The diversity of benthic macroinvertebrates as an indicator of water quality and ecosystem health: a case study for Brazil

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Abstract

The state of Minas Gerais still has some nearly pristine aquatic ecosystems, thus representing strategic aquatic resources for Brazil. Rivers and creeks of Serra do Cipó (19° - 20° S, 43° - 44° W) constitute an example of natural ecosystems in preserved conditions where a broad research project was initiated in 1996 aimed at the assessment of aquatic biodiversity and water quality characterisation. This area is the natural water division between the hydrographic basins of Doce and São Francisco rivers, two of the most important watersheds of Minas Gerais. The main goal of this study was to assess the diversity of benthic macroinvertebrate communities and use them as bioindicators of water quality. A secondary goal was to classify the benthic communities into three categories: 1) non-affected communities: those preserving a pristine structure, which are significant for fragile ecosystems, 2) median-affected communities: those receiving some degree of impacts, formed by a mixture of stenotopic and euritopic populations capable of adapting to new conditions thus reflecting the ecosystem's resilience, and 3) heavily-affected communities: those with very poor diversity, generally subject to severe human impact with destructive effects, but that are still important for the functioning of these degraded ecosystems.

Keywords: biodiversity, bioindicators

1. Introduction

Recently, biological methods have been replacing or complementing physical and chemical measurements in assessing river conditions (Karr, 1991; Resh et al., 1995; Wright, 1995). Furthermore, Norris and Thoms (1999) suggest that the effects on biota are usually the final point of environmental degradation and pollution of rivers and thus are an important indication of ecosystem health. However, ecosystem health is a relatively new concept (Shrader-Frechette, 1994) attempting to integrate ecology, environmental management and medicine under the normative influence of socially defined goals for the environment (Fairweather, 1999), and as such it constitutes a controversial topic (Karr, 1999).

According to Rapport (1989) and Norris and Thoms (1999), three approaches might differentiate 'healthy' from 'sick' ecosystems: 1) the absence of distress defined by measured characteristics or indicators; 2) the ability of an ecosystem to handle stress, or bounce back – its resilience (Holling, 1973); and 3) the identification of risk factors such as industrial or sewage effluents. However, Norris and Thoms (1999) point out that the ecosystem health approach emphasises the biota, ig-

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noring the use of non-biological parts of the ecosystem that may operate independently from biological ones but on which the biota may be dependent.

Biodiversity represents not only the organisms living in an area plus the ecological processes necessary for their maintenance but includes the interactions between these two components which can be translated in the capacity of the ecosystem to support a number of living forms (Barbosa et al., 1997, 1999; Galdean and Staicu, 1997).

There are many biological indicators (Chessman et al., 1999; Harris and Silveira, 1999; Kingsford, 1999) among which the most commonly used have been benthic macroinvertebrates (Resh and Jackson, 1993; Kay et al., 1999; Smith et al., 1999). Furthermore, Norris and Thoms (1999) pointed out that taxonomic richness of invertebrates is central to the British RIVPACS (River InVertebrate Prediction And Classification System) proposal (Wright, 1995) and the Australian River Assessment System (Simpson et al., 1997). The central role of community was emphasized in two recent proposals for two watersheds in Minas Gerais (Junqueira and Campos, 1998; Barbosa et al, 1999). The use of benthic macroinvertebrates as bioindicators is supported by the fact that they are usually stable in time and space, thus reflecting the changes the ecosystem had gone through (Rosenberg and Resh, 1993). However, it may not be possible to characterize major processes using specific organisms; it may be necessary to take into account trophic categories or other ecological units (Barbosa and Galdean, 1997).

The present study is based on the concept of the hydrographic basin as the unit of study. The uses of water and socio-economic aspects are considered as basic elements necessary to understand the structure and function of the ecosystem. These elements are essential for the definition of policies and strategies for conservation and management. This approach introduces new spatial/temporal scales, the need for interdisciplinary activities, and offers an opportunity for training specialists capable of dealing with the urgent practical problems of modern societies (Tundisi and Barbosa, 1995).

