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PRIMARY RESEARCH PAPER

Use of the BEAST model for biomonitoring water quality in a neotropical basin

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Abstract The use of predictive models in Neotropical basins is relatively new, and applying these models in large basins is hindered by the lack of ecological, geographical, and social-environmental knowledge. Despite these difficulties, we used data from the das Velhas River basin to apply the BEAST (Benthic Assessment of SedimenT) methodology to evaluate and classify the level of environmental degradation. Our two main objectives were to modify and implement the BEAST methodology for use in biomonitoring programs of Brazilian basins, and to test the hypothesis that a gradient of environmental degradation determines a gradient in the structure and composition of benthic macroinvertebrate assemblages. We evaluated 37 sites: 8 in the main river, 15 in the main tributaries with different impact levels, and 14 in tributaries with minimally disturbed conditions (MDC). The BEAST model allowed us to classify 16 test sites: two as natural, four as altered, three as highly altered, and seven as degraded. Our results indicated degradation of the das Velhas River basin near its urban areas. The BEAST model indicated that the pollution gradient found among the sites generated a gradient of the macroinvertebrate assemblages, corroborating the hypothesis.

Keywords Environmental impact · Benthic macroinvertebrates · Das Velhas River · Bioindicators · Urban basin · Assemblages

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Introduction

River flows are a renewable resource that provides benefits to humans including water for drinking and industrial processes, irrigation, navigation, recreation, waste disposal, and electric power (Jackson et al., 2001). All these activities reduce water quality and aquatic biodiversity (Burgmer et al., 2007).

Environmental degradation and public pressures have stimulated environmental evaluations that aid assessment of the failure or success of programs that are intended to rehabilitate poor environmental conditions. The scientific community has recently developed and extended biomonitoring programs (Norris & Hawkins, 2000; Passy, 2007). Aquatic macroinvertebrate assemblages are frequently used as indicators of environmental quality, allowing the detection and evaluation of ecosystem impacts (Melo

& Froehlich, 2001; Roque et al., 2003; Moreno & Callisto, 2006).

The United States, Australia, and the European Union use drainage basins as their study, planning, and management units (Allan et al., 1997; Statzner et al., 2001; Barth, 2002; Allan, 2004). Recently, Brazil has employed drainage basins to study its waterbodies through Law 9433 of the National Policy on Water Resources (Tundisi, 2003). In this context, we developed a biomonitoring program that evaluates the level of environmental degradation in the das Velhas River basin.

Biological monitoring is less used in developing countries than in developed ones. However, the need for biomonitoring approaches to evaluate the impacts of human activities on natural environments has increased the number of water-quality monitoring programs in developing countries (Ogbeibu & Oribhabor, 2002, Figueroa et al., 2003; Soldner et al., 2004; Castillo et al., 2006, Resh, 2007).

Globally, modern tools have been used in biomonitoring programs since the 1970s (Bonada et al., 2006, Bailey et al., 2007). Biomonitoring programs typically compare the ecological conditions of assemblages from test sites against those from reference sites with minimal alterations (Statzner et al., 2001; Bailey et al., 2005). A predictive model was developed for such studies in the UK (Wright et al., 1984, 1993), and later in Canada (Reynoldson et al., 1995), Australia (Smith et al., 1999), the United States (Hawkins et al., 2000), Portugal (Feio et al., 2007), and Bolivia (Moya et al., 2007).

This approach allows the evaluation of water quality in a basin through multivariate analyses, where sites are evaluated by their physical and chemical characteristics plus the structure and composition of their benthic macrofauna (Barbour et al., 1996; Reynoldson et al., 1997; Barbour et al., 2000). For this study, the minimally disturbed condition (MDC) concept suggested by Stoddard et al. (2006) was employed, considering reference sites as those without significant human disturbances.

We applied the BEAST (BEnthic Assessment of SedimenT) model to MDS sites in the das Velhas River basin. This model was originally developed and applied in Canada by Reynoldson et al. (1995, 1997). The model tests whether a new locality fits into a confidence limit specified by multidimensional scaling (MDS), defined previously from reference sites. The model evaluates whether the new locality is similar or not to the MDC (Feio et al., 2007).

Our objectives were to adapt and implement the BEAST methodology for use in biomonitoring programs for Brazilian drainage basins, and to test the hypothesis that a gradient of environmental degradation determines a gradient in the structure and composition of benthic macroinvertebrate assemblages. Our premise was that the structure and composition of benthic assemblages are altered, when water quality is modified by human disturbances (Rosenberg & Resh, 1993). Consequently, it is expected that environments with high levels of human disturbance will contain simplified invertebrate assemblages that are similar to those found in environments located in different regions but subject to similar levels of disturbance.

