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ARTICLE

Environmental conditions in river segments intercepted by culverts

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ABSTRACT: (Environmental conditions in river segments intercepted by culverts). The conservation and maintenance of the quality of the rheophilic environment are directly related to knowledge of the physical and chemical characteristics and structural patterns of these systems, especially in streams. Long stretches of small water bodies are highly altered by the construction of highways and roads, which tend to modify their natural characteristics, affecting the environmental quality. This study describes vegetation and morphogeometric parameters of streams with culverts along their courses, reporting spatial differences in environmental characteristics (vegetation, morphogeometric, physical, and chemical) between sampling points upstream and downstream of the culvert. Specifically, we evaluated the width, depth, riparian vegetation, substrate background, and physical and chemical properties of the water, to identify possible differences between the sections above and below (upstream and downstream) of the culvert. The rapid assessment protocol (RAP) was applied to stretches of 200 meters upstream and downstream of culverts in two Neotropical streams, between the months of November 2009 and October 2010. The vegetation and morphogeometric attributes differed between the portions upstream and downstream of the culverts, the latter because of the impoundment effect of these structures. The upstream section becomes flooded, is often shallow, and directly influences the movement of sediment. The physical and chemical variables of the water showed no spatial variation.

Key words: Riparian vegetation, environmental quality, structural attributes, Neotropical streams.

RESUMO: (Condições ambientais de segmentos fluviais interceptados por bueiros). A conservação e a manutenção da qualidade ambiental do ambiente reofílico está diretamente relacionada ao conhecimento de características físicas e químicas e dos padrões estruturais destes sistemas, especialmente em riachos. Longos trechos de pequenos corpos aquáticos são altamente alterados pela construção de rodovias e estradas e tende a modificar as suas características naturais, interferindo na qualidade ambiental. Neste sentido, o objetivo deste estudo foi descrever parâmetros fito-morfogeométricos de riachos com bueiros em seu curso longitudinal, reportando diferenças espaciais nas características ambientais (fito-morfogeométricos e físico-químicas) entre os pontos amostrados (montante e jusante do bueiro). Especificamente, avaliamos a largura, a profundidade, vegetação ripária, substrato de fundo e atributos físicos e químicos da água, verificando as possíveis divergências entre os trechos de acima e abaixo (montante e jusante) do bueiro. Para isso, o protocolo de avaliação rápida (PAR) foi aplicado em trechos de 200 metros a montante, bem como a jusante de bueiros em dois riachos neotropicais entre os meses de novembro de 2009 e outubro de 2010. Verificou-se que os atributos fito-morfogeométricos diferem entre os trechos de montante e jusante, pois o bueiro tem efeito de represamento. Esse fato transforma o trecho a montante em ambiente alagado, muitas vezes rasos e influenciando diretamente o movimento de sedimentos. As variáveis físicas e químicas da água não apresentaram variação espacial.

Palavras-chave: Vegetação ripária, qualidade ambiental, atributos estruturais, riachos neotropicais.

INTRODUCTION

Streams are small-sized, linear lotic environments with continuous unidirectional water flow, alternating habitats, and unstable riverbeds (Uieda & Castro 1999). Watercourses are also tridimensional systems (Petts & Amoros 1996), comprising transverse (width, riparian vegetation and flooding area), vertical (depth and groundwater), and longitudinal dimensions (headwater to mouth) (Ward 1989). These characteristics create hydrological, geomorphological, and hydraulic gradients, forming a complex structure of mutually dependent habitats and ecological niches (Vannote *et al.* 1980), which provide ideal and stable conditions for the survival, growth, and reproduction of organisms.

Hence, streams are first considered as longitudinally connected systems, where the zonation of aquatic organisms follows a structural and functional organization related to the longitudinal geomorphological profile. However, on the longitudinal gradient, different and sequential habitats are evident. This habitat differentiation is known as environmental heterogeneity (Metzger 2001) and is related to the different distributions of abiotic and biotic factors from headwater to mouth.

The continuity and heterogeneity of streams is frequently disrupted, altering or even destroying characteristics and habitats (pool, riffle and run), due to human activities that profoundly affect the integrity of continental aquatic systems (Naiman *et al.* 2005, Ferreira *et al.* 2012). This is worrisome, since streams are drastically altered

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by factors such as water contamination; regularization, channeling and artificialization of the natural riverbed; removal of riparian vegetation; inadequate use of the soil; industrial expansion; and construction of dams and roads. These alterations increase the load of allochthonous materials in water bodies, changing the transport and dynamics of the sediment, as well as the physical and chemical characteristics of the water (Callisto *et al.* 2002, Corgosinho *et al.* 2004).

