MINIMUM FLOW EFFECTS ON BENTHIC MACROINVERTEBRATES AS BIOINDICATORS DOWNSTREAM OF HYDROELECTRIC DAMS

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Dams pose serious threats to freshwater biota and water quality due to their negative effects on natural river flow, fluvial habitats, and the maintenance, growth, and reproduction of many aquatic species. Economic development in Brazil continues to further the construction of new dams despite their negative ecological consequences. The objective of this study was to assess the ecological effects of reduced flow downstream of hydroelectric dams in Brazil in two contexts: (i) reduced flow reach and (ii) flow manipulation experiments. Data collection occurred (a) downstream of the Amador Aguiar Power Plant I both before (lotic phase) and after (semi-lentic phase) the mean flow of the Araguari river was reduced from 346 to 7 $m^3{\cdot}s$-1; and (b) during discharge manipulations over seasonal (rainy-dry) and daily (periods) time scales, downstream of the Itutinga dam on the Grande River, southeast Brazil. The results show that the reduced flow leads to increases in invertebrate densities within a year and alter taxonomic composition despite considerable overlap in community composition between the lotic and semi-lentic phases. Pollution-tolerant macroinvertebrate groups dominated benthic communities, indicating human disturbance; in addition, alien bivalve species are abundant. The discharge flow experiments resulted in significant changes in water quality (e.g., temperature, turbidity, oxygen, and alkalinity) between the rainy and dry seasons, in daily flow (e.g., turbidity), and in the composition of benthic communities. We discuss the often competing demands of environmental and operation management and energy demands, relevant to human socio-economic development and the need for freshwater wildlife conservation.

1 INTRODUCTION

Reservoirs act as barriers, fragmenting rivers and causing substantial changes in the composition and abundance of aquatic communities. Shifts from lotic to lentic ecosystems arise due to changes in water flow and habitat availability (Molozzi *et al*. [6]).

Over 600 dams have been constructed in Brazil and are used primarily for hydropower, enhancing social and economic development. The construction of reservoirs is one of the oldest forms of human intervention in aquatic ecosystems. Reservoirs cause a series of changes in aquatic ecosystems, including changes to the natural hydrologic regime, water temperature and sediment transport. These changes in the physical environment can subsequently affect abiotic features that are important to aquatic organisms such as benthic macroinvertebrates.

Hydroelectric power plants control the amount of water released downstream, and changes in flow rate occur daily. These variations can disturb aquatic ecosystems by rapidly altering river depth, speed and water quality. Furthermore, the velocity of the current can modify the composition of the substrate, resulting in a more homogeneous substrate downstream. This reduction of substrate heterogeneity reduces the diversity of available habitats for macroinvertebrates; as a result, macroinvertebrate abundance and diversity decline. Benthic macroinvertebrates are one of the aquatic communities most strongly affected by reduced flow rates. Constant low flow rate affects benthic communities by altering sediment texture, temperature, and amounts of dissolved oxygen. Many species show changes in growth and foraging behavior. Such changes are most apparent in taxa with morphological adaptations for coping with high velocity flow, such as mayflies and caddisflies.

Reduced flow accentuates predation and competition by altering current velocity and by limiting species distribution to within residual pools. Preys are forced to escape through drift to avoid the increased densities of predators. The entry of invertebrates in the water column can be active or passive and arise via several factors, including (1) changes in flow and water velocity, (2) the presence of benthic predators, (3) changes in the physical and chemical characteristics of the water, and (4) the redistribution of invertebrate populations in response to competitive pressures. Differences in drift densities may also vary within species, and drift probabilities can vary depending upon life cycle stage or emergence time. Macroinvertebrate drift is important to aquatic ecosystem function because it strongly influences the redistribution and colonization of aquatic macroinvertebrates and is a prominent resource for predators in the water column, such as fish.

Flow changes downstream of reservoirs present major challenges for the conservation and management of freshwater ecosystems. In particular, variation in discharge greatly impacts biological communities downstream, as the magnitude, frequency, duration and predictability of water flow, which regulates ecological processes, are drastically altered. The region of river downstream of a dam is subject to daily and seasonal variation in flow as plant operation and logistics vary annual water storage. Thus, these changes affect aquatic biodiversity and biotic integrity downstream.

