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Environmental typology of rivers from the Brazilian semiarid as a first step for the application of the index of biotic integrity: the case of the Chapada Diamantina

Environmental typology of rivers in the Brazilian semiarid

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ABSTRACT

Defining environmental river types is an essential step in the development of accurate fish-based methods (IBI, Index of Biotic Integrity) to assess the environmental quality of aquatic ecosystems. In this study, the environmental typology of the rivers and streams in the region of Chapada Diamantina was developed. Thirty-five sampling sites representative of the upper Paraguaçu River and its main tributaries were characterized to characterize the fish assemblages and abiotic environmental descriptors. A cluster analysis based on fish species CPUE was performed to define a first biological typology. Then, a discriminant analysis model was developed to select the environmental descriptors that explained the fish-based river types. The model selected eleven environmental variables and classified 91% of the cases. The river typology defined in this study will be used for the development of an IBI to assess the ecological status of the Chapada Diamantina rivers. It is expected that both the typology developed here and the future IBI will provide important and useful tools to develop and apply nature conservation-oriented management schemes in the Chapada Diamantina aquatic ecosystems.

KEYWORDS: river typology, fish, environmental quality, conservation, management

INTRODUCTION

Biotic integrity is the ecosystem ability to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region (Karr and Dudley 1981). In running waters, biotic integrity depends mainly on flow, energy input, water quality, biological interactions, and habitat structure (Karr et al. 1986; Hughes and Gammon, 1987; Karr, 1991).

The index of biotic integrity (IBI) (Karr, 1981) influenced the development of almost all fish-based methods to assess human-induced impacts on aquatic ecosystems. Although IBIs have been developed and applied worldwide (e.g. Angermeier & Karr, 1986; Lyons, 1992; Oberdorff & Hughes, 1992; Ganasan & Hughes, 1998; Kamdem Toham & Teugels, 1999; Joy & Death, 2004; Rodríguez-Olarte et al., 2006; Casatti et al., 2009), appropriate definition of environmental river types is a major issue in developing regional IBIs (Strange, 1998) because of large-scale natural variability in fish communities (Schmutz et al, 2007). The underlying principle of this approach is that rivers are understood as a sequence of distinct segments with homogeneous abiotic and biotic characteristics and, thus, the entire river network can be classified into distinct types. For each river type, the basic functional unit, undisturbed conditions can be accurately formulated and the deviation from these conditions provide the quantitative measure of the ecological status (Turak & Koop, 2008). The fish metrics used to measure the deviation from reference conditions are formulated for each river type making them more robust and adequate to respond significantly to human pressures (Steedman, 1988; Daniels et al., 2002; Roset, et al., 2007).

This was the approach used by the European Union Water Framework Directive (WFD, European Commission, 2000) in the development of biotic indices to assess the ecological status of European water bodies. The WFD postulates two options for establishing the typologies, both using strictly abiotic criteria: System A and B (Annex II of the WFD). System A uses fixed categories of three parameters to classify rivers: three altitude ranges, four basin size ranges, and three geological categories. On the other hand, System B proposes to establish river types analyzing different factors considered as obligatory and optional. However, as the hypothesis is the lower the biotic heterogeneity within each type the greater the IBI accuracy (Fausch et al., 1990; Smogor & Angermeier, 2001), developing environmental typologies without a biological component is considered an inadequate approach.

An alternative approach for the development of abiotic river environmental typologies that takes into account the biological communities was successfully carried out in the development of IBIs to assess the ecological status of rivers from the Iberian Peninsula that accurately evaluated the ecological status of all river types, from highland rivers to intermittent streams in semiarid zones (Sostoa et al. 2004; Segurado et al. 2014). First a strictly biological typology based on fish assemblages was performed. Then, an analysis of the abiotic descriptors that better explained the biological typology was carried out. At the end, the final product was an environmental typology based on the WFD system B variables but with an underpinning biological river classification.