This condition is aggravated by human population growth and the consequent need for energy, technology, and food, culminating in industrial, energy, and agricultural expansion, which directly affect the expansion of the road network in order to provide access to crops and improve the distribution of goods. Many roads intercept fluvial segments, which are channeled with concrete or corrugated-steel culverts, due to their lower cost compared to other structures such as bridges, which are considered more environmentally benign (Warren 1998, Harper & Quigley 2000).

The road network is directly related to habitat fragmentation (Vos & Chardon 1998), and its expansion alters the hydrology of river basins through changes in the quantity and quality of water, morphology of the stream channel, and water level in the soil, which increase the impermeable surface and erosion (Noss 1995). A regulation of the highway department of the state of Paraná, Brazil (DER 2005) states that during the construction of culverts, natural conditions of the aquatic segment should be preserved, although this rule is seldom observed.

Based on the assumption that stream ecosystems are longitudinally continuous and heterogeneous (Bührnheim 2002), we hypothesized that stream segments intercepted by culverts have discontinuous structural and abiotic patterns, as well as decreased habitat heterogeneity. The objective of the present study was to assess the environmental, physical and chemical factors of the water in stream segments intercepted by culverts. This study was designed to answer the following questions: i) Are there differences in environmental characteristics (vegetation, morphogeometric, and physical and chemical) between the upstream and downstream sections of streams intercepted by culverts? ii) Do the longitudinal habitats (pool, riffle, run) differ in structural attributes between the upstream and downstream sections?

MATERIAL AND METHODS

Study area

The sampling was carried out in two second-order streams (Pindorama, 12.2 km long and 41.0 km^2 in watershed area; and Lopeí, 23.6 km and 65.9 km^2) relatively homogeneous (channel unit) tributaries of the São Francisco Verdadeiro River, in the Upper Paraná River basin (Fig. 1). These streams were chosen because they

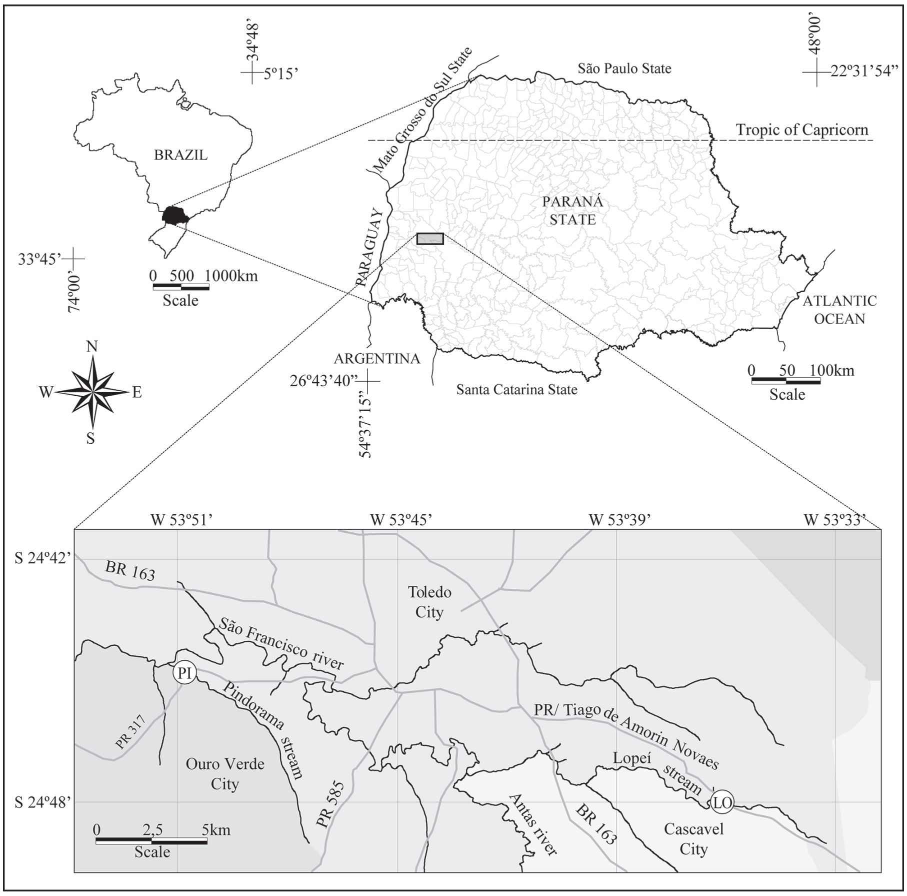

Figure 1. Study area: location of the Pindorama (PI) and Lopeí (LO) streams, both intercepted by culverts.

have culverts: one in Pindorama stream, located on the road PR317, between the municipalities of Toledo and Ouro Verde do Oeste (24º44'44.6"S and 53º50'48.5"W); and another in Lopeí stream, on the road OT-525 (24º47'47.6"S and 53º36'17.1"W) near the district of Bom Princípio (municipality of Toledo), both in the state of Paraná, Brazil.

