Influence of peak flow changes on the macroinvertebrate drift downstream of a Brazilian hydroelectric dam

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Received September 13, 2012 - Accepted November 20, 2012 - Distributed November 29, 2013
(With 7 figures)

Abstract

Successive daily peak flows from hydropower plants can disrupt aquatic ecosystems and alter the composition and structure of macroinvertebrates downstream. We evaluated the influence of peak flow changes on macroinvertebrate drift downstream of a hydroelectric plant as a basis for determining ecological flows that might reduce the disturbance of aquatic biota. The aim of this study was to assess the influence of flow fluctuations on the seasonal and daily drift patterns of macroinvertebrates. We collected macroinvertebrates during fixed flow rates (323 $m^3.s^{-1}$ in the wet season and 111 $m^3.s^{-1}$ in the dry season) and when peak flows fluctuated (378 to 481 $m^3.s^{-1}$ in the wet season, and 109 to 173 $m^3.s^{-1}$ in the dry season) in 2010. We collected 31,924 organisms belonging to 46 taxa in the four sampling periods. Taxonomic composition and densities of drifting invertebrates differed between fixed and fluctuating flows, in both wet and dry seasons, but family richness varied insignificantly. We conclude that macroinvertebrate assemblages downstream of dams are influenced by daily peak flow fluctuations. When making environmental flow decisions for dams, it would be wise to consider drifting macroinvertebrates because they reflect ecological changes in downstream biological assemblages.

Keywords: downstream, ecological flow, aquatic insects, community, flood pulse.

Influência de alterações de vazão sobre a deriva de macroinvertebrados a jusante de uma barragem hidrelétrica brasileira

Resumo

Os sucessivos pulsos diários de vazão decorrentes da operação de usinas hidrelétricas podem perturbar os ecossistemas aquáticos e alterar a composição e estrutura de macroinvertebrados a jusante de barramentos. Nós avaliamos a influência de alterações de vazão sobre a deriva de macroinvertebrados a jusante de uma barragem hidrelétrica como subsídio para a determinação de vazões ecológicas que podem reduzir os distúrbios sobre a biota aquática. O objetivo deste estudo foi avaliar a influência das flutuações de vazão sobre os padrões sazonais e diários de deriva de macroinvertebrados. Nós coletamos os macroinvertebrados durante períodos de vazão fixa (323 $m^3.s^{-1}$ na estação de chuvas e 111 $m^3.s^{-1}$ na estação seca) e com flutuações de vazão (378 - 481 $m^3.s^{-1}$ na estação de chuvas e 109 - 173 $m^3.s^{-1}$ na estação seca) no ano de 2010. Foram coletados 31.924 organismos distribuídos em 46 taxa nos quatro períodos amostrais. A composição taxonômica e a densidade de invertebrados a deriva diferiram entre os períodos com vazão fixa e flutuante, tanto na estação de chuvas quanto na seca, mas a riqueza taxonômica não variou significativamente. Em conclusão, as comunidades de macroinvertebrados a jusante de barragens são influenciadas pelas flutuações diárias na vazão. Portanto, os macroinvertebrados a deriva devem ser considerados nos cálculos de vazões ambientais, pois eles claramente refletem as mudanças ecológicas nas comunidades biológicas a jusante de barragens hidrelétricas.

Palavras-chave: jusante, vazão ecológica, insetos aquáticos, comunidade, pulsos de vazão.

1. Introduction

Aquatic ecosystems are essential for the development of human societies, offering goods and services of fundamental importance, such as water supply, flood control, transportation, and power generation (Hay et al., 2008; Arthington et al., 2010). However, rivers have suffered countless influences of human activities, primarily from waste releases, introductions of alien species, construction of barriers, and alteration of flow regimes (Agostinho et al., 2005). Most major rivers in the world are altered by dams and flow regulation (Nilsson et al.,

DOI: 10.1590/S1519-69842013000400013

2005) and the number of rivers impounded for power generation has increased significantly in almost all Brazilian river basins since the 1970s (Agostinho et al., 2007). Dams and reservoirs change natural flow regimes (Agostinho et al., 2008), water quality (Lauters et al., 1996), sediment transport and substrate composition (Petts, 1984), and channel morphology and habitat diversity (Richter et al., 2003). Although dozens more large dams are proposed for Brazil, mainly in Amazonia (Empresa de Pesquisa Energética, 2010), dams are increasingly being removed in the USA because of their serious ecological effects and potential economic liabilities (Hughes, 2012).

