcalinity (mEq/L CO_2)	Total N (mg/L)	Total P (µg/L)	Ortofosfate (µg/L)	Nitrate (µg/L)	Nitrite (µg/L)
1	524,7 ± 62,6	0,06 ± 0,03	9,9 ± 2,3	7,8 ± 2,0	0,015 ± 0,011	0,085 ± 0,028
2	572,1 ± 56,6	0,05 ± 0,02	9,4 ± 2,4	6,8 ± 1,8	0,015 ± 0,012	0,093 ± 0,039
3	566,2 ± 87,7	0,07 ± 0,02	10,2 ± 2,4	6,4 ± 1,3	0,016 ± 0,011	0,070 ± 0,042
4	602,8 ± 45,2	0,06 ± 0,02	13,8 ± 4,9	7,9 ± 2,7	0,017 ± 0,013	0,092 ± 0,052

macroinvertebrate assemblages' complexity, eco-exergy and specific eco-exergy values were calculated for each sampling site. Eco-exergy was computed as follows (Jørgensen et al., 2010):

$$EX = \sum_{i}^{i=0} \beta ici$$

Where $\boldsymbol{\beta i}$ is a weighting factor based on the information contained in the components (**i**) of the ecosystem (Table 1), defined by Jørgensen et al. (2005) and **ci** is the concentration (biomass) of component **i** in the ecosystem.

Specific eco-exergy is given by:

$$SpEX = \frac{EX}{BM}$$

Where ***EX*** is the total eco-exergy and ***BM*** is the total biomass.

2.6. Data Analysis

A Generalized Linear Model (GLM) with a Gaussian error structure was used to test if the Shannon-Wienner and Simpson diversity indices (hypothesis 1) and eco-exergy and specific eco-exergy (hypothesis 3) were significantly different between the free-flowing stretch (P1) and the other sampling sites. The same tests were used to test if the ecological impacts will be restricted to the river stretches directly affected by the dam (hypothesis 4). The model's significance was tested by an Analysis of Deviance (F test) (Kaur et al., 1996).

A Generalized Linear Model (GLM) with a Quasibinomial error structure was used to test if the proportion of the biomass of the invasive species to the total biomass (hypothesis 2) was significantly different between the free-flowing stretch (P1) and the other sampling sites. The model's significance was tested by an Analysis of Deviance (F test) (Kaur et al., 1996).

To characterize the water physical and chemical variables for the sampling sites a Generalized Linear Model (GLM) with a Gaussian error structure was used to test if temperature, turbidity, pH, conductivity, total dissolved solids, phosphate, total nitrogen, nitrate and nitrites were significantly different between the free-flowing stretch (P1) and the other sampling sites. For the granulometry variables we used A Generalized Linear Model (GLM) with a Quasibinomial error structure to test if there were significantly differences between the free-flowing stretch (P1) and the other sampling sites. The models' significance were tested by an Analysis of Deviance (F test) (Kaur et al., 1996).

3. Results

The water physical and chemical variables for the sampling sites were characterized (Table 2). Temperature, turbidity, pH, conductivity, total dissolved solids, phosphate, total nitrogen, nitrate and nitrites did not show any significant differences among the sampling sites (Fig. 2).

Considering the sediment granulometry (Table 3), all sampling sites were mostly composed by sandy sediments. P2 granulometry showed a significant difference (Fig. 3), as composed mostly of fine sand (64.1%), while P1, P3 and P4 were mostly composed of very fine sediment (respectively 67.4, 59.3 and 89.5). P4 also had significant differences in relation to P1, with granulometry composition showing significantly higher very coarse sand, coarse sand, medium sand and silt percentages and significantly lower percentage of fine sand.

A total of 30,094 benthic macroinvertebrate specimens belonging to 61 taxa were sampled, 37 taxa were sampled in P1, 47 in P2, 41 in P3 and 35 in P4. The Shannon-Wienner and Simpson diversity indices showed significant differences between P1 and the sampling sites directly affected by the dam (Fig. 4). P2 showed significantly lower values, while P3 showed significantly higher values for both indices. Only P4 showed no significant differences in relation to P1.