In the central region of the state of Bahia, in the Brazilian semiarid, typical rock formations develop, where the matrix vegetation is the Caatinga (Brazilian semiarid vegetation). Due to its isolation within the semiarid domain, these rupestrian grasslands, a mosaic of herbaceous and shrubby physiognomies, are characterized by high levels of endemism and the presence of rare species. Areas of rupestrian grass land are located on quartzite or ironstone soils in highlands usually above 900 m (Harley 1995; Giulietti et al. 1997). From the 19th century until the 1980s, the rivers of the Chapada Diamantina were impacted by mechanized diamond mining and this exploration resulted in drastic changes in the riverbeds and banks due to burning the vegetation and soil excavation. At present, the main impacts are related to the deforestation and unregulated tourism activities (Santos & Caramaschi, 2011). Notwithstanding the importance and the high incidence of different types of environmental degradation, no studies on the environmental quality of the rivers has been carried out.

Due to the rich and endemic ichthyofauna of the Chapada Diamantina rivers and streams (de Pinna, 1992) and the threats that these aquatic ecosystems were, and still are, subjected to, the evaluation of the ecological status is necessary. Adequate management schemes that ensure nature conservation can only be applied after the completion of an accurate ecological diagnosis carried out with assessment methods capable of detecting human-induced impacts on the aquatic ecosystems. A fish based IBI will definitely provide a useful assessment tool and the first step to develop such a method is to develop a river typology. Due to the high variability of both environment and fish fauna of the Chapada Diamantina rivers and streams, the development of an environmental typology based on both biological communities and abiotic variables would be the most adequate approach. In this study an environmental river typology was defined as a first step for the development of an IBI to assess the ecological status of the rivers and streams from the Chapada Diamantina region in the Brazilian semiarid.

MATERIALS AND METHODS

Study area

The study was conducted in the Chapada Diamantina region (state of Bahia, NE Brazil), which is part of the Paraguaçu River basin and contains the rivers and streams that form the source of Paraguaçu River (Fig. 1). The Paraguaçu River is about 500 km long, from the Chapada Diamantina region to the mouth in the western region of the Todos os Santos bay. This river basin is one of the largest in northeastern Brazil and supports a very rich endemic fish fauna (de Pinna, 1992). The Chapada Diamantina is a mountainous region with an area of 41,751 km2 and an altitude varying between 400 and 1700 m. The climate is semiarid with maximum rainfall of approximately 175.8 mm, occurring between November and December. Temperatures are milder than in the surrounding regions, with annual averages lower than 22 °C and low winter temperatures, reaching 0 °C (CPRM, 1994). Thirty-five river stretches (sampling sites) were selected to cover all the environmental variability along the longitudinal gradient, ranging from rivers at higher altitude and from lower order to larger and more complex rivers located at a lower altitude (Fig 1).

Sampling

The sampling was carried out from April 2008 to March 2009. In each sampling site a stretch with all representative mesohabitats present (runs, riffles and pools) was selected. Every stretch had a length of 10 times the river width with a minimum of 50 m long. To sample the fish community two blocking nets of 8 mm mesh size were settled in the beginning and end of each stretch. Fishes were collected using a standard active method consisting of the use of two sieves on the riverbanks and a beach seine (locally known as "picaré") in the middle of the river channel (Ueida & Castro, 1999). These sampling methods are suitable and very efficient for rapid ecological or faunistic surveys (Ribeiro & Zuanon, 2006). The sampling effort was proportional to the river size, allowing the calculation of the catch per unit of effort (CPUE) for each species and sampling site. The collected fish were anesthetized with menthol and then preserved in 4% formaldehyde and packed in plastic bags, properly identified for transport to the Laboratory of Ichthyology of the State University of Feira de Santana (UEFS). In the Laboratory, the fishes were identified to the lowest possible taxonomic level and counted. The relative fish abundance (%

CPUE) was estimated for each species and sampling site.

Each sampling site was characterized with a set of environmental parameters (Table I). These included geographic positioning, altitude, slope, hydromorphology, habitat features and the physical and chemical water characteristics. Depending on the variable, data was gathered from geographic information systems or measured in situ (Table I).

River typology

A cluster analysis was performed to group sampling sites according to fish relative abundance (%CPUE). For this purpose, the squared Euclidean distance was calculated between the sampling sites followed by the application of the Ward grouping method (Ward, 1963). This agglomerative technique is recommended to obtain clusters from environmental and biological data (Cao et al., 1997). Subsequently, the environmental parameters that best explained the biological clustering were identified using a forward stepwise discriminant analysis (McGarigal, 2000). In this type of analysis, a discriminant model is created step by step and at each stage, all variables are reviewed and evaluated to determine which variable will contribute most to discrimination between groups. The data used in the discriminant analysis was log transformed and, in the case of proportions, square root transformed (Underwood, 1997). The variables were selected according to the criteria of the greater F-value to be included in the model, with a minimum value of 1. Finally, a comparison was made between the biological and abiotic grouping (observed vs. predicted grouping) to evaluate the discriminant analysis model adequacy. The analyses were performed with Statistica Version 7.0 software.