The abiotic changes resulting from dams, reservoirs, and flow alterations can change important biotic parameters, including benthic macroinvertebrate (Callisto et al., 2005; Hay et al., 2008) and fish (Rinne et al., 2005; Pompeu et al., 2012) assemblages. The reduction of substrate heterogeneity reduces the diversity of available habitats for macroinvertebrates, decreasing their abundance and diversity (Patterson and Smokorowski, 2011). Natural river discharge fluctuations increase habitat heterogeneity and help maintain community richness and complexity. According to Connell (1978), species diversity is maximized at an intermediate level of disturbance, which can be caused by natural discharge fluctuations. However, flows created by dam operations lack natural seasonal extremes and predictability (Poff et al., 1997), leading to a loss of biodiversity. Thus, flow alterations downstream of reservoirs are a major challenge for the conservation and management of freshwater ecosystems (Acreman and Ferguson, 2010) because they alter natural ecological processes (Poff et al., 1997; Bunn and Arthington, 2002; Agostinho et al., 2007) and biological condition (Agostinho et al., 2007, Poff and Zimmerman, 2010). Growing needs to reconcile economic development with environmental conservation produced the concept of ecological flows, which refer to the flow regimes needed to sustain aquatic ecosystem biodiversity and the ecological services on which human society depends (Poff et al., 2010).

Insects and other invertebrates are transported naturally downstream by the current in a phenomenon known as drift (Brittain and Eikeland, 1988). The entry of invertebrates into the water column can be active or passive, as the result of several factors, including changes in flows and velocity (Poff and Ward, 1991), water quality (Brittain and Eikeland, 1988), predators (Huhta et al., 2000), and competitors (Brittain and Eikeland, 1988). The downstream transport of invertebrates is not constant and varies with season, day, and time of day (Brittain and Eikeland, 1988). Differences in drift densities may also vary by species and life cycle stage (Hansen and Closs, 2007). Macroinvertebrate drift is very important to aquatic ecosystem function, because it is a primary mechanism for the redistribution and colonisation of aquatic macroinvertebrates (Hay et al., 2008) and offers prey for predators such as fish (Flecker, 1992). Invertebrates downstream are affected by constant changes resulting from plant operations and may have different behaviours in the drift (Troelstrup and Hergenrader, 1990). Invertebrate drift can be stimulated by flow reductions (Cushman, 1985; Minshall and Winger, 1968) and increases (Scullion and Sinton, 1983; Lauters et al., 1996). Moreover, daily peak flow changes favour organisms best adapted to such conditions and eliminate those that are poorly adapted (Armitage, 1978).

Unlike temperate regions, invertebrate drift in tropical rivers is still poorly studied. Researchers have addressed the behaviour, dynamics and composition of invertebrate drift in tropical streams (Flecker, 1992; Ramirez and Pringle, 1998; Callisto and Goulart, 2005), but not the influence of flow fluctuations downstream of dams. Current ecological flow models do not consider such measures of aquatic assemblages as density, taxonomic richness, and taxonomic composition, which may respond to altered flows downstream of hydroelectric dams (Bunn and Arthington, 2002). Flow manipulation experiments, and subsequent impact assessments on biological assemblages, offer an important tool to determine ecological flows. Therefore, the objectives of this study were to investigate the seasonal and daily variations in macroinvertebrate drift in response to intentional flow manipulations. We hypothesised that fluctuating flows would (1) alter drift taxonomic composition, and (2) increase drift density and richness in both the rainy and dry seasons.

2. Methods

2.1. Study area

We conducted this study in 2010, 5 km downstream of the Itutinga Hydroelectric Power Plant in a 150 m wide reach of the upper Rio Grande, Minas Gerais, Brazil. The Rio Grande rises in the Serra da Mantiqueira, on the border of the states of Minas Gerais and São Paulo, and flows 1,300 km to the Rio Paranaíba (Figure 1). The river flows through cerrado (savanna) vegetation where average annual temperature is 19-21 °C and the climate is semi-humid, with 4-5 months of drought, a 6 month rainy season, and mean annual rainfall of 1200-1500 mm (Pompeu et al., 2009).