For each segment containing a culvert, two sections were delimited: one upstream and the other downstream of the culvert (Fig. 2). These sections have meandering courses with some stretches of alluvial sediments. They are composed of natural sites intercalated with semi-lentic, relatively deep and wide waters (pools), stretches of semi-lotic and lotic waters, swiftly flowing, little to no surface agitation, approximately uniform flow with no major obstructions, substrates of variable particle size (run), followed by stretches of fast-flowing turbulent waters characterized by small hydraulic jumps over rough bed material, causing small ripples, waves, and eddies, without breaking the surface tension (riffles) (Fig. 2), according to the modified versions of the diagrams by Strahler (1957) and Fitzpatrick *et al.* (1998), which show the characteristic environments (sites) of streams intercepted by culverts (pool, run, and riffle).

Characterization of the stream structure

To evaluate the structural variables, we used a modified version of the rapid assessment protocol (RAP) proposed by Callisto *et al.* (2002) and Minatti-Ferreira & Beaumord (2004, 2006). Our modifications were necessary to adjust the protocol to our research. The samples were taken monthly from October 2009 through November 2010, in stretches above (200 m) and below (200 m) the culverts. Riparian vegetation and substrate were quantified as the percentage of occurrence in each sampled segment. Morphometric data were measured in centimeters (cm) (Appendix I). The substrate size was determined according to ABNT NRB 6502 (1995) and Bain & Stevenson (1999). To characterize and describe the sites (pool, riffle and run) in each section (upstream and downstream) as well as, to better represent the range of the descriptor variables, these sections were divided into 10-m parts corresponding to 20 sampling points, both above (upstream – 200 m) and below (downstream – 200 m) the culvert, for a total sample of 400 m and 40 sampling points in the transverse direction per stream. We used a width of 30 m to quantify and qualify the riparian vegetation, according to the environmental laws on riparian vegetation (Law No. 7.803 of 18.7.1989).

We analyzed the structural variables (Table 1), including the vegetation type, through the percentage of occurrence (%), depth of the stream (cm), width of the stream (cm) and texture of the streambed substrate, through surveys carried out with the aid of a Petersen dredge. Measurements of the range of variation in the water level (cm) were taken to represent the variation in the water body after rainy periods, since this index allows inferring the maximum rainfall, as the measurements were taken during a period of sparse rain. To measure the depth, range of variation in the water level, and width of the stream we used a 50-m measuring tape, with three repetitions every 10 m, using RAP (Table 1).

Physical and chemical (abiotic) water variables were measured one day per month from November 2009 through October 2010; four samples were taken at two points in each section (upstream and downstream) within a 24-h period; i.e., samples were taken every 6 h (Table 1). The water oxygen content and temperature were measured with a portable digital oximeter (YSI 550A), electrical conductivity with a conductivity meter (MB-11p series - 4796/805), turbidity with a turbidimeter (AP 2000 iR series - 1825), and pH with a pH meter (MB-10p series - 4494/805). Air temperature was measured with a mercury thermometer, placed in a shaded location.

Statistical analysis

The transverse (width) and vertical (depth) dimensional variables were tested with an analysis of variance (for parametric data), or a Kruskal-Wallis test (for non-parametric data) to characterize each section (upstream and downstream).

Vegetation and morphogeometric data (structural variables) were recorded on worksheets and categorized in sections (upstream and downstream) and sites (pool, riffle and run) for each stream. Depth and width were first graphically explored to search for longitudinal (headwater to mouth) and transverse patterns (riparian vegetation and flooding area). Physical and chemical data were grouped for the upstream and downstream sections.

Matrices of vegetation, morphogeometric (structural

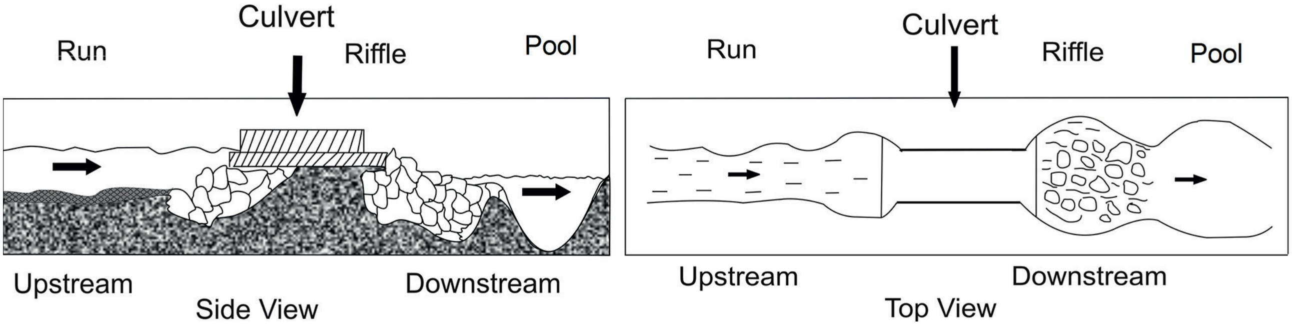

Figure 2. Sketch of stream segments and their upstream and downstream sections, showing the culverts in the stream flow (horizontal arrows show flow direction).