Finally it must be stressed that the ecological study of an aquatic ecosystem must consider the general landscape surrounding it (Turner, 1998), taking into consideration the spatial arrangement of ecosystems and the large-scale processes linking them (Beeby and Brennan, 1997). Water quality is directly influenced by the predominate uses of the land and resources within the watershed, making these uses necessary elements to assess the existing relationships between aquatic and terrestrial ecosystems since the quality and quantity of the terrestrial inputs are determinant factors for the ongoing processes within the aquatic ecosystem (Wallace et al., 1997).

There are a few studies of the river ecology of Brazil, including the work of Baptista et al. (1998), who tested the River Continuum Concept of Vannote et al. (1980), those of Diniz-Filho et al. (1998), Oliveira and Froehlich (1996; 1997a), Oliveira et al. (1997), Bispo and Oliveira (1998), Froehlich and Oliveira (1997), Oliveira and Froehlich (1997b) who assessed aquatic insects (Ephemeroptera, Plecoptera, Trichoptera). The freshwater biodiversity of Serra do Cipó has been evaluated by Maia-Barbosa et al. (in press), Galdean et al. (1999), and Galdean et al. (in press).

The main objective of this research was to use the diversity of benthic macroinvertebrates as indicators of water quality, in order to characterize the ecosystem health of some lotic ecosystems of Minas Gerais, Brazil.

2. Methods and materials

2.1 Study area

Within its 587,187 km^2, the state of Minas Gerais shows a considerable variety of geological and climatic features, resulting in several landscapes varying from mountains to wetlands with distinct types of vegetation of which rain forests, savannas and rupestrian fields cover considerable areas. In addition there are considerable pasture and agricultural areas and large *Eucalyptus* spp. plantations. In terms of terrestrial vegetation, the state ranks number one in natural vegetation types comprising deciduous dry forests (Caatinga) in the northeast, savanna occupying large areas in the centre, grasslands mainly along the mountains in the east, and the Atlantic Forest (Mata Atlântica) originally north to south along the Atlantic coast, now replaced in most areas by pasture and agricultural areas.

Minas Gerais is particularly rich in aquatic resources possessing 14 watersheds among which eight are considered medium to large. Among these, the Rio Doce and Rio São Francisco are of paramount importance for the eastern part of the country. About 90 man-made lakes and reservoirs have been built since early 1960s mainly to provide electricity to support the growing demands of the country. The diversity of natural lakes is not very high, restricted to the Rio Doce Lake District and the karstic lakes of the Lagoa Santa Plateau.

The data presented here were gathered from river

Figure 1 Map of the studied area showing the rivers Cipó, Peixe, Preto do Itambé and the streams Congonhas and Indaiá.

stretches of the São Francisco and Doce rivers. River stretches examined in the Rio São Francisco were restricted to headwaters at Serra do Cipó (Figure 1), while the examined areas of the Rio Doce are located at its middle course. Preliminary studies (Barbosa et al., 1996) have shown that the waters of Serra do Cipó are of high quality, in general slightly acidic (pH ranging between 6.65 and 7.46), well oxygenated (usually > 90% saturation, and with low nutrient concentrations (< 35 µg l^{-1} total P; 90-360 µg l^{-1} total N). On the other hand, the waters at the middle Rio Doce are mostly impacted by industry such as mining, iron and steel plants and by *Eucalyptus* spp. plantations and the cellulose industry, and receive considerable amounts of untreated domestic and industrial sewage (80,000 m^3 in 1992), resulting in areas with up to 765 µg l^{-1} total P and up to 6,600 µg l^{-1} total N (Barbosa et al., 1997).

Despite the heavy degree of degradation, the existing biodiversity of Rio Doce is still remarkable, there being identified 169 taxa of phytoplankton, 65 taxa of zooplankton, 84 taxa of benthic invertebrates and 25 species of fishes, among which five were introduced (Barbosa et al., 1997; 1999).

2.2 Sampling and analysis

Benthic samples for Serra do Cipó were collected from 18 sampling sites at rivers Cipó, Peixe, and Preto do Itambé, and streams Indaiá and Congonhas, during the rainy (February/March) and dry (October/November) periods of 1997. The organisms were collected from stones, mud, leaves, mosses, aquatic macrophytes, and sand beds, by hand and the use of an Eckman dredge and immediately preserved in 10% formalin. In the laboratory, samples were washed through a 0.125 mm sieve, using tap water. After sorting and identification, the organisms were preserved with 70% alcohol and deposited in the collection of benthic macroinvertebrates of the Federal University of Minas Gerais.