RESULTS

Biological characteristics of the river types

In the 35 sampling sites, 3316 fish belonging to 47 species and 14 families were captured (Table II). Fish specimens were preserved and registered in the fish division collection of the UEFS Zoology Museum. The dominant species were *Astyanax* aff. *scabripinnis* and *Astyanax* sp., with 1826 and 1135 specimens, respectively. The cluster analysis identified three river groups based on the ichthyofauna (Figure 2). Group 1 was characterized by the exclusive dominance of common species, such as species from the genus *Astyanax and Hoplias*. Rivers belonging to group 2 were characterized by the presence of accessory species from the genus *Geophagus, Hoplerythrinus, Hyphessobrycon, Parotocinclus* and

Rhandia. Group 3 was compose of river supporting rare species of the genus *Parotocinclus, Tetragonopterus, Parauchenipterus, Leporinus, Hemigrammus, Cyphocarax, Cichlasoma, Copionodon, and Hypostomus*.

Environmental river typology

Among the 23 environmental variables recorded in this study, 11 were selected by the discriminant analysis model, and five were significant: Altitude, geomorphology, depth, type of vegetation, and latitude (Table III). The classification function resulted in 91% of well-classified cases and the model characterized rivers with three environmental types, cultivated areas, rupestrian fields and forest areas (Table IV).

DISCUSSION

In semiarid regions, human population frequently experience irregularly flowing freshwater ecosystems that exhibit unpredictable and high year-to-year variability in precipitation resulting in lengthy periods of drought and floods (Caiola et al., 2001a,b; Ferreira et al., 2007a,b). Man has responded to this hydrological variability with numerous water projects that affect water quantity. These include impoundment of river waters and alterations to channel morphology, mainly for agriculture practices, flood prevention and industrial uses (Fieseler & Wolter, 2006). In addition, industrial waste and sewage effluents also cause water quality to deteriorate. The Chapada Diamantina region has suffered, historically, from these and other impacts related mainly to the mechanized diamond mining. It is a unique place in the world and, therefore, nature conservation actions including river restoration are needed.

The basis for using biology for aquatic ecosystems monitoring is that human activities that alter physical and chemical processes associated with water resources also modify the resident communities (Esteves & Valim, 2011). Even though the IBI is applied in different aquatic ecosystems, studies on the analysis of the relationship between these methods and the historical land use are scarce (Oberdorff et al., 2002). Fish based methods to assess ecological quality of running waters have proved to be very useful in the detection of human induced impacts on the aquatic ecosystems. These methods were able to detect, not only water quality impacts, but also environmental disfunctions related with insufficient discharge (Caiola et al., 2014; Belmar et al., 2018, 2019). The development of an IBI for the Chapada Diamantina running waters is, thus of great importance.

In the development or adaptation of an IBI, first reference conditions (pristine or least disturbed) are established and then the biotic metrics will measure the deviation regarding present conditions. In most of the adaptations of the IBI, it remains unclear how reference conditions were established (Jaramillo-Villa & Caramaschi, 2008). The absence of previous studies on the Chapada Diamantina ichthyofauna do not allow the establishment of reference conditions based on historical datasets (Santos & Caramaschi, 2007; 2011). In these cases of scarce or non-existent historical data, reference conditions can be formulated on the basis of potential fish distribution modelling (Canning 2018; Zogaris et al., 2018) or expert judgement (Virbickas & Kesminas, 2007; Pardo et al. 2012). In either case, it is much more accurate to formulate reference conditions for homogeneous functional river types. The river typology developed here will allow defining reliable reference conditions for each river type that will assist in the development of a useful IBI for the Chapada Diamantina. This so-called spatially based approach for the development of IBIs, which implies the definition of river typologies prior to the definition of the metrics that constitute the assessment method itself, has been successfully applied in several regions of the world (Sostoa et al. 2004; Turak & Koop, 2008). This approach has been proven to produce more accurate IBIs in regions with high hydrological stress and characterized by a highly endemic native fish fauna (Segurado et al., 2014). This spatially based approach can be applied to wider areas. Previous attempts to develop fish based assessment methods in Brazil are limited to homogeneous areas such as the upper or mid-course of similar geomorphological rivers (Araujo et al., 2003; Bozzeti & Schultz, 2004, Casatti et al., 2009; Casatti & Teresa, 2012).