Table 1. Description of the vegetation, morphogeometric, and physical and chemical variables analyzed in the sections upstream and downstream of the culverts.

Vegetation and morphogeometric data	Physicochemical data
Vegetation (%)	Water temperature (°C)
Native, exotic, Arboreous, Shrubby, Herbaceous	Air temperature (°C)
Substrate (Soil) (%)	Dissolved Oxygen (mg/L)
Pebbles (small, medium, large), cobble, Sand, organic matter, silt/clay,	Dissolved Oxygen (%)
Depth (cm)	Turbidity (NTU)
Right margin, middle, left margin	pH
Range of variation in the hydrological level (cm)	
Right and left margins	
Width (m)	

variables) and physical and chemical (abiotic) data were sorted with a principal components analysis (PCA) (Pearson 1901, Humphries *et al.* 1981, Gauch Jr. 1986), allowing visualization of patterns in tridimensional space (sections and sites). The principal components that had eigenvalues higher than those randomized with the Broken-Stick model (Jackson 1993) were retained for data interpretation. Calculations were made in the program PC-ORD® version 4.1 (McCune & Mefford 1997).

Differences between sections (upstream and downstream), sites (pool, riffle, and run) were tested with an analysis of variance (one-way ANOVA) for parametric data, and a Kruskal-Wallis test (KW) for non-parametric data. For this procedure we used the axes of the PCA (dependent variable) retained for data interpretation (matrices of structural variables - vegetation, morphometric, and abiotic factors). Multiple comparison tests (Tukey HSD and Z') were used to test for pairwise differences between categories. This procedure is complementary to the ANOVA and KW, and aims to identify which categories, taken in pairs, differ significantly from each other. The normality and homogeneity of the axes generated by the PCA were tested. We used Statistic 7.0 (StatSoft 1998) for these analyses. The significance level adopted was 5%.

RESULTS

The segments of the two streams differed in the composition of the surrounding vegetation. The upstream section was shady, with the presence of exotic species (38.35%) of the genera *Pinus* and *Eucalyptus*, surrounded by native species (62.4%); both exotic and native species consisted of trees (59.2%), shrubs (31.52%) and herbs (9.28%). Among these plants was *Dicksonia sellowiana*, locally known as Samambaiaçu or Xaxim, an endangered species listed by the Brazilian Ministry of the Environment (MMA, 2008). The downstream section had less riparian vegetation, with trees (31.63%) and shrubs (41.07%), mainly on the right bank, allowing a higher incidence of sunlight; its matrix was surrounded by sparse grasses (herbs 27.3%) and exotic species (21.42%), such as eucalyptus.

The variables related to the vertical [depth – $F(1,78) = 10.42$; $p < 0.002$] and transverse dimensions [width - $H(1,80) = 9.40$; $p < 0.003$] differed graphically between sections. The mean total depth of the thalweg (deepest channel) upstream was 39.62 cm, whereas the downstream section was shallower, with a mean of 30.93 cm, ca. 10 cm less (Fig. 3), which indicated the damming effect caused by the culvert.

The mean width was greater in the downstream section (mean 6.28 m), suggesting that after the culvert retains the water, the water dissipates downstream, increasing the section's width.

These variables of dimension (depth and width) were analyzed in the PCA together with other environmental variables (vegetation and morphogeometric) (Table 1). The first four principal components had higher eigenvalues (4.1, 3.9, 2.7, and 2.0 for PC 1, 2, 3, and 4, respectively) than those randomized with the Broken-Stick model (3.5, 2.5, 1.9, and 1.6, respectively), explaining 71.5% of the variation. However, only the first two PCA axes (PC 1 and 2) were chosen for data interpretation, as they explained a higher percentage of the variation (22.8 and 22%, respectively). The size and percentages of each substrate type are shown in Table 2.