Materials and methods

Study area

The das Velhas River is a tributary of the São Francisco River, which is 2,700 km long. The São Francisco River basin has great importance for Brazil because of the large volume of water transported through the semi-arid northeast region, the river's potential for human use, and its socio-economic contributions to the region. The São Francisco River has 168 tributaries, of which 99 are perennial (Camargos, 2005).

The das Velhas River is one of the most important tributaries of the São Francisco River, regarding both water volume and pollution. The das Velhas River basin is located in the central region of the state of Minas Gerais, between 17°15′ and 20°25′ S and 43°25′ and 44°50′ W, and has an elongated shape in the north–south direction. The basin is 761 km long, with a mean width of 384 m, and drains an area of 29,173 km^2 (Polignano et al., 2001) (Fig. 1).

The basin is heavily urbanized, with 51 municipalities, including the metropolitan area of Belo Horizonte, the capital of Minas Gerais, which has a total population of 4.5 million. In addition, much of the river, together with some of its headwater streams, is located in the "Quadrilátero Ferrífero" region where iron and gold-mining industries are concentrated (Polignano et al., 2001).

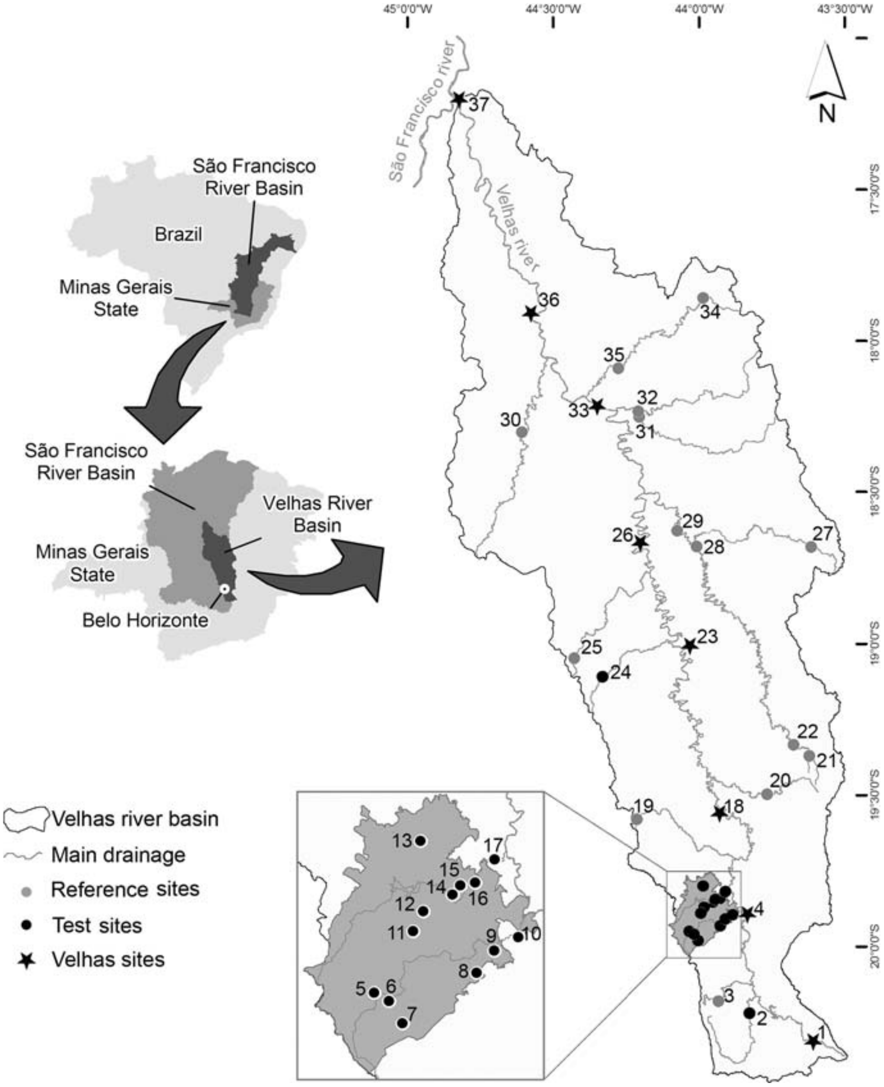

Fig. 1 Das Velhas River basin in Brazil and the sampling network. *Source*: MapBase: Projeto GeoMinas, modified by Projeto Manuelzão/UFMG, 2004

Methods

Biomonitoring program

The sites were selected according to two criteria: (i) sites considered receptors of pollution and other human disturbances, and (ii) river stretches considered of great importance for the water volume of the das Velhas River. The biomonitoring program in the das Velhas River basin included 37 sites: 8 in the main river and 29 in selected tributaries (15 in areas with different levels of environmental impact, and 14 considered minimally altered).