2.2. Hydraulic manipulations

We sampled in four different periods in 2010: wet season with fixed flow (323 $m^3.s^{-1}$), wet season with fluctuating flow (378-481 $m^3.s^{-1}$), dry season with fixed flow (111 $m^3.s^{-1}$), and dry season with fluctuating flow (109-173 $m^3.s^1$). The flows were held by Companhia Energética de Minas Gerais (CEMIG) based at the historical monthly average for the river in the last 20 years before the dam construction (Figure 2). In each sampling period, flows were held constant for 34 consecutive days (323 $m^3.s^{-1}$ for the wet season and 111 $m^3.s^{-1}$ for the dry season). After the constant flow periods, Itutinga hydroelectric plant began daily peak flow fluctuations for four days. The onset of increased flows began at 17:00, and

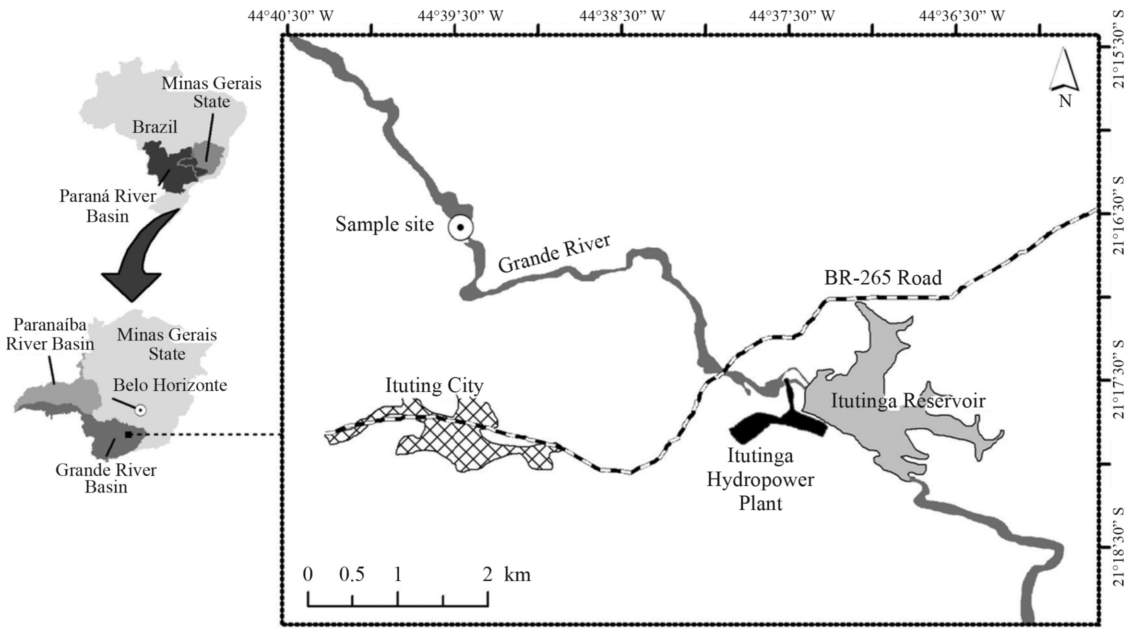

Figure 1 - Study area map and drift sampling location in the Rio Grande downstream of Itutinga Hydroelectric Power Plant, Minas Gerais, Brazil.

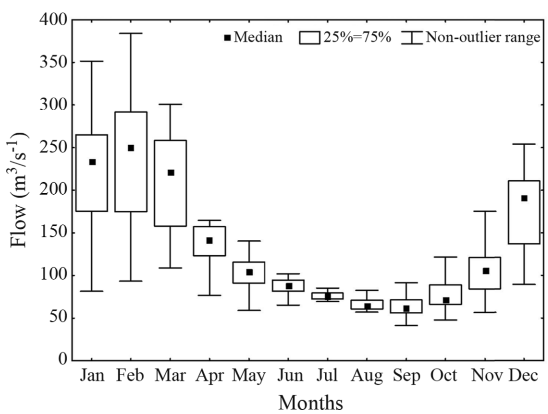

Figure 2 - Amplitude, medians and percentiles of the flows based on the historical monthly average for the river in the last 20 years before the Itutinga Hydroelectric Power Plant construction.

reached a maximum at 18:30. At 21:00, flows began being reduced, returning to the initial flows at 23:00.

2.3. Drift sampling

We sampled drifting invertebrates during the last four days of the constant flow periods and the four days of peaking flows through use of three nets (40 x 40 cm opening; 1 m length, 250 μm mesh) placed in areas with laminar flow. The nets were fixed on the substrate through use of steel bars and remained in place 24 h per day with individual samples removed every 8 hours (23:00-07:00, 07:00-15:00, 15:00-23:00).