In the ordination of points (Fig. 4) in PC 1, the variables with the highest positive effects were organic material,

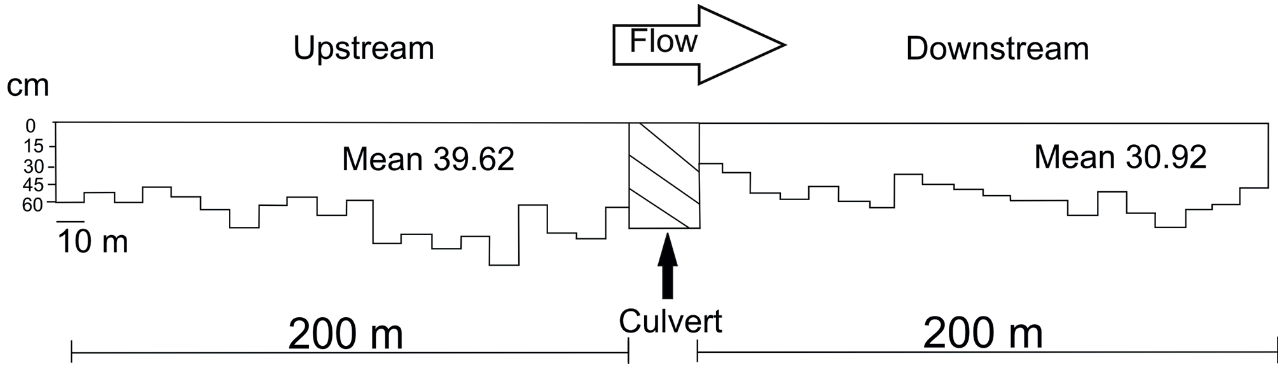

Figure 3. Longitudinal depth profile with mean values of three repetitions for each sampling point, in the sections upstream and downstream of the culverts.

Table 2. Size and proportion of each substrate found in the bottom of the stream sections upstream and downstream of the culverts, following the modifications proposed by Folk & Ward (1957).

Substrate (Soil)	Size ranges (mm)	Upstream (%)	Downstream (%)
Silt/clay	<0.06	46.88	31.85
Sand	0.06 – 4	1.98	0.60
Small pebbles	4 – 16	21.60	8.50
Medium pebbles	16 – 65	6.05	8.90
Large pebbles	65 – 90	2.95	10.83
Cobble	>90	1.05	23.73
Organic matter	vegetation debris	19.50	15.60

Table 3. Eigenvalues of PC 1 and PC 2 associated with the vegetation and morphogeometric variables, and the means of these parameters in the stream sections. Variables that contributed most to the formation of the axes are in bold.

Structural data	PC 1	PC 2
Organic matter	**0.4122**	0.1618
Silt/Clay	**0.2925**	-0.0819
Depth (middle)	**0.2911**	-0.2315
Depth (right)	0.2866	0.1413
Small pebbles	0.2821	-0.1939
Depth (left)	0.1841	0.2131
Herbaceous Vegetation	0.1755	-0.1309
Native Vegetation	0.1111	**0.4963**
Shrubby	0.1585	**0.3261**
Medium pebbles	0.0386	0.0656
Hydrological level (left)	0.0062	-0.0973
Hydrological level (right)	0.1135	**-0.2657**
Sand	0.1207	**-0.2677**
Exotic Vegetation	-0.0533	**-0.4765**
Arborous Vegetation	-0.2483	-0.1522
Large pebbles	-0.2561	-0.0111
Width	**-0.2809**	0.1219
Cobble	**-0.3975**	0.1397

depth (right bank), and shrub vegetation, whereas tree vegetation and width had negative eigenvalues (Table 3). Hence, the points located to the left of the ordination had higher values of tree vegetation and lower values of width.

The variables exotic vegetation, depth (thalweg), and sand (higher values for the upstream section) were negatively correlated with the PC 2. The variables native vegetation and cobble fell in the positive space of the PC 2. Hence, the data located in the upper region of the ordination had higher values of these variables (Fig. 4; Tables 2 and 3).

The range of variation in the water level showed a mean of 54.50 cm upstream and 48.13 cm downstream.

The ANOVA applied to principal components 1 and 2, categorized in sections (F(1, 18) = 25.15; p < 0.001) and sites (F(2, 17) = 3.75; p = 0.044), showed significant differences for PC 2 (Fig. 5 A and B). Hence, the upstream and downstream sections differed in exotic vegetation, depth (thalweg), sand content, native vegetation, and cobble (Fig. 5 A). For the habitats formed longitudinally (pool, riffle and run), the Tukey test indicated differences between the run and the other habitats (Fig. 5B), since only this habitat was located in the downstream section, indicating a decrease in the longitudinal heterogeneity that is characteristic of streams.