The growing need to reconcile economic development with environmental conservation motivates the study of ecological or environmental flow; i.e., the quantity, quality and pattern of flow needed to sustain aquatic ecosystems and their biodiversity and to maintain ecological services upon which human society depends.

The objective of this study is to assess the ecological effects of flow reduction downstream of hydroelectric dams in Brazil with respect to: (i) a reduced flow reach and (ii) flow manipulation experiments.

2 MATERIALS AND METHODS

A reduced flow reach

The study was carried out in a reach of the Araguari River located downstream of the Amador Aguiar I Reservoir, between 18 ˚ 48 ´ S and 48 ˚ 9 ’ W and 20 ˚ 10 ´ S and 48 ˚ 50 ´ W. This 9 km long reach is 90 m wide and drains areas of sandstone and basalt; the valley bottom is comprised of weathered granite and gneiss. The average annual rainfall is 1555 mm year^{-1}. The rainy season extends from October to March and the dry season from May to September. The mean annual temperature is 22 ˚C. Pasture is the dominant vegetation around the reduced flow reach.

Six sites were random sampled along the flow reach. It was considered two stages: the first (lotic phase) was characterized by natural reach conditions, with well-developed riffles and pools free from the reservoir influences. The second stage (semi-lentic phase) occurred after dam construction when the mean flow of the downstream reach was reduced from 346 to 7 m^3.s^{-1}. To reestablish the water level, five small dams (spillways) were built in the reduced flow reach. The six sites were visited 4 times: once during the lotic phase in both June and October 2005 and once during the semi-lentic phase in both June and December 2008.

Flow manipulation experiments

This study was conducted 5 km downstream from the Itutinga Reservoir in the high Grande River basin (21° 16 ' S and 44 ° 39 ' W). The region of the river where samples were collected has an average width of 150 m, and cerrado vegetation is prevalent in the surrounding areas. The average annual temperature varies between 19 and 21 °C. The climate is classified as semi-humid, with 4-5 months of drought and 1200 to 1500 mm of rainfall per year.

Hydraulic experiments

For hydraulic experiments involving the manipulation of the flow released by the plant, we conducted four different sampling periods in both the rainy and dry seasons in 2010: rainfall with fixed flow (380 m .s^{-1}), rainfall with fluctuating flow (380 - 430 m .s^{-1}), drought with fixed flow (100 m .s^{-1}), and drought with fluctuating flow (100 - 180 m .s^{-1}).

Physical and chemical variables in the water column

During sampling, physical and chemical characteristics of the water were measured daily. Water temperature, electrical conductivity, pH and turbidity were measured in the field using a YSI 6600 multiparameter probe. Concentrations of total phosphorus, total nitrogen and dissolved oxygen were measured in the laboratory.

After transforming the data (Kosmolgorov-Smirrnov), we performed a T-test to test for differences between the rainy and dry seasons and between hydraulic moments (i.e., fixed discharge and daily fluctuation discharge).

Benthic macroinvertebrate sampling

Sediment samples were collected with a van Veen (0.045 m^2) and Petersen (0.038 m^2) dredges according to sediment type. Sediment samples were washed through 1.0 and 0.5 mm sieves, and all remaining organisms were identified according to the literature. Abundance data were log transformed (Log x + 1) and analyzed via nMDS with Bray-Curtis. We then used an ANOSIM based on a Bray-Curtis to evaluate differences between macroinvertebrate groups. A PERMANOVA with Bray-Curtis was used to evaluate differences in the community structure. All analyses were performed using Primer 6 software.

Drift samples were collected using three nets (40 x 40 cm opening; mesh size 250 µm) that were partially submerged (by 60%) into the water column approximately 50 cm deep and positioned at locations with constant water flow. The nets were fixed to the substrate with steel bars and remained there 24 h per day, with samples collected every 8 hours (at 7:00, 15:00, and 23:00 hrs).