On the other hand, both P2 and P3 showed significantly higher

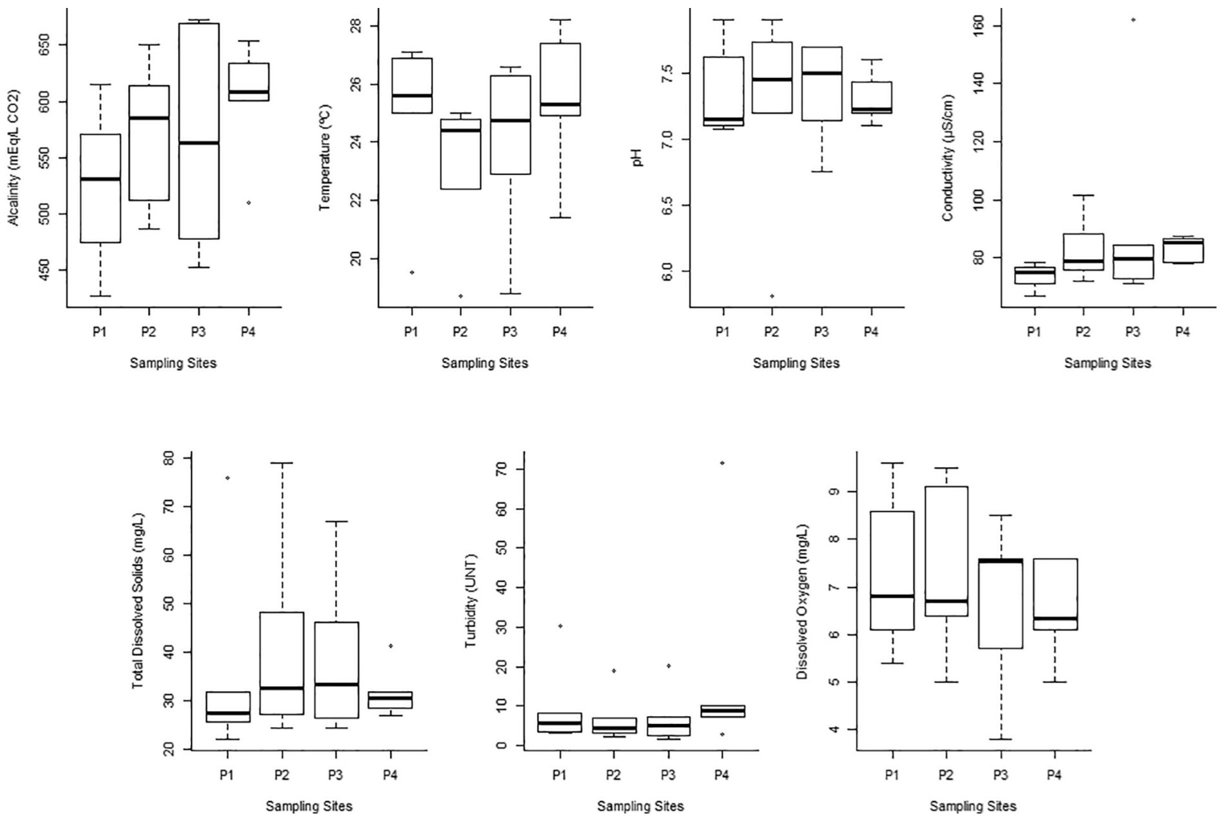

Fig. 2. Water column physical and chemical variables for the different sampling sites. "*" mark significantly different values from P1.

Table 3
Granulometry variables for the selected sampling sites.