The physical and chemical variables were ordinated

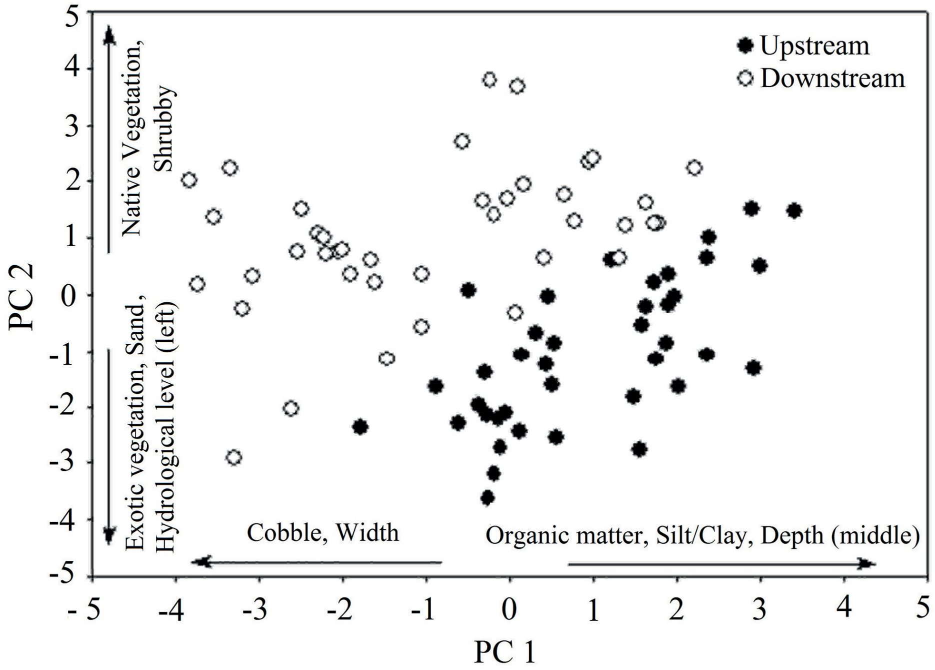

Figure 4. Ordination of the upstream and downstream sections along principal components 1 and 2 (PC 1 and PC 2), related to vegetation and morphogeometric variables.

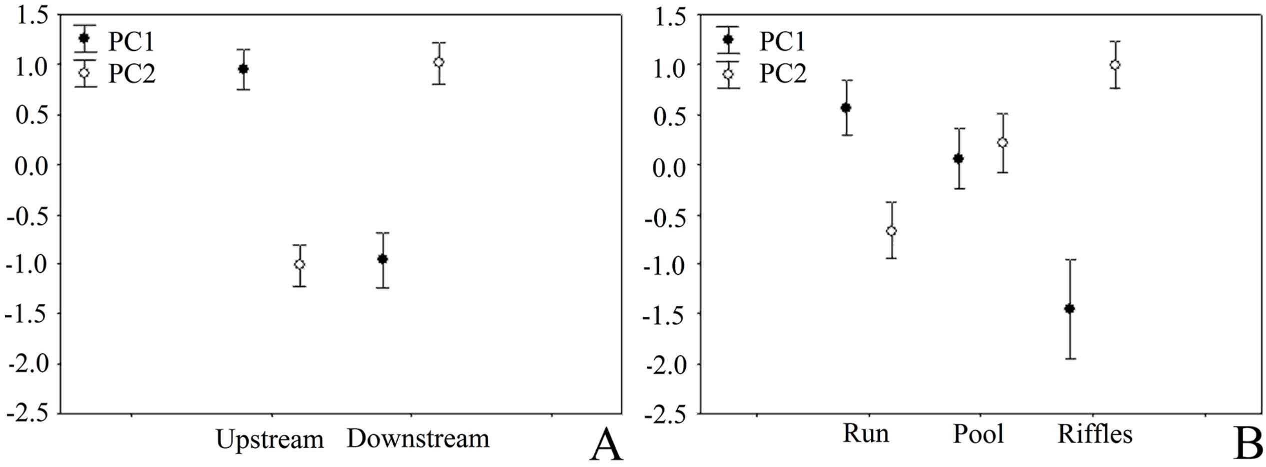

Figure 5. Means (± standard error) of the PCA axes associated with vegetation and morphogeometric variables in the upstream and downstream sections (A) and in the characteristic habitats of streams (B).

in the PCA. The correlation matrix extracted three axes with eigenvalues (2.79, 1.89, and 1.22 for PC 1, PC 2, and PC 3, respectively) higher than those of the Broken-stick model, together explaining 84.35% of the variation. However, to standardize the graphical presentation of results, we used the same procedure as in the PCA with vegetation and morphogeometric data: we retained only the first two axes, because they had the highest values. Principal component 1 (PC 1) explained 39.87% of the variation in the abiotic factors, and principal component 2 (PC 2), 27.02%.

Analyzing the ordination of points (Fig. 6B) in PC 1, the factors with the highest positive effects, pH and DO (mg/L), were close to the center, whereas the other variables had negative eigenvalues (Fig. 6A), which were more negative for turbidity, water, and ambient temperature. PC 2 was positively correlated with ambient temperature and negatively with DO (mg/L and %). The mean values of the physical and chemical parameters are shown in Table 4. Due to the number of temporal samples (abiotic) during the study, and the wide variation in the abiotic factors over time, it is difficult to interpret this ordination (Fig. 6A, B). The mean values of physical and chemical parameters by season in each stretch (upstream and downstream) are shown in Table 5. In order to solve this problem, we constructed plots using the factors as categorical variables (Fig. 7). The result of the abiotic PCA suggests that the upstream and downstream sections are similarly correlated with the physical and chemical variables, in both PC 1 and PC 2 (Fig. 7).