We sampled every three months from August 2004 through May 2006, four times during both the dry and wet seasons, to evaluate seasonal influences. We measured digital-cartographic, physical habitat, and biological variables.

The abiotic variables temperature, conductivity, pH, turbidity, total dissolved solids, current velocity, and depth were measured in situ using portable YSI 60 and 85 m (Yellow Springs, Ohio). Concentrations of dissolved oxygen, total phosphorus (Strickland & Parsons, 1960), and total nitrogen (Mackereth et al., 1978) were determined in the laboratory. Sediment organic matter content was estimated gravimetrically, and the granulometric composition was estimated following Suguio (1973), modified by Callisto & Esteves (1996).

Benthic macroinvertebrates were sampled through use of a Surber sampler (0.09 m^2), and abundance was calculated as the percentage of individuals in each taxon that were present in a sample. Three samples were collected at each site, and the sediment was stored in plastic bags. In the laboratory, the samples were washed over sieves with 1, 0.5, and 0.25 mm mesh size, and the organisms were processed using a stereoscopic microscope (40× magnification). The specimens were identified to the lowest possible taxonomic level, fixed in 70% ethanol, and deposited at the Benthic Macroinvertebrate Reference Collection of the UFMG Biological Sciences Institute, as described by Callisto et al. (1998) and França & Callisto (2007).

In addition to using the BEAST model, we evaluated the structure of the macroinvertebrate assemblages through the Shannon-Wiener diversity index, Pielou's equitability index (according to Magurran, 1991), density (individuals.m^{-2}), dominance (% individuals), and taxonomic richness (number of taxa). All calculations were based on the total organisms collected during each sampling period for each site.

Reference sites

For this study, six MDC sites in the das Velhas River basin were chosen because of their relatively natural ecological characteristics. The sites were located in environmental protection areas and in national and state parks (Fig. 1).

The variables measured at all sites were compared with the values from the primary reference areas, to select additional reference sites. We classified the remaining sites through the use of discriminant analysis (DA) (Jackknife with crossed validation classification using Alpha-to-Enter = 0.150 and Alpha-to-Remove = 0.200). The analysis was carried out with Statistica software 2001, version 6, StatSoft, Inc., using abiotic variables that are susceptible to changes due to human activities. All variables except pH were normalized for these analyses.

Predictor variables included total-P, pH, total dissolved solids, conductivity, results of a Rapid Assessment Protocol for characterization of ecological conditions (Callisto et al., 2002), temperature, organic matter, granulometric composition, and dissolved oxygen concentration. We rejected sites where pH, conductivity, total-N, and total-P values exceeded limits defined by the IGAM (State water management institute) for primary contact with water.

Using the Mahalanobis distance matrix generated by the Discriminant Analysis, we generated a hierarchical cluster analysis in PRIMER software (2001, version 6 Beta, PRIMER-E Ltd., Plymouth, UK; Clarke and Warwick, 2001). This analysis allowed the recruitment of additional sites as reference sites.

To evaluate the consistency of the reference sites as a uniform group, we used SIMPER analysis (PRIMER Software). This analysis reveals similarities between primary reference sites and new reference sites based on their invertebrate assemblages (Feio et al., 2007).

Waterbody monitoring

We used BEAST to classify the impact levels of the sampling sites. The method assumes that the quality of a test site is determined by the decrease in the degree of similarity of this site compared with the reference sites. To use the BEAST model, sites on the das Velhas River with stream order greater than 6 were removed. These large-river sites supported different macroinvertebrate assemblages in our analysis, and also in the literature (Vannote et al., 1980; Buss et al., 2002, 2004). We also evaluated the effect of wet and dry seasons on macroinvertebrate-assemblage richness and density, through use of SIMPER analysis and a Repeated Measures Analysis (ANOVA, Statistica Software).