Physical and chemical variables (water temperature, pH, conductivity, dissolved oxygen, and redox potential) were measured *in situ* using a Hydrolab multiprobe apparatus in order to assess water quality. Water samples were taken to the laboratory to determine the concentrations of total N, total P, soluble 'reactive' P, ammonium-, nitrite-, and nitrate-N, according to Golterman et al. (1978) and Mackereth et al. (1978).

Plecoptera, Ephemeroptera, Trichoptera, and Diptera-Chironomidae were characterized according to their trophic needs, based on laboratory analysis, field observations, and the available literature (Wiederholm, 1983; Merritt and Cummins, 1988; Epler, 1995; Pescador, 1997), as well as the taxonomic composition, genera richness and trophic groups.

The distribution of benthic macroinvertebrates along the rivers was also studied, taking the communities as subsystems of the lotic ecosystem and estimating their importance for the main ecological processes. The central focus of the study was the role of the communities in maintaining diversity using the available trophic resources. The diversity of benthic communities was evaluated considering the existing trophic groups (grazers, filtering collectors, gathering collectors, piercers, general detritivorous and predators) and the dominant species or group of species, taking into account their sensitivity, dispersal area and dependence on a particular trophic resource.

Furthermore, the structure of the communities included taxonomic composition, numerical relations among the recorded taxa and trophic dominance. The main trophic resources (periphyton, mosses with fine particulate organic matter, and allochthonous organic matter) and the trophic relations were also recorded, with special emphasis on the importance of predators as controlling elements.

3. Results and discussion

3.1 Aquatic ecosystem health in Minas Gerais

The highly diverse aquatic ecosystems of Minas Gerais show distinct levels of trophic status and health (Table 1). Deserving special attention are those areas of high quality waters, particularly streams and creeks in high altitude areas (e.g., Parque Nacional da Serra do Cipó, Parque Natural do Caraça, Parque Nacional da Serra da Canastra) which are the main sources of important rivers in the country (e.g., São Francisco, Doce, Paraná), and those waters within protected areas, such as the Rio Doce lake system at Rio Doce State Park.

The high water quality referred to above is reflected by: 1) the high abundance of very sensitive taxas (Plecoptera, Gripopterygidae; Coleoptera, Psephenidae; Trichoptera, Hydrobiosidae; Diptera, Chironomidae, Tanytarsini) as suggested by Corkum (1989) and Pinder (1995), and 2) the low conductivity of the waters, and oligotrophy which results in low accumulation of nutrients (Galdean and Staicu, 1997).

In addition to the high altitude waters and those waters within protected areas there also exist aquatic ecosystems showing good quality waters, despite some degree of impacts. Good examples of these are some

Table 1 Physical and chemical characteristics, typical taxa and Shannon-Weamer indices of benthic macroinvertebrate communities for some freshwater ecosystems of Minas Gerais, Brazil. Non and median affected systems from Galdean et al. (1999 and in press); Heavily affected systems from Barbosa et al. (1997, 1999).

	Non-affected	Median affected	Heavily affected
Ecosystems	Indaiá and Congonhas streams	Cipó river at Santana do Pirapama and Sumidouro localities	Piracicaba river
pH	≤ 4.5	5.0 – 6.5	> 6.5
Total alkalinity (mEq CO_2 l^{-1})	≤ 0.2	0.2 – 0.5	≥ 0.5
Conductivity	≤ 20.0	20.0 – 50.0	≥ 50.0
Dissolved oxygen (% sat.)	≥ 6.0	3.5 - 5.9	≤ 3.5
Total N (µg l^{-1})	≤ 100.0	100.0 – 390.0	> 400.0
Total P (µg l^{-1})	< 50.0	50.0 – 149.0	> 150.0
typical taxa	Gripopterygidae *Hermanella* *Spanophlebia* Hydrobiosidae Psephenidae	*Farrodes* *Thraulodes* Baetidae *Marilia* *Chironomus* Naididae	*Chironomus* Tubificidae
Shannon diversity index	≥ 3.0	1.5≤H'<3.0	≤1.5

tributaries of the upper Piracicaba river (e.g., Caraça and Santa Bárbara rivers) on the middle stretch of Doce river. These ecosystems are sufficiently stable to maintain a good resource utilization by their natural biota (Barbosa et al., 1997; 1999).