Site	Gravel	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Silt
1	0,0 ± 0,0	0,0 ± 0,0	0,0 ± 0,0	0,1 ± 0,1	31,8 ± 19,7	67,4 ± 19,2	0,6 ± 0,6
2	0,0 ± 0,0	0,0 ± 0,0	0,2 ± 0,1	1,1 ± 0,6	64,1 ± 28,6	34,1 ± 28,5	0,6 ± 0,6
3	0,0 ± 0,0	0,0 ± 0,0	0,1 ± 0,1	0,2 ± 0,1	39,8 ± 15,8	59,3 ± 15,3	0,7 ± 0,4
4	0,0 ± 0,1	0,2 ± 0,2	1,0 ± 0,4	1,8 ± 0,5	2,1 ± 0,6	89,5 ± 2,6	5,3 ± 1,6

proportion of invasive species biomass than P1, while P4 showed no significant differences as compared to P1 (Fig. 5).

Eco-exergy and specific eco-exergy exhibited significant higher values in P2, as compared to P1 (Fig. 6), but no significant differences were observed in relation to P3 and P4.

4. Discussion

Our first hypothesis, that the presence of the dam would diminish local diversity of the benthic macroinvertebrate assemblages compared to the free-flowing stretch of the river was only partially corroborated by the results. In fact, while the Shannon-Wienner and Simpson diversity indices were significantly lower in the reservoir stretch (P2) as compared to the upstream free-flowing stretch (P1), they were significantly higher in the next to the dam stretch (P3). The hypothesis that the presence of the dam would result in a more propitious habitat to the establishment of invasive species was corroborated, as the proportion of biomass belonging to invasive species was higher in both P2 and P3. The hypothesis that the presence of the dam would result in a lower complexity of local benthic macroinvertebrate assemblages was not corroborated, as eco-exergy and specific eco-exergy exhibited significantly higher values in P2 as compared to P1, while no significant differences were found in P3. Finally, the hypothesis that the ecological impacts would be restricted to the sites directly affected by the dam was corroborated, as no significant differences were found between P1 and P4 for all the tested indicators.

For the reservoir stretch (P2), the differences in diversity can be explained by the alterations of the physical habitat caused by the dam itself, namely in the form of granulometry (Chester and Norris, 2006; Kloehn et al., 2008; Van Looy et al., 2014). These changes away from the natural physical environment of the Pandeiros river may be the cause of shifts in the benthic macroinvertebrate assemblages taxonomic composition, which may explain the lower diversity of its benthic macroinvertebrate assemblages. For the downstream stretch next to the dam (P3), the presence of rock outcroppings provide hard substrate for the benthic macroinvertebrate assemblages, which may explain the observed higher diversity. This allowed the establishment of taxa that otherwise would be rarer or not present under in the Pandeiros river, which is largely characterized sandy bottoms (Fonseca et al., 2008). This, however, cannot be reliably linked to the presence of the dam and may be a natural occurrence of this stretch of the Pandeiros river. While the land use in the margins varied among sites, the influence of anthropogenic activities other than the dam over benthic macroinvertebrate assemblages was probably minor, as there were no significant differences in physical and chemical characteristics, such as nutrient content.

The dominance of invasive species populations is likely another consequence of the physical alterations caused by the dam. Anthropogenically altered habitats, such as impoundments, often support larger populations of invasive species, facilitating their