River typology, like many other ecosystem classifications, is a simplification of nature. It is a static representation of a complex and continuous situation and with a highly dynamic spatial pattern. Moreover, due to zoogeographic aspects it has been shown that relatively undisturbed short river reaches in close proximity to one another may differ greatly with regard to to fish species richness (Turak & Koop, 2008). Therefore, some typologies established using only abiotic descriptors may not be useful in the subsequent development of IBI fish metrics. Considering that both biological and abiotic variables are included in this typology and that there is a very high concordance between the biological and abiotic river classifications (91 % of well classified cases), it is expected that the future Chapada Diamantina IBI will allow an accurate assessment of the ecological status. Another advantage of this high concordance between the fish-based clustering and the abiotic discriminant model, is that there is a high confidence level for the classification of new river stretches that were not sampled in this study. It is important to point out that the objective of this typology is not to describe the biogeography of the fish species from the Chapada Diamantina and, therefore, it cannot be used alone to make accurate predictions of a fish species occurrence in the study area. However, the attribution of any river stretch to an ecological type provides an indication of the fish community composition expected in this stretch.

Although the rivers typology in Chapada Diamantina is an important first step for the development of an IBI suitable to assess the ecological status of running waters in this region, there are still some weaknesses that should be overcome. In the present study, many fishes were identified only on a generic level, indicating the necessity for investment in studies on the ichthyofauna of the Paraguaçu basin. Since the 1990's, studies on the systematic and ecology of ichthyofauna from the Chapada Diamantina have became more frequent. These studies have described, around 20 news fish species. Moreover, the information on the life history traits of most species is scarce (Jaramillo-Villa & Caramaschi, 2008). This lack of information is common due to the high diversity of tropical fishes. This is a challenge for the development of IBIs in the Neotropical realm mainly because IBI fish metrics are based on functional groups and, in order to attribute functional guilds to fish species, it is necessary to know life history and other ecological traits.

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Table I. Abiotic variables used in the analysis and the methods employed for the data gathering.

Variable	**Method**
pH	Field measurement with U-50 Multiparameter - HORIBA
Electrical conductivity (µS)	Field measurement with U-50 Multiparameter - HORIBA
Dissolved Oxygen (mg/l)	Field measurement with U-50 Multiparameter - HORIBA
Water temperature (C⁰)	Field measurement with thermometer
Air temperature (C⁰)	Field measurement with thermometer
Transparence (m)	Field measurement with Secchi disc
Dominant substrate	% Cover of silt, sand, gravel, pebble, stone or rock
Dominant mesohabitat	% of pool, table or riffle
Riparian vegetation	% Cover of
Dominant vegetation	% Cover of Trees, shrubs, and herbs
Aquatic vegetation	% of
Water color	Assessed visually in the field
River order	Determined from maps
Average Flow (m^3/s)	Field measurement with fluxometer
Average river width (m)	Average of the width of water assessed visually in the field
Average river depth (m)	Average of the depth of water assessed visually in the field
Elevation (m)	Determined from GPS
Mean annual rainfall (mm)	Determined from GIS
Geology	Determined from GIS
Vegetation type	Determined from GIS
Geomorphology	Determined from GIS
Soil	Determined from GIS
Latitude, longitude	Determined from GPS

Table II. List of species, families, and vernacular names of fishes recorded in Chapada Diamantina region.