The data on macroinvertebrate assemblages at each test site were compared with the data obtained from the reference sites. For this comparison, we used a nonparametric multidimensional scaling analysis (MDS in the PRIMER software). The three-dimensional order generated by the MDS analysis was plotted using Statistica software to build probability ellipses using the scatterplot method (three ellipses of 90, 99, and 99.9% probability of difference). The layers formed by the ellipses indicated natural sites (<90%), altered sites (>90% and<99%), highly altered sites (>99% and<99.9%), and degraded sites (>99.9%) (Reynoldson et al., 2000). Three bi-dimensional representations generated by the ordination for each site were produced (axis 1 vs. axis 2, axis 2 vs. axis 3, and axis 1 vs. axis 3). The graphical representation chosen for each test site was that which attributed the worst position in relation to the reference sites. Therefore, our conclusions about the test sites were conservative. The macroinvertebrate assemblages found in the sites classified by the BEAST model were evaluated, and the main groups of organisms that characterize the zones between the ellipses were identified.

Results

We collected 355,803 aquatic macroinvertebrates. All specimens were identified to family level, in 87 taxa (1 Platyhelminthes, 1 Nemathelminthes, 2 Annelida, 71 Arthropoda, and 12 Mollusca).

With the exception of the das Velhas River, the tributaries showed higher insect abundances, followed by annelids (Table 1). In addition, higher taxonomic richness, diversity, and equitability scores were obtained at the reference sites (Fig. 2).

Discriminant analysis of the abiotic variables allowed us to add nine sites considered in MDC to the six primary reference sites (Fig. 3). The SIMPER analysis of primary reference sites and the added sites indicated great similarity (Dissimilarity = 34.86). Consequently, the reference sites totaled 14 sites. This number allowed us to use the BEAST model for the das Velhas River basin, because it exceeded the minimum number of 10 recommended by Reynoldson & Wright (2000) for the reference group.

Reynoldson & Wright (2000) also recommended subsequent sampling to evaluate natural changes in reference sites. In this analysis, a dissimilarity of 56.90 was observed between the wet and dry seasons. In addition, the repeated measures ANOVA indicated that there were no significant differences between seasons, when the taxonomic richness indexes ($F36 = 1.10$, $P = 0.343$) and the organismal densities ($F36 = 1.36$, $P = 0.115$) were evaluated. The BEAST allowed us to classify 16 test sites (Fig. 4), 2 of which were classified as natural, 4 as altered, 3 as highly altered, and 7 as degraded.

The BEAST model generated a site gradient as a function of the benthic macroinvertebrate assemblages. Some of the taxonomic groups, besides appearing at the reference sites, were also characteristic of the localities classified in another ellipse. Seven macroinvertebrate families (Calamoceratidae, Hydrobiosidae, and Leptoceridae—Trichoptera; Megapodagrionidae, Calopterygidae, and Gomphidae—Odonata; Gripopterigidae—Plecoptera) represented non-impacted sites. In altered sites, 12 families were found (Baetidae and Leptophlebiidae—Ephemeroptera; Psephenidae—Coleoptera; Belostomatidae, Corixidae, and Naucoridae—Heteroptera; Corydalidae—Megaloptera; Gomphidae and Libellulidae—Odonata; Hydropsychidae and Philopotamidae—Trichoptera; Simuliidae—Diptera). In sites classified as highly altered and degraded, we found, respectively, two (Canacidae—Diptera; Planorbiidae—Gastropoda) and five families (Anthomyidae and Dolichopodidae—Diptera; Veliidae—Heteroptera; Physidae—Gastropoda; Sphaeriidae—Bivalvia).

In reference sites, we found eight families that were absent from all the other sites studied in the basin (Dytiscidae—Coleoptera; Oligoneuriidae and Polymitarcyidae—Ephemeroptera; Hebridae, Notonectidae, and Pleiidae—Heteroptera; Odontoceridae and Xiphocentronidae—Trichoptera).

Discussion

Ecological information is frequently used in social and environmental arenas to help decision makers implement environmental policies, environmental management, biodiversity conservation, environmental rehabilitation, and water-resources management, and to evaluate climate changes (Barbosa et al., 2004). The biomonitoring program of the das Velhas River basin offers a new prospect for Brazilian water-resources policy, because it focuses on an entire large basin (29,173 km^2) that suffers from many human disturbances (mining, urbanization, forest clearance, agriculture, etc.). Long-term study will allow us to identify future changes in the drainage basin and in the water quality, as waste-treatment facilities come on line.