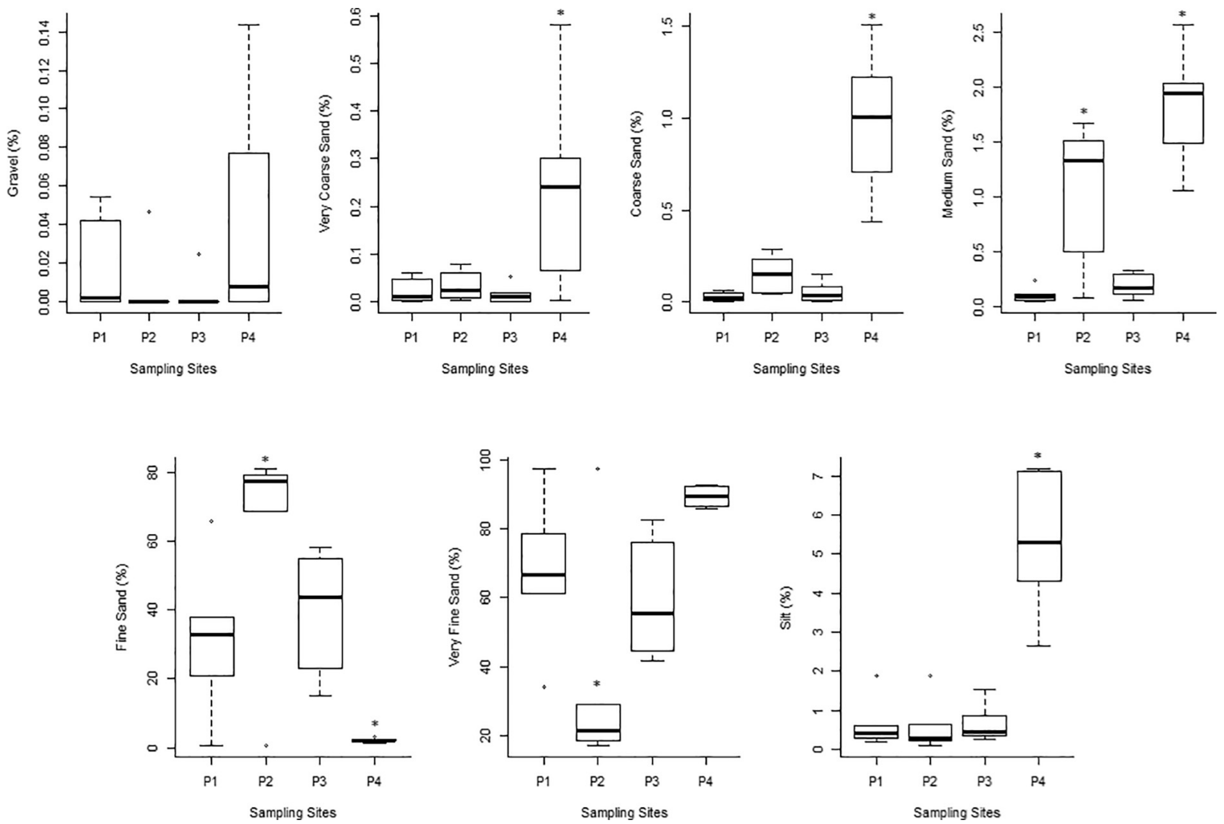

Fig. 3. Granulometry variables for the different sampling sites. "*" mark significantly different values from P1.