The material retained in the nets was removed, washed through a 250 μm sieve, packaged in vials in 70% alcohol, and returned to the laboratory for sorting. We identified aquatic individuals to family through use of Pérez (1988), Merritt and Cummins (1996), and Mugnai et al. (2010). Average current velocity ($m.s^{-1}$) was measured with a Global Flow Probe at each net mouth at the beginnings and ends of the three daily 8 h sampling periods. The filtered volumes (m^3) through each of the three nets were calculated by multiplying the net submerged area by the average water velocity by the sampling time. The densities of organisms in the drift were recorded as the number of invertebrates per 100 m^3 filtered water (Allan and Russek, 1985).

2.4. Water quality

During the four sampling periods, we measured water quality variables daily at the drift nets. Water temperature (°C), electrical conductivity ($\mu S.cm^{-1}$), pH, and turbidity (NTU) were measured through use of a YSI 6600 multiprobe. We determined total phosphorus ($mg.L^{-1}$), total nitrogen ($mg.L^{-1}$), and dissolved oxygen ($mg.L^{-1}$) in the laboratory following standard methods (APHA, 1992).

2.5. Data analyses

Taxonomic richness was estimated as the total number of taxa per sample and by rarefaction curves (Gotelli and Colwell, 2001) to reduce the effect of different densities in the samples. Similarity Analysis (ANOSIM) was performed to test differences in taxonomic composition between periods of fixed and fluctuating flows during wet and dry seasons. We used Non Metric Multidimensional Scaling (NMDS) to plot results from a Bray-Curtis dissimilarity matrix on square root transformed abundance data and from a Jaccard similarity matrix on taxa presence/absence data. Both NMDS and ANOSIM were performed with PRIMER 6.0 + PERMANOVA software (Clarke and Warwick, 2001).

Differences in richness and density were compared between periods of fixed and fluctuating flow by two-way ANOVAs, where the categorical variables were flow (fixed x fluctuating) and sample period start time (07:00, 15:00, 23:00). We used the Tukey *post-hoc* test to identify differences between the factors when tests were significant. We evaluated differences in water quality variables through use of *t*-tests. Data were square root transformed when necessary to meet assumptions of normality (Kolmogorov-Smirnov) and homogeneity of variances (Zar, 1996). We conducted these tests with Statistica 8.0 software.

3. Results

3.1. Water quality

We found no significant water quality differences between fixed and fluctuating flows in the wet season, but there was a significant difference in pH between fixed and fluctuating flows in the dry season ($t = 3.09$, $df = 6$, $p = 0.021$, Table 1).

3.2.Drift composition

We collected 31,924 organisms and 46 taxa; 99% were aquatic insects and 69.8% were Simuliidae. Drifting invertebrates differed significantly in taxonomic composition between periods of fixed and fluctuating flows in the wet season (ANOSIM, $R = 0.41$, $p < 0.001$, Figure 3a). The Simuliidae (30.1%), Chaoboridae (23.5%), and Hydropsychidae (21.5%) were most abundant under fixed flows, whereas the Hydropsychidae (38.2%), Chaoboridae (26.5%), and Chironomidae (12.1%) were the most abundant taxa under fluctuating flows (Figure 4). In the dry season, we also observed significant differences in taxonomic composition of drifting invertebrates collected during periods of fixed and fluctuating flows (ANOSIM, $R = 0.26$, $p = 0.035$, Figure 3b). The Simuliidae were the most abundant taxa during fixed (92.2%) and fluctuating (86.4%) flows (Figure 4). These changes support hypothesis 1 (fluctuating flows alter taxonomic composition of drifting macroinvertebrates).