To offer an updated biomonitoring methodology for the das Velhas River basin, we compared minimally disturbed reference sites (Stoddard et al., 2006) against test sites with a range of disturbance. Others have also found that reference sites are important and efficient tools for evaluating (Stoddard et al., 2006) and preserving lotic ecosystems and their biodiversity (Agostinho et al., 2004; Takeda et al., 2004; Train & Rodrigues, 2004). The BEAST model indicated that

Table 1 Total numbers of organisms found in natural, altered, highly altered, and degraded sites, in the das Velhas River

	Reference sites	Natural sites	Altered sites	Highly altered sites	Degraded sites	Das Velhas River
Diptera						
Anthomyidae					5	4
Canacidae	14		1	1		
Ceratopogonidae	788	273	61	15	100	278
Chironomidae	52539	10891	41439	6110	2981	29039
Culicidae	22		21	3	893	
Dolichopodidae	2		3		1	4
Empididae	281	96	7	1	8	73
Ephydridae			3		1	
Muscidae	1		2	1	6	2
Psychodidae	34	30	2508	1158	4779	101
Simuliidae	23316	528	548			43
Stratiomyidae		2	331	43	925	2
Tabanidae	28	2	3			4
Tipulidae	283	2	31	2	38	3
Trichoptera						
Calamoceratidae	24	6				
Ecnomidae	8		2			
Glossosomatidae	263	1	10			67
Helicopsychidae	40	6	103			3120
Hydrobiosidae	49	9				
Hydropsychidae	3937	59	1424			12616
Hydroptilidae	900	81	36			42
Leptoceridae	326	14				10
Odontoceridae	66					5
Philopotamidae	4043		402			5
Polycentropodidae	105	2	1			1
Xiphocentronidae	7					
Ephemeroptera						
Baetidae	8039	807	883			1281
Caenidae	190	14	1			
Leptohyphidae	4647	195	608			253
Leptophlebiidae	3670	10	742			89
Oligoneuriidae	3					
Polymitarcyidae	39					21
Plecoptera						
Gripopterigidae		20				
Perlidae	289	26	39			1
Coleoptera						
Dytiscidae	94					2
Elmidae	4839	304	1295		2	61
Gyrinidae	61	3	1			1
Hydraenidae						1

Table 1 continued

	Reference sites	Natural sites	Altered sites	Highly altered sites	Degraded sites	Das Velhas River
Hydrophilidae	193	14	21	1	29	15
Psephenidae	6		3			1
Staphylinidae	3	1	1	1	1	15
Heteroptera						
Belostomatidae	10		3			
Belostomidae	12		3			
Corixidae	155		2			91
Gerridae	5	1				4
Hebridae	2					
Naucoridae	474	32	47			7
Notonectidae	16					2
Pleidae	5					
Veliidae	83	3			1	8
Megaloptera						
Corydalidae	151	10	69			14
Odonata						
Aeshnidae	36	2	5			
Calopterygidae	34	3	1			2
Coenagrionidae	181	1	22			1
Gomphidae	277	27	2			28
Libellulidae	531	12	13			49
Megapodagrionidae	12	2				
Annelida						
Oligochaeta	4059	3087	11293	3512	22572	71489
Total	115192	16576	61990	10848	32342	118855

two river sites that have undergone moderate human disturbance still support benthic assemblages that allow them to be classified as natural (Itabirito River and das Velhas headwaters). That is, they still have well-preserved ecological characteristics (high-quality ecosystems). The benthic assemblages in the other test sites indicated varying levels of environmental alterations and reduced benthic biodiversity. The majority of the test sites (13) are distributed inside an urban and densely-populated region of the basin. Those human settlements produce countless environmental stressors, and the uncontrolled urbanization of the cities increases anthropogenic pressures on aquatic ecosystems (Walters et al., 2003; Camargos, 2005). Rivers and streams receive high loads of untreated domestic sewage and industrial effluents which drastically diminish the quality of the environmental services afforded by the ecosystems (Callisto et al., 2005). The use of benthic macroinvertebrates as bioindicators of water quality in sites of the das Velhas River basin has indicated extreme alterations. We observed some highly degraded sites with high densities of pollution-tolerant benthic groups, as well as well-preserved areas with a high richness of pollution-sensitive macroinvertebrate groups.