DISCUSSION

Urban and rural growth is affecting natural environ-

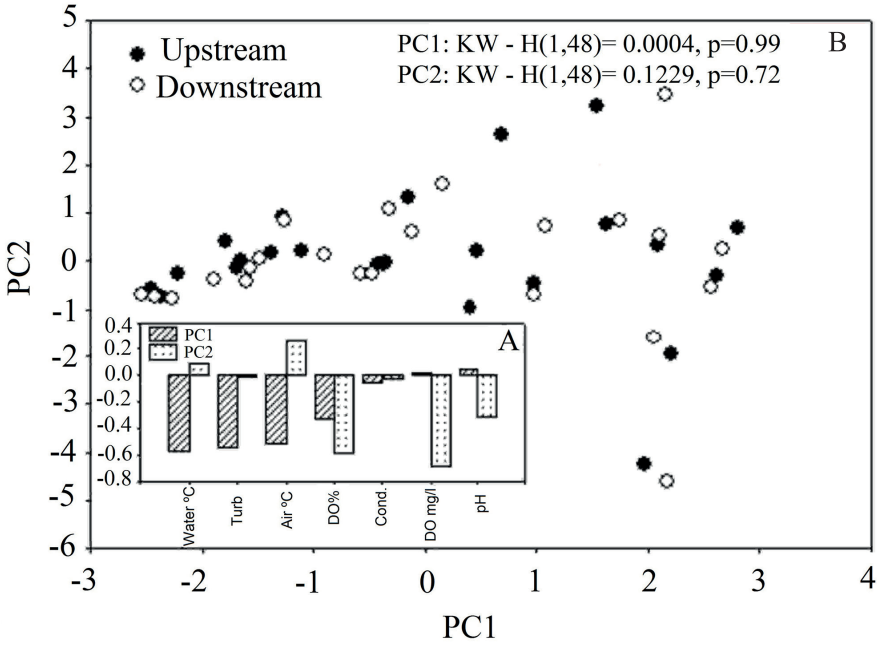

Figure. 6. Ordination of the sampling points (upstream and downstram) along principal components 1 and 2 (PC 1 and PC 2) (A),associated with physical and chemical variables (B).

Table 4. Eigenvalues PC 1 and PC 2 associated with the physical and chemical variables and the means of these parameters in the stream sections. Variables that contributed most to the formation of the axes are in bold.

Abiotic factors	PCA 1	PCA 2	Upstream	Downstream
pH	0.0399	-0.3136	7.21	7.22
Dissolved oxygen DO (mg/L)	0.0071	**-0.6924**	8.09	**8.16**
Conductivity (µs/cm)	-0.0623	-0.022	37.16	36.62
Dissolved oxygen DO (%)	-0.3274	**-0.5871**	89.70	**89.89**
Air temperature (°C)	-0.5207	0.2663	19.64	20.00
Turbidity (NTU)	**-0.5402**	-0.0129	**25.66**	24.83
Water temperature (°C)	**-0.5695**	0.0781	20.32	**20.40**

Table 5. Means of the abiotic factors associated with seasons per section. Variables that contributed most to the formation of the axes are in bold.

	Upstream				Downstream			
Abiotic Factors	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring
Air temperature (°C)	**23.1**	18.7	17.1	19.6	**23.4**	19.4	17.5	19.7
Water temperature (°C)	**22.5**	20.5	18.1	20.1	**22.6**	20.6	18.1	20.2
Dissolved oxygen DO (mg/L)	8.0	8.3	8.3	7.7	8.2	8.3	8.3	7.9
Dissolved oxygen DO (%)	93.6	92.1	87.8	85.2	94.5	92.4	87.8	84.8
pH	7.2	7.3	7.2	7.0	7.2	7.3	7.3	7.1
Conductivity (µs/cm)	34.5	39.3	38.4	36.5	35.5	37.4	38.1	35.5
Turbidity (UNT)	**40.9**	21.7	17.0	22.9	**40.0**	21.6	16.0	21.8

ments. Mining and road construction (Forman & Deblinger 2000) are among the greatest impacts on environmental geomorphology (Hooke 1988). Water bodies are altered by engineering projects, the negative effects of which are observed not only in loco, but also upstream and downstream of the constructions (Brookes & Gregory 1988).