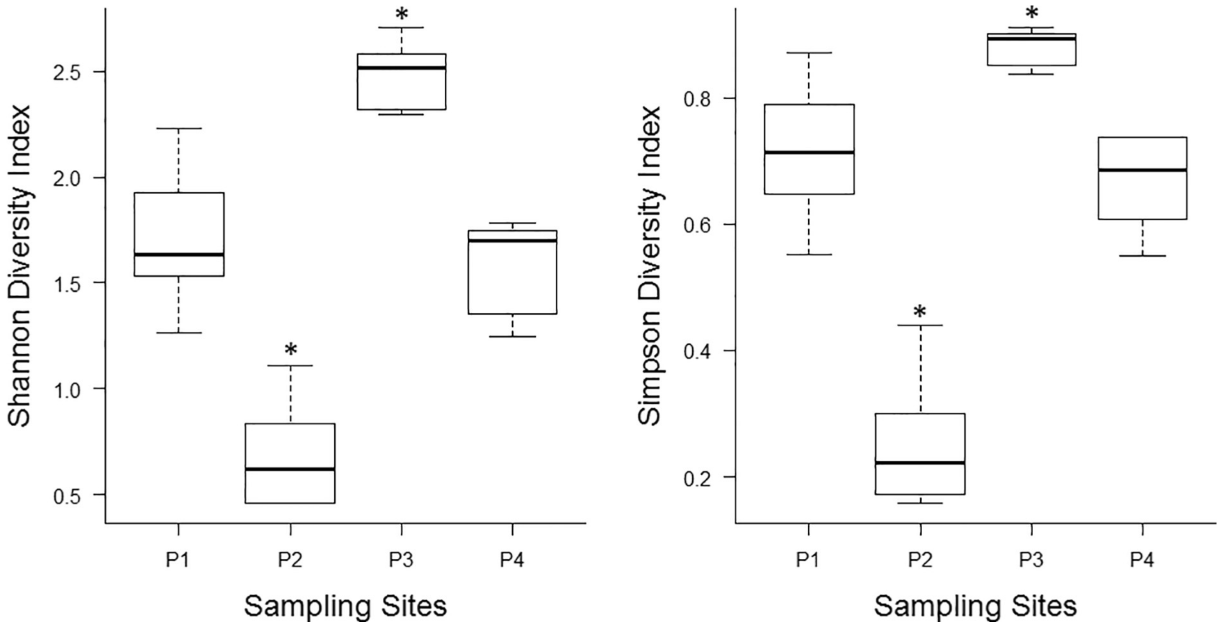

Fig. 4. Shannon-Wienner and Simpson diversity indices for the different sampling sites. "*" mark significantly different values from P1.

introduction and acting as refuges for them (Johnson et al., 2008; Oliveira et al., 2011). This is supported by the observation that while both invasive species are commonly found in large densities throughout the São Francisco basin (Fernandez et al., 2003; Rodrigues et al., 2007), in the Pandeiros river main channel they are only found in large densities in the sites directly affected by the dam.

The fact that eco-exergy and specific eco-exergy exhibited higher values in the dam reservoir suggests that the occurrence of high densities and biomass of *C. fluminea* and *M. tubertulata* without visible negative impacts on the native species, therefore adds to the overall structure of the benthic macroinvertebrate assemblage (Hall et al., 2001; Strayer et al., 1999). This result suggests the opening a new energetic pathway, as the invasive species access resources that were not previously available for the assemblage (Marchi et al., 2010). Similar results were found in reservoirs invaded by two species of invasive bivalves, where in sites dominated by the invasive species showed higher eco-exergy and specific eco-exergy, suggesting that a new energetic pathway was opened for benthic macroinvertebrate assemblages

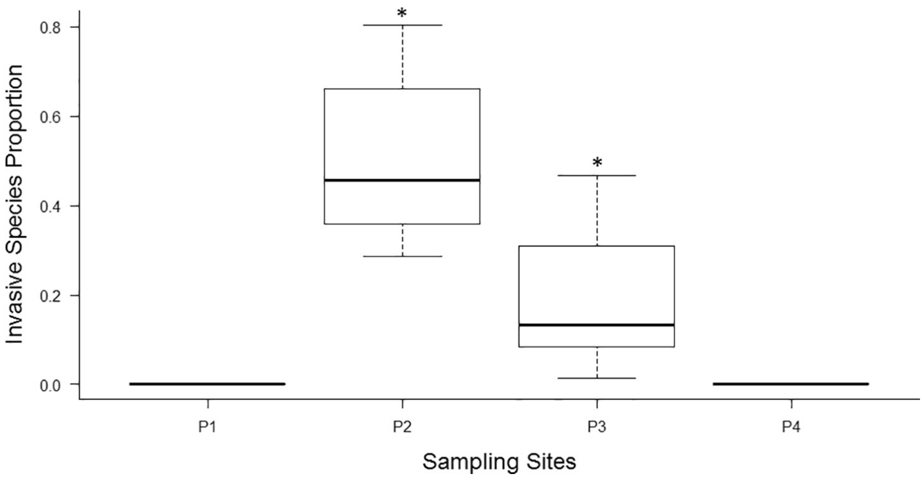

Fig. 5. Proportion of the invasive species biomass for the different habitats. "*" mark significantly different values from P1.