Other studies have treated the differences between altered and natural areas in Brazil (Marques & Barbosa, 2001; Buss et al., 2002; Buss & Salles, 2007). However, a methodology, capable of classifying degradation levels and distinguishing a gradient of anthropogenic alterations has long been sought in studies monitoring human impacts on waterbodies

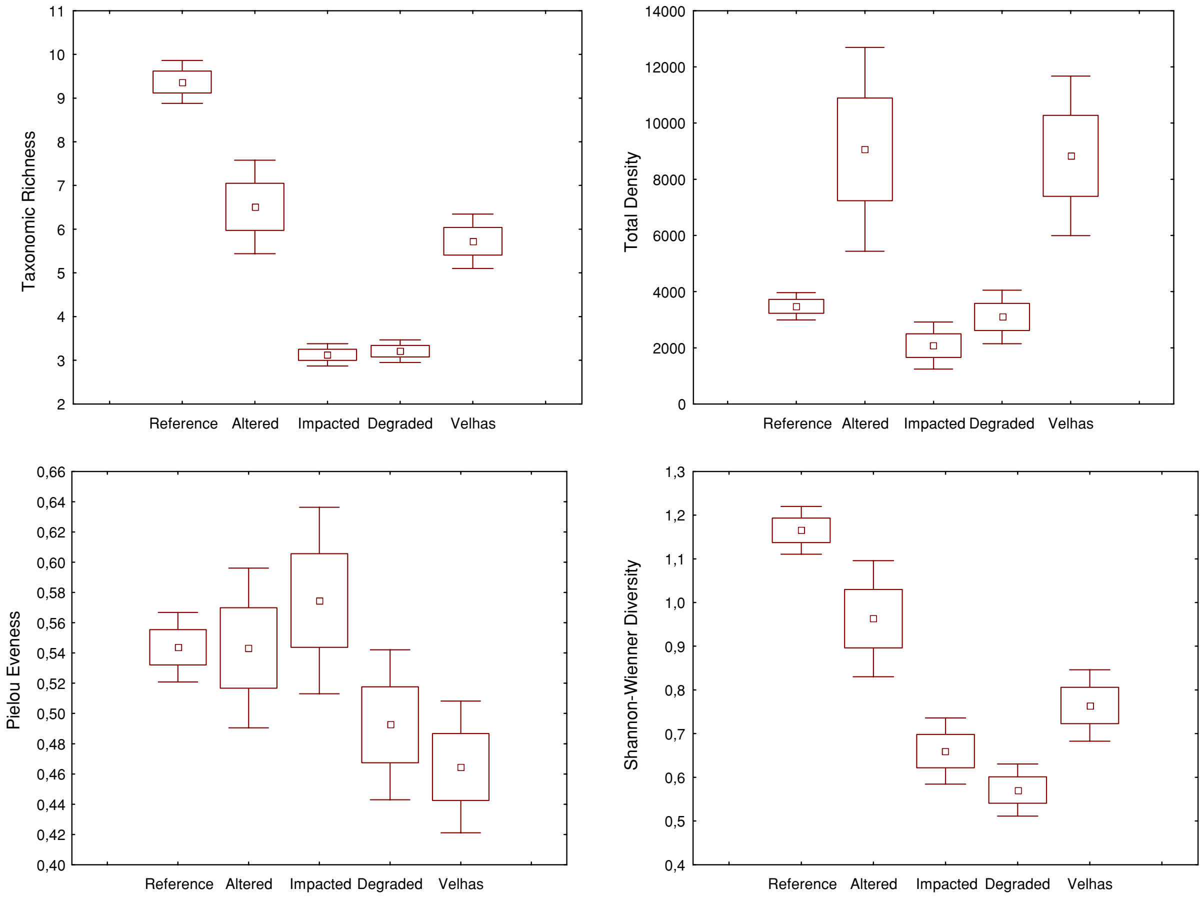

Fig. 2 Macroinvertebrate assemblage structure indexes of das Velhas River basin sites

(Norris et al., 2007). This study indicates that the BEAST approach may have considerable potential for doing so in tropical waters.

Combining data from our biomonitoring program (biological indexes and water quality) with the information produced by the BEAST model, it was possible to demonstrate a pollution gradient among sites. In other words, similar water-quality conditions were found among sites, independently of their spatial distribution. In addition, similar benthic macroinvertebrate assemblages were found at the localities studied, irrespective of their locations.

It was also evident that the effects of anthropogenic alterations on aquatic ecosystems became more drastic when there was a sewage discharge, riparian vegetation clearance, and sediment accumulation in the riverbed, all characteristics of the river segments classified as degraded. These alterations caused large differences between benthic macroinvertebrate assemblages at these sites and those at the reference sites. However, the modifications found at sites classified as moderately altered still maintain macroinvertebrate assemblages that are more similar to those found in reference sites.