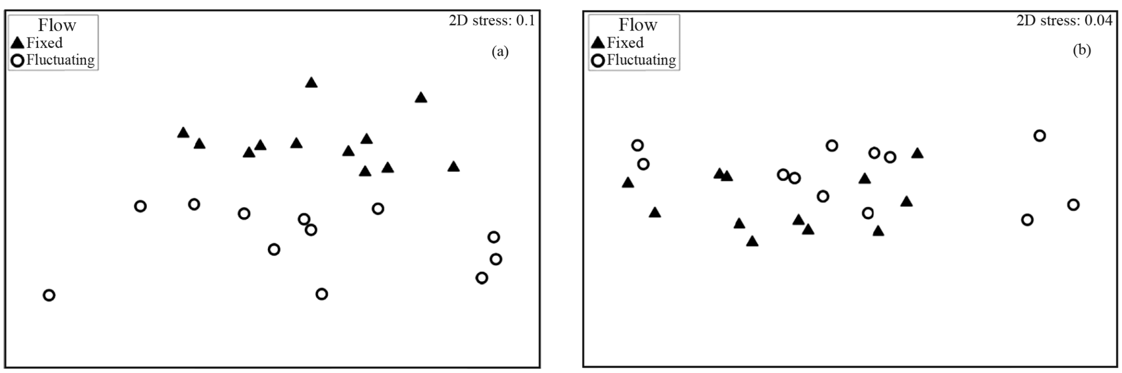

Figure 3 - NMDS of the taxonomic composition based on abundance of drifting macroinvertebrates during fixed (triangles) and fluctuating (circles) flows in the wet (a) and dry (b) seasons.

Table 1 - Water quality (mean ± SD) during the wet (January) and dry (July) seasons. The significant difference in dry season pH is in bold.

	Wet season		Dry season	
	Fixed flow	Fluctuating flow	Fixed flow	Fluctuating flow
Water temperature (°C)	25.10 ± 0.10	25.16 ± 0.09	17.94 ± 0.05	17.99 ± 0.12
pH	7.24 ± 0.30	7.11 ± 0.12	**7.52 ± 0.11**	**7.33 ± 0.06**
Electrical conductivity ($\mu S.cm^{-1}$)	13.25 ± 0.50	13.00 ± 0.82	15.50 ± 1.00	16.00 ± 0.82
Turbidity (NTU)	51.68 ± 6.31	57.23 ± 7.49	2.01 ± 0.14	1.95 ± 0.11
Dissolved oxygen ($mg.L^{-1}$)	7.73 ± 0.26	7.30 ± 0.82	8.90 ± 0.14	8.83 ± 0.15
Total Nitrogen ($mg.L^{-1}$)	0.07 ± 0.01	0.07 ± 0.02	0.05 ± 0.01	0.05 ± 0.01
Total Phosphorus ($mg.L^{-1}$)	0.06 ± 0.02	0.06 ± 0.04	0.03 ± 0.00	0.03 ± 0.00

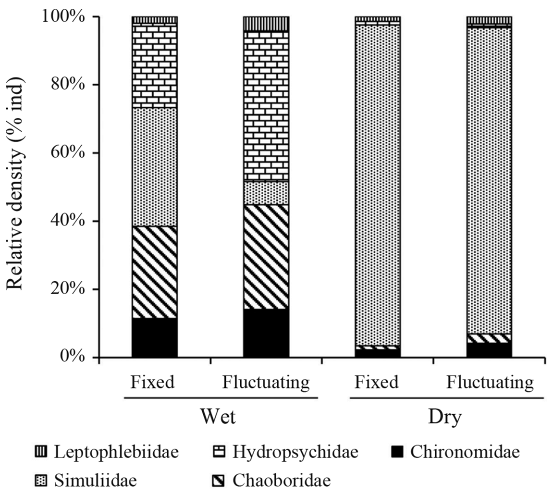

Figure 4 - Relative density of major drifting macroinvertebrate families during fixed and fluctuating flows in the wet (January/2010) and dry (July/2010) seasons.

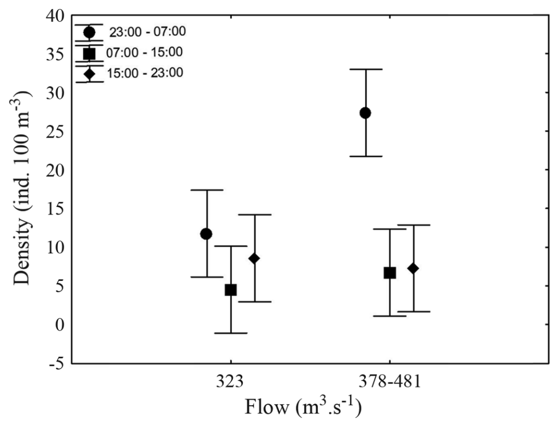

Figure 5 - Density differences of drifting macroinvertebrates comparing fixed and fluctuating flows in the wet season (January/2010).