3 RESULTS AND DISCUSSION

A reduced flow reach

The spillways and Amador Aguiar I Dam operations may have resulted in lower electric conductivity, decreased turbidity, reduced nutrient levels, and increased water temperature; conversely, the high levels of precipitation in 2008 should have had opposite effects (Maroneze *et al*. [3]). The reservoir falls formed by the Amador Aguiar I Dam, together with the upstream Nova Ponte and Miranda reservoirs, have likely incorporated most of the collected phosphorus and nitrogen, resulting in higher quality water downstream. Similar patterns were observed for the Tietê River (Barbosa *et al*. [1]), Paraná River (Roberto *et al*. [9]) but not the lower São Francisco River (Callisto *et al*. [2]).

Aquatic fauna often rely on particular habitat characteristics and flow regime conditions that are independent of water quality (Maroneze *et al*. [3]). Taxonomic diversity often declines in benthic macroinvertebrate communities in reaches with reduced flow (Maroneze *et al*. [3, 4, 5]). Decreases in water volume result in habitat loss and decreases in the quantity and quality of food, sometimes leading to species loss. In the area of the Araguari River, the benthic community was previously dominated by generalist groups (e.g., Chironomidae, Ceratopogonidae and Oligochaeta) tolerant to human disturbance (Morais *et al*. [8]). Although many species of macroinvertebrates are sensitive to limited flow, some generalist species are less affected by flow alterations and can thrive in environments with variable hydraulic conditions. The presence of alien mollusks *Corbicula fluminea* and *Melanoides tuberculatus* during the lotic phase suggests that the local benthic macroinvertebrate communities had already been altered prior to flow reduction and spillway construction (Maroneze *et al*. [3, 4]). In undammed rivers, flood and drought events often act as selective forces, eliminating alien invaders not adapted to such conditions. Therefore, by reducing peak flows, increasing low flows and creating semi-lentic reservoirs, dams may facilitate bioinvasion. Significant changes in the taxonomic composition and total density of macroinvertebrates were detected after flow reduction and spillway construction. Since the early 1990s, the Araguari River basin has undergone dam construction and the replacement of native vegetation by pasture and crops, leading to altered biological communities and altered ecosystem functions (Maroneze *et al*. [3, 4, 5]).

Flow manipulation experiments

Physical and chemical variables in the water column

Seasonality: Significant differences between the wet and dry seasons were observed for most of the abiotic parameters measured (Table 1).

Seasonality: Wet season vs. dry season

The taxonomic composition of benthic communities differed significantly by season, (ANOSIM, $R = 0.319$, $p < 0.001$) but with some similarities. Benthic community structure differed significantly by season (PERMANOVA One-way, $F = 12.277$, $p = 0.0001$).

Wet season

Sampling during the wet season identified benthic communities of different taxonomic compositions between fixed discharge and daily fluctuations (ANOSIM, $R = 0.307$, $p < 0.001$). Community structure differed between the two hydraulic conditions (PERMANOVA One-way, (Pseudo F) = 0.913, $p = 0.4548$).

Table 1: T-test of differences in abiotic parameters measured downstream of the Itutinga Reservoir (Grande River, Minas Gerais State, Brazil) between: (A) wet and dry seasons in 2010, (B) fixed discharge and daily fluctuations during the wet season in 2010, and (C) fixed discharge and daily fluctuations during the dry season in 2010. Significance levels: (*) $p < 0.05$; (**) $p < 0.01$; (***) $p < 0.001$.