In evaluating the resistance and resilience of macroinvertebrate assemblages, Melo et al. (2003) observed that small environmental alterations, or alterations that do not drastically affect habitat and water quality, do not alter assemblage richness. Although we did not evaluate the stability mechanisms of macroinvertebrate assemblages, we believe that the capacity reported by Melo et al. (2003) can explain the maintenance of a considerable part of the benthic macroinvertebrate taxa in altered river segments.

Besides their use in predictive models and in the development of biological indexes for environmental monitoring, benthic macroinvertebrates can also be used as impact “detectors” or “sensors” (Cairns &

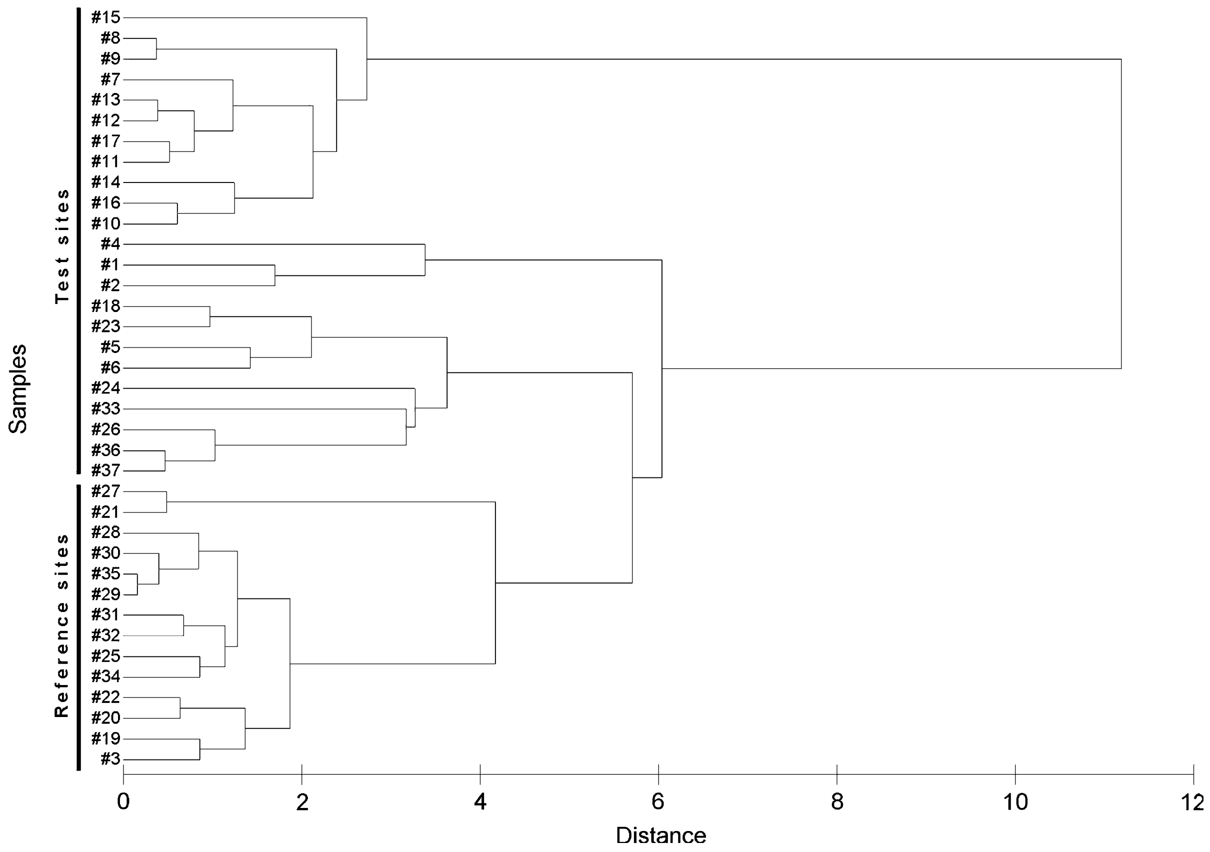

Fig. 3 Site groups as a function of physical and chemical water quality characteristics in the das Velhas River basin

Pratt, 1993; Spellerberg, 1994; Friberg & Johnson, 1995; Callisto & Gonçalves, 2002). In this study, Trichoptera had the broadest distribution and highest abundance in the das Velhas River basin, and could be used as an important detector of human activities in the basin. Trichoptera are considered as an excellent indicator because of their richness of species and genera (Vieira-Lanero, 2000), which include organisms that are sensitive and others that are tolerant to water pollution (Rosenberg & Resh, 1993).