The riparian vegetation differed between the upstream and downstream sections, but this difference is probably more related to the boundaries between properties than to the effects of the culverts. This result indicates the need to make landowners aware of the importance of riparian vegetation. Riparian vegetation constitutes an important energy source for low-order streams and is essential for their maintenance (Carvalho & Uieda 2010). Within the area of riparian vegetation assessed (30 m), we observed the exotic genera *Eucalyptus* and *Pinus*. These genera are the most frequently planted worldwide, and their use is encouraged due to advanced technical knowledge of their biology, good adaptability, and resistance to adverse conditions (Kageyama 1989). The inadequate knowledge

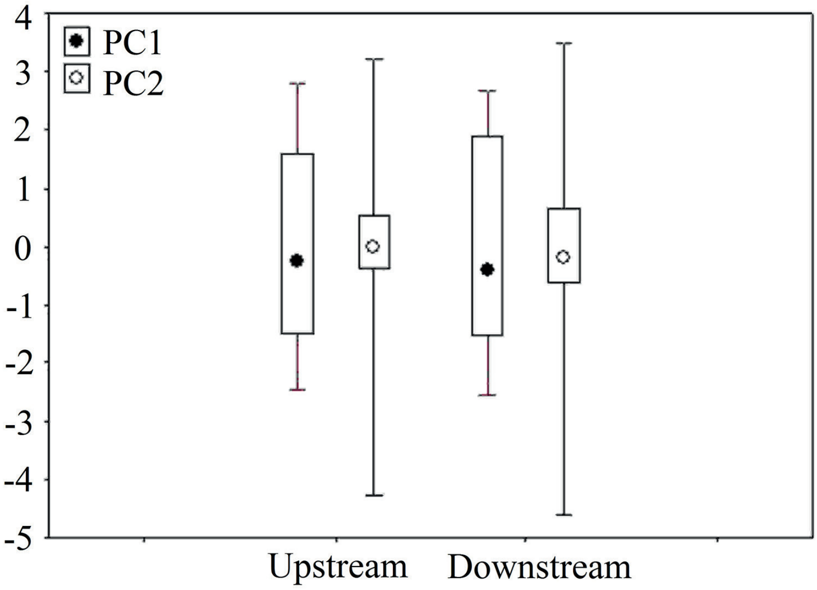

Figure 7. Means (box: 25%-75%) of the PCA scores associated with the physical and chemical variables per section.

of landowners about the importance of the native riparian vegetation affects this habitat, because changes in its composition lead to alterations in the structure and ecological processes of streams, mainly those related to the input of sediments to the riverbed (Carvalho & Uieda 2010).

According to Guerra & Marçal (2010), human alterations in natural environments change the dynamics of sediment transport, which explains the differences in substrate between the stream sections analyzed here. In the upstream section there was more silt, organic matter, and small pebbles, whereas in the downstream section there was more silt, cobble, and organic matter. The lower water velocity in the upstream section may decrease the input of heavier sediments, such as cobble and large pebbles.

Furthermore, the concrete base on which the culverts were fixed functions as a barrier for the movement of sediments. This base hinders the free movement of sediments and retains them in the upstream section; over the years, substrates in the downstream section become buried. According to the continuum concept of Vannote *et al.* (1980), river basin have similar longitudinal patterns from the headwater to the mouth.

This damming effect is also confirmed by the greater depth of the upstream section, which has an important role in the distribution of habitats and species (Angermeier & Karr 1984, Martin-Smith 1998). A flood of the run in the upstream section was observed, suggesting that the accumulation of water modifies the natural flow of the river, consequently decreasing environmental heterogeneity. Similar patterns were observed by Wheeler *et al.* (2005). The streams were also wider in the downstream section, mainly in the sector closest to the culvert, probably a result of high flow velocities out of the culvert.

The physical and chemical variables did not differ between sections, but the air and water temperature varied seasonally. This was expected due to the humid mesothermal subtropical climate of the region, with warm summers and mean temperatures above 22°C, and winters with temperatures below 18°C (SIMEPAR 2010). Turbidity also varied seasonally; the frequent summer rains increase the load of alluvial sediments in streams, making the water more turbid (Uieda & Castro 1999).

However, Angermeier & Karr (1984) reported that changes in the physical and chemical characteristics of tropical rivers are unpredictable, mainly due to the sequential processing of organic matter along the longitudinal gradient, and to biotic interactions.

Our results lead to the conclusion that, despite the visually apparent formation of two environments (upstream and downstream) mediated by the interception of the culvert in the fluvial segment, the continuity of the physical and chemical factors (longitudinal) does not change significantly. Seasonal differences are explained by seasonal climatic influences. Notably, morphogeometric factors differed between sections due to a loss in heterogeneity, since the concrete formed by the excavation and culvert insertion retained the water, increasing the depth and submerging the shallower parts of the run, turning them into semi-lentic environments. These characteristics showed the influence of culverts on the upstream and downstream stretches in the streams.

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