Abiotic parameters	wet x dry seasons			*Fixed flow x daily fluctuations (wet)*			*Fixed flow x daily fluctuations (dry)*		
	df	t	P	Df	t	p	df	t	p
Air temperature (ºC)	10	3.118	0.011**	9	1.985	0.078	10	-1.101	0.297
Water temperature (ºC)	10	79.048	0.000***	10	1.793	0.103	10	-0.564	0.585
pH	10	-1.075	0.308	10	0.844	0.419	10	0.175	0.865
Conductivity (µS/cm)	10	-1.745	0.112	10	1.14	0.281	10	-1.643	0.131
TDS (µg/L)	10	-1.464	0.174	10	1.574	0.147	10	-0.237	0.817
Turbidity (NTU)	10	17.762	0.000***	10	-2.765	0.020*	10	0.138	0.893
Redox water (mV)	10	-0.067	0.948	10	2.237	0.049*	10	1.192	0.261
Redox sediment (mV)	10	-11.451	0.000***	10	-4.922	0.001	10	-4.592	0.001***
Oxygen (mg/L)	10	-8.327	0.000***	10	0.837	0.422	10	2.015	0.072
Total Nitrogen (mg/L)	10	4.152	0.002***	10	-0.128	0.901	10	0	1
Total Phosphorus (mg/L)	10	2.408	0.037*	10	2.372	0.039*	10	-0.804	0.44
Oxygen (% saturation)	10	-1.659	0.128	10	0.837	0.422	10	2.015	0.072
Total Alcalinity (µEq/L CO_2)	10	-7.697	0.000***	10	-0.07	0.945	10	0.509	0.622
Total CO_2 (umol/L)	10	-7.014	0.000***	-	-	-	10	0.554	0.592

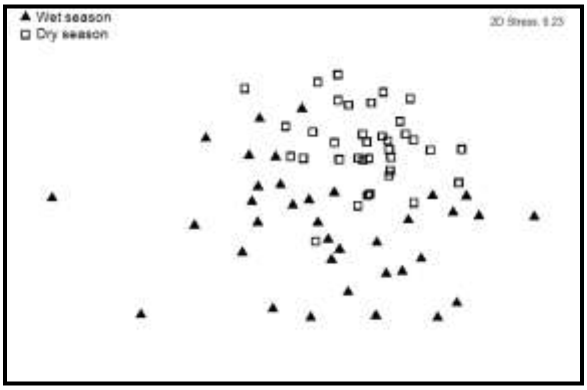

Figure 1. NMDS results of the analysis of taxonomic composition of macroinvertebrates in sediment in the wet and dry seasons of 2010, downstream of the Itutinga Reservoir (Grande River, Minas Gerais State, Brazil).

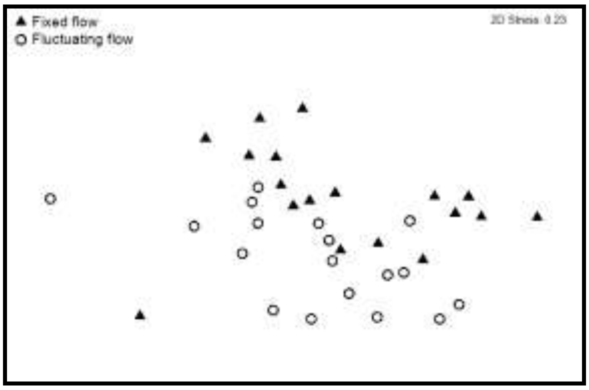

Figure 2. NMDS results of the analysis of taxonomic composition of benthic macroinvertebrates between periods of fixed (triangles) and fluctuating flow (circles) in the rainy season of 2010, downstream of the Itutinga Reservoir (Grande River, Minas Gerais State, Brazil).

Dry season

Sampling during the dry season identified benthic communities did not differed taxonomic compositions between fixed discharge and daily fluctuations (ANOSIM, $R = 0.135$, $p < 0.01$). Community structure differed between the two hydraulic conditions (PERMANOVA One-way, $F = 2.190$, $p = 0.0602$).

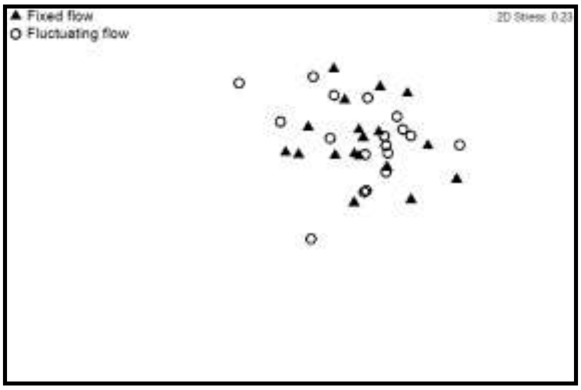

Figure 3. NMDS results of the analysis of taxonomic composition of macroinvertebrates in the drift between periods of fixed (triangles) and fluctuating flow (circles) in the dry season of 2010, downstream of the Itutinga Reservoir (Grande River, Minas Gerais State, Brazil).