The biomonitoring program of the das Velhas River basin is another study (Barbosa, 1994; Moreno & Callisto, 2006) supporting the use of biological tools in environmental monitoring programs in a tropical region. This study pioneers use of the MDC in Brazil. One of the main difficulties in bioassessment is the establishment of reference sites, free of present and historic human disturbance. The das Velhas River basin is an example of this difficulty, because its rivers have suffered modifications since the beginning of the sixteenth century, when gold and diamonds were discovered in the basin (Núbia et al., 2003). Nonetheless, minimally disturbed sites served to provide reference sites adequate to distinguish three levels of alteration.

We and others (Norris & Hawkins, 2000; Bonada et al., 2006, Bailey et al., 2007) have shown that predictive models and other biological metrics offer countless advantages for evaluating water quality. In the das Velhas River basin, we support the use of benthic assemblages in ecological models for understanding, evaluating, and mapping the environmental condition of hydrographic basins. Improved biological monitoring facilitates better basin management and documents the results of those improvements. This monitoring capacity is of fundamental importance for the preservation of freshwater ecosystems.

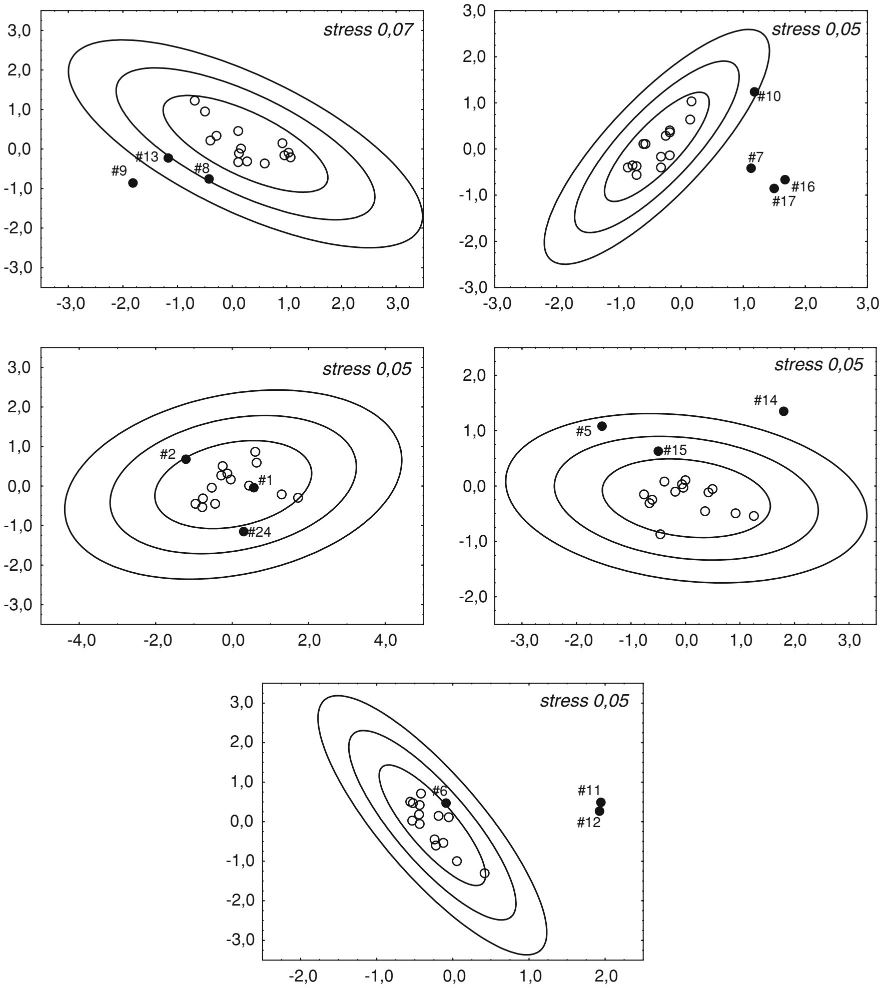

Fig. 4 BEAST modeling results between test (*black circle*) and reference (*white circle*) sites in the das Velhas River basin. Three ellipses of 90, 99, and 99.9% probability of difference indicated natural, altered, highly altered, and degraded sites

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