Taxonomic List	Vernacular Names
CHARACIFORMES	
PARODONTIDAE	
Apareiodon itapicuruensis Eigenmann & Henn	Canivete
CURIMATIDAE	
Cyphocharax gilberti (Quoy & Gaimard, 1824)	Sabarona
ANOSTOMIDAE	
Leporinus bahiensis Steindachner, 1875	Piau
CRENUCHIDAE	
Characidium cf. *bahiensis* Almeida, 1971	Piaba-charuto
Characidium cf. *bimaculatum* Fowler, 1941	Piaba-charuto
Characidium cf. *zebra* Eigenmann 1909	Piaba-charuto
Characidium clistenesi Melo & Espíndola, 2016	Piaba-charuto
CHARACIDAE	
INCERTAE SEDIS	
Astyanax aff. *scabripinnis*	Piaba
Astyanax gr. *bimaculatus* (Linaeus, 1758)	Piaba-dedo-de-moça
Astyanax cf. *fasciatus* (Cuvier, 1819)	Piaba
Astyanax sp.1	Piaba
Astyanax sp.2	Piaba
Astyanax sp.3	Piaba
Astyanax sp.4	Piaba
Hyphessobrycon negodagua Lima & Gerhard 2001	Piaba
Hemigrammus marginatus Ellis, 1911	Piaba
Knodus sp.	Piaba
Moenkhausia diamantina Benine, Castro & Santos 2007	Piaba
Myxiops aphos Zanata & Akama, 2004	Piaba

Piabina argentea Reinhardt, 1867	Piaba
CHARACINAE	
Phenacogaster franciscoensis Eigenmann 1911	Piaba
CHEIRODONTINAE	
Serrapinnus heterodon (Eigenmann, 1915)	Piaba
TETRAGONOPTERINAE	
Tetragonopterus chalceus Agassiz, 1829	Piaba-zoião
ERYTHRINIDAE	
Hoplerytrinus unitaeniatus (Schneider, 1829)	Uiu
Hoplias cf *lacerdae,* Ribeiro, 1908	Traira-cabeça-fina
Hoplias malabaricus (Bloch, 1794)	Traira-cabeça-de-lama
SILURIFORMES	
TRICHOMYCTERIDAE	
Copionodon pecten de Pinna, 1992	Jundiá
Trichomycterus gr. *brasiliensis* Lutken, 1874	Jundiá
Trichomycterus sp.	Jundiá
CALLICHTHYIDAE	
Aspidoras psammatides Britto, Lima & Santos, 2005	Cascudinho
Corydoras cf. *garbei* (Ihering, 1910)	Cascudinho
LORICARIIDAE	
Hypostomus crhysostiktos Birindelli & Zanata, 2007	Cari
Hypostomus sp.	Cari
Parotocinclus adamanteus Pereira, Santos, de Pinna &Reis 2019	Cascudinho
Parotocinclus sp.	Cascudinho
HEPTAPTERIDAE	
Heptapterus sp.	Jundiá
Pimelodella sp.	Jundiá
Rhamdia cf. *quelen* (Quoy & Gaimard, 1824)	Jundiá
AUCHENIPTERIDAE	
Parauchenipterus galeatus Linnaeus, 1766	Cumbá/molé/bate-papo

GYMNOTIFORMES	
GYMNOTIDAE	
Gymnotus gr. *carapo* Linnaeus, 1758	Peixe-cobra
CYPRINODONTIFORMES	
POECILIIDAE	
Pamphorichthys hollandi (Henn, 1916)	Barrigudinho, pariviva
Pamphorichthys sp.n	Barrigudinho, pariviva
Pamphorichthys sp.	Barrigudinho, pariviva
Poecilia reticulata Peters, 1859	Barrigudinho, pariviva
PERCIFORMES	
CICHLIDAE	
Cichlasoma sanctifranciscense	Corró-branco
Cichlasoma sp.	Corró
Geophagus diamantinensis Mattos, Costa & Santos, 2015	Corró