Influence of flow change on invertebrate drift

There were significant differences in the taxonomic composition of invertebrates in the drift during the rainy season between samples collected during periods of fixed flow and during periods of fluctuating flow, as evidenced by NMDS and similarity analysis (ANOSIM, $R = 0.406$, $p < 0.001$) (Figure 2a). The most abundant families collected in the rainy season during periods of fixed flow were Simuliidae (30.1 %), Chaoboridae (23.5 %), Hydropsychidae (21.5 %), Chironomidae (9.9 %), Leptohyphidae (46.0 %), Polycentropodidae (2.5 %), Hydroptilidae (1.8 %) and Leptophlebiidae (1.7 %), whereas the most abundant families collected in periods with daily fluctuations were Hydropsychidae (38.2 %) Chaoboridae (26.5 %), Chironomidae (12.1 %), Simuliidae (5.9 %), Polycentropodidae (3.9 %), Leptohyphidae (3.8 %), Leptophlebiidae (3.6 %) and Hydroptilidae (2.3 %) (Figure 3).

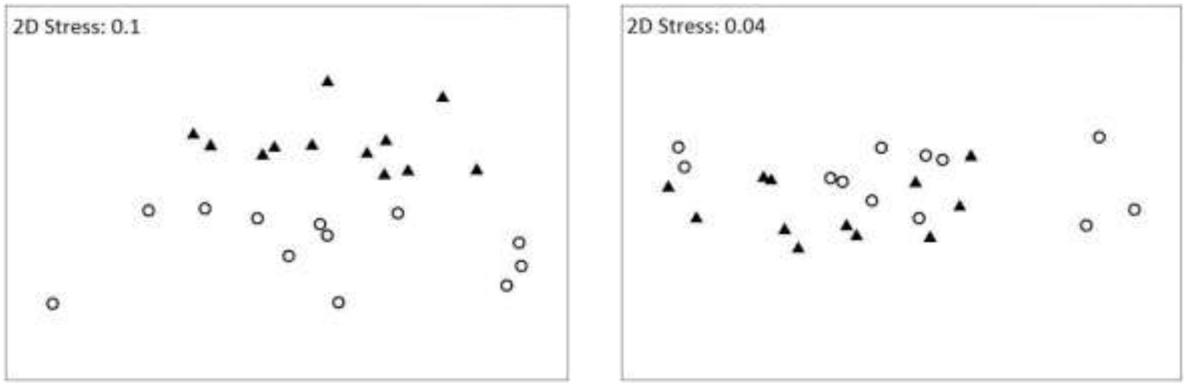

Figure 4: NMDS results of the analysis of taxonomic composition of macroinvertebrates in the drift between periods of fixed (triangles) and fluctuating flow (circles) in the rainy season (A) and dry season (B) in 2010 downstream of the Itutinga Reservoir (Grande River, Minas Gerais State, Brazil).

During the dry season, significant differences were also observed in taxonomic composition of drift invertebrates between the samples collected during periods of fixed flow and those collected during fluctuating flow (ANOSIM, $R = 0.257$, $p = 0.035$) (Figure 2b). The most abundant family in the samples collected in dry season with fixed flow was Simuliidae (92.2 %), followed by Chironomidae (2.3 %), Leptophlebiidae (1.4 %), Chaoboridae (1.1 %) and Hydropsychidae (1.0 %). For the period with daily fluctuations, the most abundant taxa sampled were Simuliidae (86.4 %), chironomids (4.0 %), Chaoboridae (2.7 %), Leptophlebiidae (2.1 %) and Leptohyphidae (1.3 %) (Figure 3). The largest differences in taxonomic composition occurred among the least abundant groups; for example, Gyrinidae and Caenidaewere collected only during the period with fixed flow, whereas Gomphidae and Psychodidae were only collected during the period with fluctuating flow.