Finally, there are within these areas, low water quality mainly as a result of mining, iron and steel plants, extensive *Eucalyptus* spp. plantations, cellulose industry and an intense urbanization process, thus rendering increasing degradation. Barão de Cocais and Ipanema rivers are well-known examples within the middle Doce river basin (Barbosa et al., 1997; 1999).

A gradual decline of water quality and biological conditions in the studied watersheds is related to the absence of obvious point-source pollution discharges, as suggested by Harding et al. (1999). This lower water quality and the decline in ecosystem health is revealed by: 1) low level of biodiversity and consequently dominance of Oligochaeta and *Chironomus* (Diptera, Chironomidae), as demonstrated by Marques and Barbosa (1997) and Marques et al. (1999) for the Piracicaba river; 2) the presence of specimens of *Chironomus* larvae with morphological deformations probably determined by accumulation of heavy metals and other mutagens, as suggested by Callisto et al. (in press) also at the Piracicaba river basin, and 3) high P and N concentrations in the water and sediments, suggesting that the ecosystem is not able to process the present concentrations of nutrients thus resulting in eutrophication (Barbosa et al., 1997; 1999).

3.2 Benthic macroinvertebrates as indicators of water quality

Based on physical (e.g., light penetration, temperature), chemical (e.g., dissolved oxygen, electrical conductivity, pH, total alkalinity, nutrient concentrations) and biological (e.g., abundance, dominance, frequency, biomass, density) parameters of the waters, limnologists have been trying to characterize water quality globally (Bunn et al., 1999).

Considering the dimensions of Minas Gerais (584,000 km^2; 7% of Brazil's landmass) the multiple uses of its aquatic resources and the high diversity of it's aquatic ecosystems, specially designed programs of assess-

Table 2 Proposed categories for benthic macroinvertebrate communities for lotic systems of Serra do Cipó, Minas Gerais.

Gathering and Filtering Collectors	Gathering Collectors	Filtering Collectors	Aquatic Macrophytes and Associated Fauna
Type *Hermanella* and Hydropsychidae	Type *Baetis* and *Farrodes*	Type Hydropsychidae and Simuliidae	Type *Farrodes* and *Marilia*
Type *Farrodes* and *Thraulodes* and Hydropsychidae	Type Cochliopsyche		Type Baetidae and Odonata
Type *Spaniophlebia*			

ment and control of quality and health of the waters are necessary (Barbosa, 1994). Rivers, as very dynamic ecosystems, reflect the quality and health of the entire watershed since they receive not only organic matter (leaves, branches, fine detritus), which is very useful for the aquatic metabolism, but also a huge range of wastes, of which nutrients from agriculture, pesticides and effluents from industries are examples (Barbosa et al., 1999).

Depending on the quality and quantity of these inputs, aquatic ecosystems may well use these allochthonous contributions to their advantage thus enhancing the existing biodiversity. The strategies of using allochthonous inputs can be understood as normal reactions of the ecosystems and they can be assessed through the analysis of the existing functional compartments (Brodersen and Lindegaard, 1999). Benthic macroinvertebrates are a representative example including different types of trophic categories (e.g., herbivores, predators) and are an important part of a functioning ecosystem (Callisto and Esteves, 1998). Aspects such as the proportion of the functional groups (guilds) of benthic macroinvertebrates reflect the modifications (in structure and function) of the ecosystem induced by human activities (Barbosa and Galdean, 1997).

A practical typology of benthic communities was established for the investigated area (Table 2): 1) Communities with a predominance of gathering and filtering collectors which occurred as three types characterized by particular fauna: a) type *Hermanella* (Ephemeroptera) and Hydropsychidae (Trichoptera); b) type *Farrodes* and *Thraulodes* (Ephemeroptera) and Hydropsychidae (Trichoptera); and c) type *Spaniophlebia* (Ephemeroptera). The significance of this last type is related with high primary production of periphyton and a good utilisation of this resource within the community. 2) Communities that have a dominance of gathering collectors in the community (type *Baetis* and *Farrodes* (Ephemeroptera); type *Cochliopsyche* (Trichoptera). 3) Communities which are dominated by filtering collectors (type Hydropsychidae (Trichoptera) and Simuliidae (Diptera). Communities (b) and (3) use large quantities of fine particulate organic matter within the community. 4) Communities that have aquatic macrophytes and associated fauna (type *Farrodes* (Ephemeroptera) and *Marilia* (Trichoptera) and type Baetidae (Ephemeroptera) and Odonata). This last type of community is very important in that it reflects the reaction of the ecosystem to the presence of high quantities of nutrients.