Total invertebrate drift densities were significantly higher for fluctuating flows in the wet season (2-way ANOVA, $F_{2,18} = 5.567$, $p = 0.013$, Figure 5), but significantly lower in the dry season (Figure 6a). Taxonomic richness (Figure 6b) did not differ significantly between fixed (38 raw taxa, 21.8 ± 3.3 rarefied) and fluctuating (35 raw, 18.1 ± 1.8 rarefied) flows in the wet season, or in the dry season, fixed (27 raw taxa, 14.9 ± 2.7 rarefied) and fluctuating (28 raw, 14.5 ± 1.2 rarefied) flows. Thus hypothesis 2 (fluctuating flows increase drift density and richness) was rejected.

4. Discussion

We observed no significant changes in water quality as a result of Itutinga Hydroelectric Power Plant operations, except for dry season pH (Table 1), unlike Naliato et al. (2009). Likely this is because Itutinga's Plant has a small reservoir (7 hm^3 useful volume), whereas large deep reservoirs exhibit thermal and chemical stratification (Straskraba, 1999), which results in water quality differences when waters from different layers are released.

We observed no significant changes in family richness between fixed and fluctuating flows, unlike what Patterson and Smokorowski (2011) suggested; however had we been able to identify taxa to genus or species, detection of richness differences may have been more likely.

Flow fluctuations increased drift densities in the rainy season, but decreased drift densities in the dry season (Figure 6a). Others have also documented positive correlations between increased flows and invertebrate drift density (Pearson and Franklin, 1968; Bird and Hynes, 1981; Scullion and Sinton, 1983). Irvine (1985) reported that invertebrate drift densities increased with flow pulses regardless of the stability of previous flows. Maintaining constant flow allows a greater stability of habitats, and consequently, the associated biological communities (Armitage, 1978). On the other hand, changes in flow may cause disturbances in the system, al-

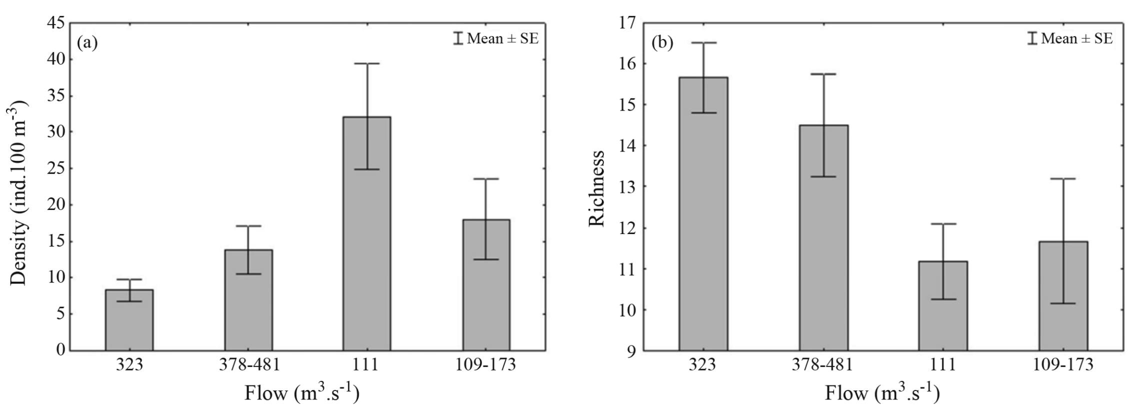

Figure 6 - Density (a) and richness (b) (mean ± SE) for drifting invertebrates during fixed and fluctuating flows in the wet and dry seasons.