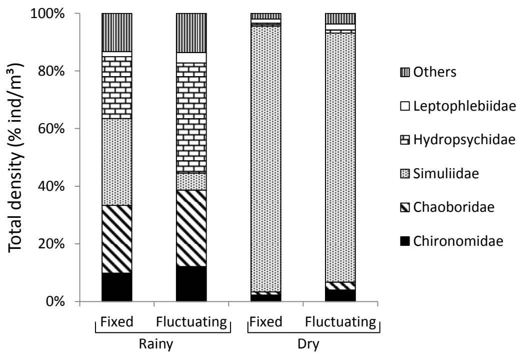

Figure 5: Major taxonomic groups within invertebrate drift (%) sampled in periods of fixed and fluctuating flow in the rainy (January/2010) and dry season (July/2010) downstream of the Itutinga Reservoir (Grande River, Minas Gerais State, Brazil).

In the rainy season, invertebrate composition in the drift differed in total density (2-way ANOVA, $F_{2,18} = 5.5674$, $p = 0.013$) between the periods of fixed and fluctuating flow, primarily in samples collected between 23:00 and 7:00 hrs. Thirty-eight different taxa were identified in samples from the period of fixed flow (4,110 organisms identified), and 35 taxa were identified from the fluctuating flow period (4,762 organisms identified). Rarefied richness during the rainy season did not differ significantly between periods (fixed flow mean ± SD: 21.8 ± 3.3; fluctuating flow mean ± SD: 18.1 ± 1.8).

In the dry season, there were no significant differences in the total density of invertebrates between the periods of fixed and fluctuating flow. Twenty-seven taxa were observed in the period of fixed flow (14,643 organisms identified) and 28 taxa in the fluctuating flow period (8,409 organisms identified). Rarefied richness did not differ significantly between periods (fixed flow mean ± SD: 14.9 ± 2.7; fluctuating flow mean ± SD: 14.5 ± 1.2).

Daily drift variation

In the rainy season during fixed flow, invertebrate density and richness did not differ by sampling time; however, during fluctuating flow, density (one-way ANOVA, $F_{2,9} = 15.670$, $p = 0.001$) and richness ($F_{2,9} = 10.311$, $p = 0.005$) differed significantly between samples collected from 23 to 7 hrs and those collected at other times (7:00 to 15:00 hrs and 15:00 to 23:00 hrs).

In the dry season during fixed flow, significant differences were observed among sampling times for both richness (one-way ANOVA, $F_{2,9} = 5.257$, $p = 0.030$) and density ($F_{2,9} = 14.670$, $p = 0.001$). Density was higher in samples taken from 23:00 and 7:00 hrs and from 15:00 to 23:00 hrs, and richness was greater in samples from 23:00 to 7:00 hrs. In the dry season during fluctuating flow, richness ($F_{2,9} = 5.6264$, $p = 0.026$) and density ($F_{2,9} = 5.7265$, $p = 0.024$) also varied significantly by sampling time, with higher values found in samples collected from 23:00 to 7:00 hrs and from 15:00 to 23:00 hrs.

Traditionally, the environmental status of reservoirs has been assessed primarily through analysis of physical and chemical parameters and of chlorophyll *a*, as the main priority has been to avoid algae blooms and to maintain water quality at a level satisfactory for domestic and agricultural purposes (Molozzi *et al*. [7]). Recently, additional efforts have been made to develop biological evaluation tools for lakes and reservoirs using assessment of benthic macroinvertebrates.

Although benthic macroinvertebrates are known to be important for the function and dynamics of aquatic ecosystems, the models used to determine environmental flow do account for some measures of aquatic communities (such as density, taxonomic richness and functional trophic groups) that may respond to changes in flow downstream of hydroelectric dams.

The use of hydraulic experiments investigating flow manipulation of hydroelectric plants and the assessment of subsequent impacts on biological communities can be an important tool in determining environmental flow.

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