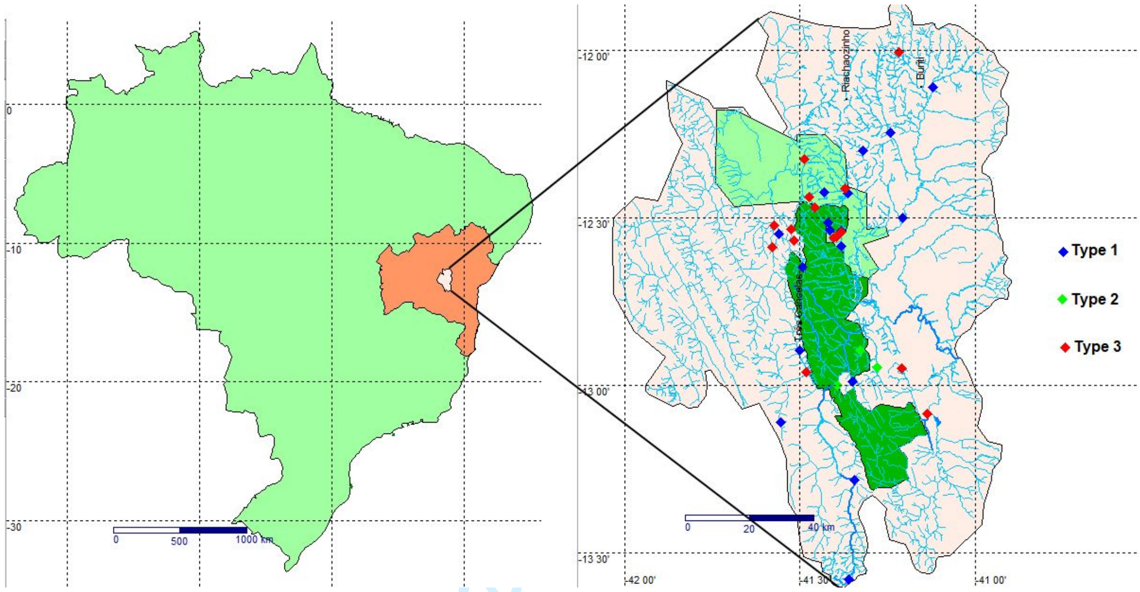
Table III. Mean, Standard deviation (SD) and Willk's Lambda generated by discriminant analysis showing separation of groups and environmental variables for the Chapada Diamantina rivers, BA.

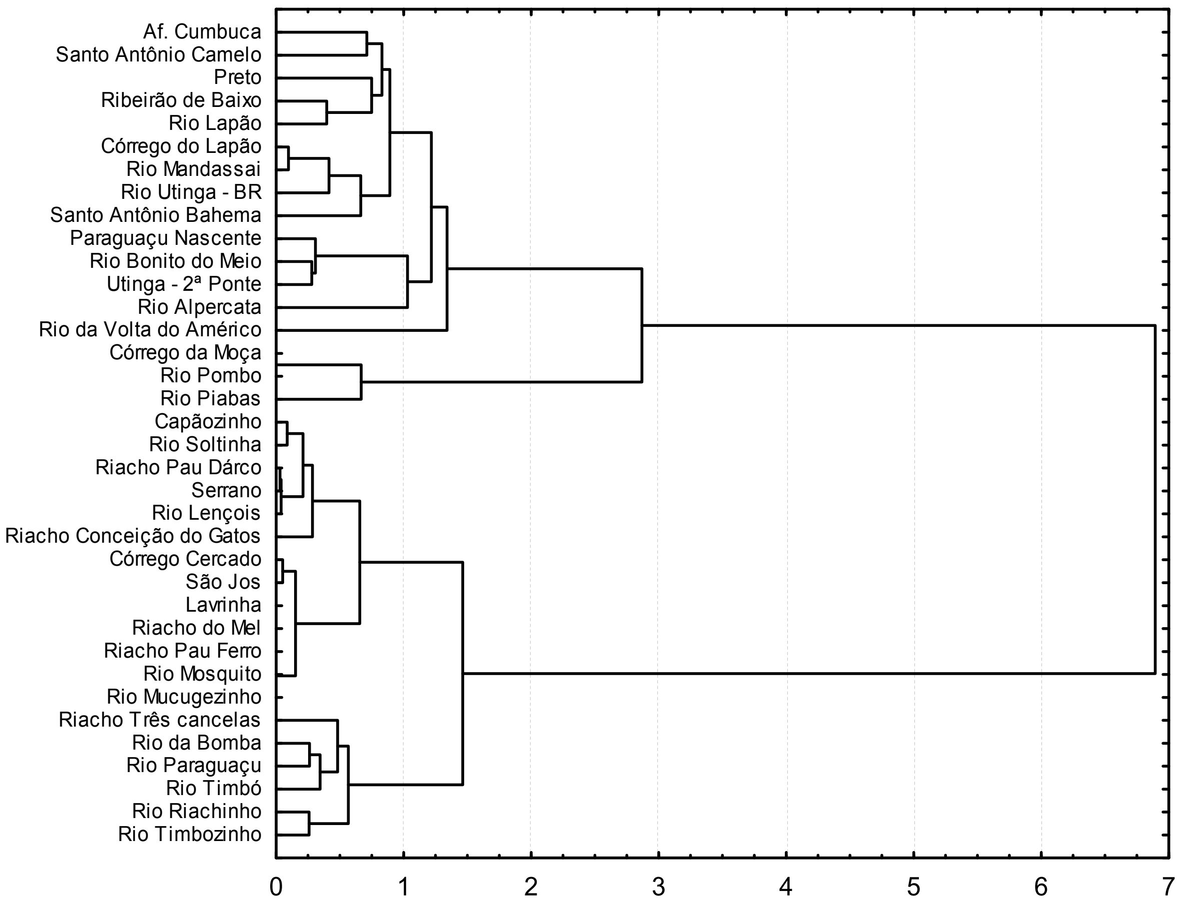
Variable	**Mean**	**SD**	**Wilks'**	**Partial**	**F**	**P**
PH	5,57	1,38	0,21	0,87	1,60	0,2239
Altitude (m)	692,81	269,81	0,45	0,41	15,67	0,0001*
Conductivity (µS/cm)	0,06	0,11	0,22	0,87	1,71	0,2036
Geomorphology	3,03	1,33	0,29	0,65	6,02	0,0008*
Mesohabitat	2,22	0,69	0,21	0,90	1,25	0,3057
Depth (cm)	36,11	19,52	0,27	0,68	5,15	0,0147*
Type of vegetation	2,75	1,84	0,27	0,69	4,99	0,0163*
Latitude (UTM)	241358,00	13757,30	0,26	0,73	4,04	0,0321*
Soil	4,25	1,23	0,22	0,86	1,78	0,1924
Vegetal cover	64,86	28,17	0,22	0,83	2,12	0,1435
Width (m)	7,16	5,38	0,22	0,84	2,07	0,1498