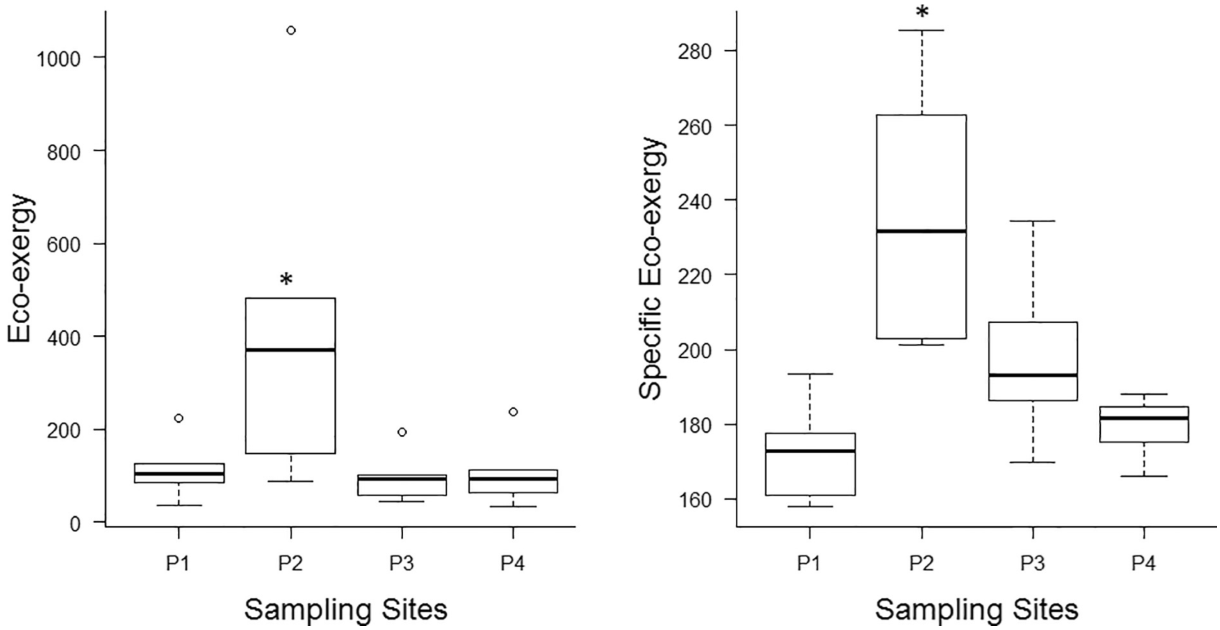

Fig. 6. Eco-exergy and specific eco-exergy for the different habitats. "*" mark significantly different values from P1.

(Linares et al., 2017, 2018).

Our results also suggest that while changes in the physical habitat downstream from the dam allowed taxa that otherwise would be rarer or not present to establish, which was captured by diversity indices, it did not affect too much the benthic assemblage taxonomic structure in terms of its complexity. In general, this suggests that changes occurred did not change the energy flows and the available energy for the benthic macroinvertebrate assemblages, thus not altering the complexity of their dissipative structure (Jørgensen, 2007b; Marchi et al., 2011; Rezende et al., 2008).

5. Conclusions

Ecological impacts occurred essentially in the dam reservoir and in the downstream river stretches next to the dam, but the fact that conditions in the reservoir allowed invasive species to become dominant constitute a risk for other habitats in the Pandeiros river basin. In fact, although the capacity of *Corbicula fluminea* and *Melanoides tuberculata*, invasive species, to establish themselves in non-altered stretches of the Pandeiros river appears to be very limited, reservoirs may be used as stepping stones for these species to spread further in the region (Johnson et al., 2008), and thus our results suggest that a future dam decommissioning is advisable.

Our results also highlight the necessity to understand physical habitat changes caused by the presence and management of run-of-river dams. Deactivated dams in particular are increasingly common and a clear understanding of their impact over benthic macroinvertebrate assemblages is key for future dam removal projects. For further studies, we suggest a greater emphasis on the effects of sediment quality over benthic macroinvertebrate assemblages' structure, namely focusing on the metacommunity and on the dynamics of *C. fluminea* and *M. tuberculata* populations in the Pandeiros river basin.

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