This typology is mainly based on a tendency for eutrophication with a gradient ranging from a high level of biodiversity and different trophic groups to a medium level of biodiversity and dominance of one trophic group, as suggested by Hawkins (1984), Corkum (1989) and Ward (1992).

Considering the significance of the community types, *Hermanella* is a genus of mayflies which is characteristic of cold waters and is very sensitive to changing of water quality (Hawkins, 1984; Dominguez and Flowers, 1989); *Farrodes* and *Thraulodes* are more resistant and widespread; while *Spaniophlebia* is an oligoneuriid mayfly very restricted to particular habitats (flat boulders) (Edmunds et al., 1976). The baetid mayflies (mainly *Baetis*) are found in many habitats, including aquatic macrophytes. Hydropsychidae are typically filtering-collectors and depending on their density may influence considerably the quality of suspended organic particles; *Marilia* is a mainly carnivorous species which therefore directly controls the abundance of benthic populations.

These categories of benthic macroinvertebrate communities in the lotic ecosystems of Serra do Cipó were used as a basis for the proposition of a general typology, hopefully useful in other hydrographic basins in Minas Gerais. Among the water bodies of Serra do Cipó there are some nearly pristine (non-affected) areas possessing some taxonomic indicators of good water quality. Some others show low level of ecological modification (median affected), presenting some indicators of mesotrophic conditions, capable of using the fine particulate organic matter, originated by antropic activities in the zone. Indicators of heavily-affected ecosystems were not recorded in that area although their presence are evident in some stretches of the Piracicaba river, particularly at its lower part (Vale do Aço), a region strongly impacted industrially and by *Eucalyptus* plantations.

The majority of the investigated communities present high diversity, capable of colonizing different habitats. Furthermore, the results show different roles played by the benthic communities, depending on the existing habitats and microhabitats and the degree of impact upon them. In order to analyse these features, a classification of benthic communities in three basic groups is proposed (Table 1): 1) non-affected communities: those preserving a pristine structure, which are significant for fragile ecosystems (see Callisto et al., 1998), 2) median-affected communities: those receiving some degree of impacts, formed by a mixture of stenotopic and euritopic populations capable of adapting to new conditions thus reflecting the ecosystem's resilience (Begon et al., 1996), and 3) heavily-affected communities, those with very poor diversity, generally under severe human impacts with destructive effects, but that are still important for the functioning of these degraded ecosystems.

The above described typology may well be used as a basis for long term monitoring programmes throughout Brazil, considering the fact that in many important hydrographic basins (i.e., Paraná, Paraibuna, São Francisco, Doce, Negro, Paraguay, Trombetas and upper Amazonas) studies using benthic macroinvertebrates as bioindicators of water quality are in progress. The proposed typology can serve as a practical tool to support these studies and also provides indications on the health of the ecosystems. Furthermore, the high population growth and consequent urbanization is likely to provide characteristics favourable both to median-affected communities (i.e., Rio Cipó) and heavily-affected ones (i.e., Rio Piracicaba). The search for nearly pristine environments (i.e., Indaiá and Congonhas streams) is essential since these rivers can be used as reference communities for restoration purposes and monitoring programmes.

4. Conclusions

The present recorded data offers a framework for assessing ecosystem health at the studied areas, using three main approaches: 1) the process of eutrophication as a specific reaction to the quantity of nutrients received from the watershed; 2) the typology of communities specifically depending on the availability and quality of trophic resources; and 3) the identification of reference systems (e.g., ecosystems preserving non-affected communities).

The results of this study allow us to conclude that water quality and ecosystem health can be assessed through the existing diversity of benthic macroinvertebrates which can be evaluated by considering taxonomic composition, the existing functional trophic groups, and the types of predominant communities.

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