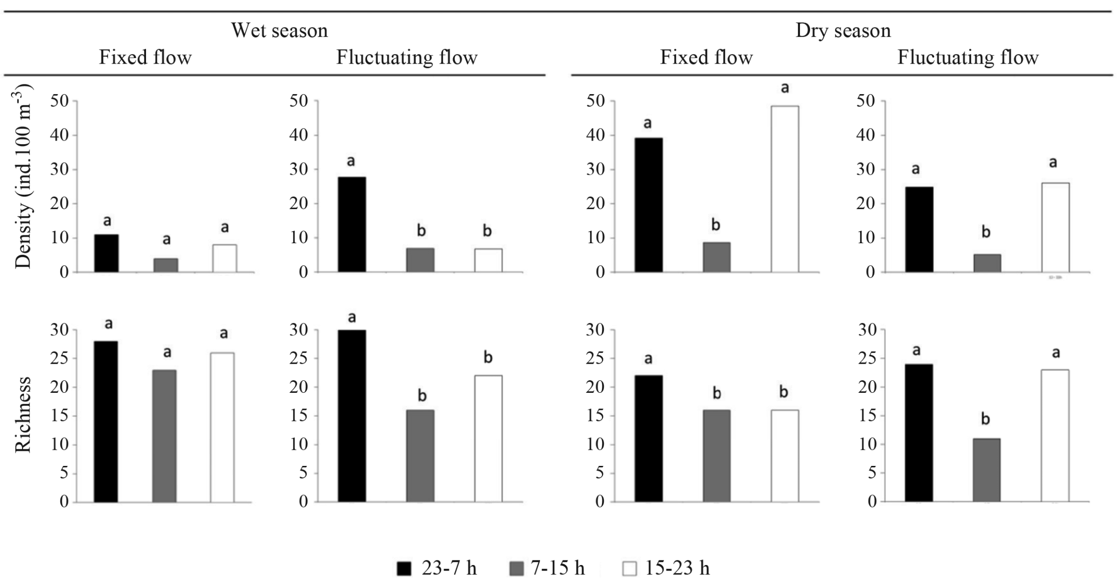

Figure 7 - Density and richness values between different sampling times for drifting invertebrates during fixed and fluctuating flows in the wet and dry seasons. The letters "a" and "b" indicate significant differences between sample times.

lowing the coexistence of settlers and more competitive species, increasing the richness (Connell, 1978).

We also observed changes in invertebrate drift composition associated with flow fluctuations in both rainy and dry seasons (Figures 3 and 4). Increased Hydropsychidae density with increased flow fluctuations in the wet season confirms the results of Elliott (1968), Troelstrup and Hergenrader (1990), and Boon (1993). Unlike Hydropsychidae, Simuliidae densities were reduced with increased flow fluctuations in the wet and dry seasons. Chance and Craig (1986) also reported that Simuliidae larvae had a lower risk of being displaced by moderate flow changes because of their hydrodynamic and morphological adaptations to cling to the substrate, which is much less true for Hydropsychidae. Chironomidae drift densities increased with increased flow fluctuations in both wet and dry seasons, corroborating the results of Irvine and Henriques (1984) but differing from the results of Gislason (1985) and Troelstrup and Hergenrader (1990).

Numerous studies have shown that drift increases at night, especially just after sunset (Poff and Ward, 1991; Ramírez and Pringle, 1998; Hansen and Closs, 2007). However in the wet season with fixed flows, we observed no differences in drift between differing sampling periods (Figure 7). Lauters et al. (1996) observed that repeated hydroelectric plant peak flows reduced nocturnal activity. Perhaps our 30-days flow stabilisation period was insufficient for invertebrate assemblages to display daily periodicity to enter the drift. On the other hand, wet season fluctuating and fixed flows and dry season fluctuating flows were associated with higher density and richness in samples taken from 23:00 - 07:00.

Because of economic and funding limits to experimentally manipulate flows, we could not study multiple power plants and unregulated river reaches. The opportunity to manipulate the flow downstream of a hydroelectric plant, a pioneer in a neotropical environment, allowed evaluating the influence of daily flow fluctuations on macroinvertebrate assemblages. However, more extensive comparative studies are needed to increase understanding of the effects of flow changes on aquatic macroinvertebrate assemblages, to establish reasonable environmental flows, and to reduce the downstream and upstream effects of dams.

Thus, the observed changes in the structure and composition of drift macroinvertebrates reflect the impact of flow fluctuations on benthic macroinvertebrate assemblages. Such changes may in turn alter nutrient processing and the food resources of fish and waterfowl. The use of drift nets and deliberate flow manipulations by dams offer useful approaches for developing environmental flows, but require long-term research both upriver and downriver of more hydroelectric power plants.

Acknowledgments

We received funding and support for this research from a P&D Project by ANEEL/Companhia Energética de Minas Gerais (CEMIG) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). Juliana França and Ana Paula Eller were responsible for water quality analyses. Colleagues from the Laboratório de Ecologia de Bentos (UFMG), especially Taynan Tupinambás, assisted with field collections. Discussions held during the Workshop on Ecological Assessment: the Foundation for Evaluating Biological Patterns (3-7 October 2011, US EPA Western Ecology Division, Corvallis, OR, USA) added further insights for this study. One anonymous referee and the editor made detailed suggestions to improve the manuscript.

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