* = Significant

Table IV. Environmental descriptors for the Chapada Diamantina Rivers.

Environmental Descriptor	**River Type**		
	I **Cultivated Areas**	**II** **Rupestrian fields**	**III** **Forest areas**
Altitude (m)	247-1138	763-1054	378-1016
Depth (cm)	11-89	20-23	09-60
Geomorphology	All types, mainly hills, and mountains	Rocky blocks and small mounds with flat tops	All types, mainly saws and mountains
Vegetation type	All types, mainly cultivated areas	Pastures and fields with predominance of rupestrian fields	All types, mainly forest areas
Latitude	North-South	Center	North-Center
Comprehensive description	Intermediate altitude and greater depth. Mountains and hills with predominance of herbaceous vegetation. Located between the municipalities of Utinga and Barra da Estiva.	High altitude and shallow rivers. Flat tops, where the rupestrian field vegetation predominates. In the vicinity of the Municipality of Mucugê.	Intermediate to high altitudes and intermediate depths, located in the north-center region. The predominant vegetation was arboreal (forest). Located between the municipalities of Bonito and Mucugê


0
-10
-20
-30
0
500
1000 km
-12 00'
-12 30'
-13 00'
-13 30'
-42 00'
-41 30'
-41 00'
0
20
40 km
Type 1
Type 2
Type 3


Af. Cumbuca
Santo Antônio Camelo
Preto
Ribeirão de Baixo
Rio Lapão
Córrego do Lapão
Rio Mandassai
Rio Utinga - BR
Santo Antônio Bahema
Paraguaçu Nascente
Rio Bonito do Meio
Utinga - 2ª Ponte
Rio Alpercata
Rio da Volta do Américo
Córrego da Moça
Rio Pombo
Rio Piabas
Capãozinho
Rio Soltinha
Riacho Pau Dárco
Serrano
Rio Lençois
Riacho Conceição do Gatos
Córrego Cercado
São Jos
Lavrinha
Riacho do Mel
Riacho Pau Ferro
Rio Mosquito
Rio Mucugezinho
Riacho Três cancelas
Rio da Bomba
Rio Paraguaçu
Rio Timbó
Rio Riachinho
Rio Timbozinho
0
1
2
3
4
5
6
7