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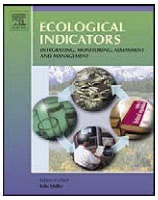

Thermodynamic oriented ecological indicators: Application of Eco-Exergy and Specific Eco-Exergy in capturing environmental changes between disturbed and non-disturbed tropical reservoirs

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ABSTRACT

Effective assessment of ecological quality in aquatic ecosystems has become an important issue for researchers and environmental managers worldwide. The potential of thermodynamic oriented ecological indicators in environmental assessment and management was tested and compared with diversity measures in three tropical reservoirs located in the basin of the Paraopeba River, Minas Gerais State-Brazil. We computed Eco-Exergy based indices (Eco-Exergy and Specific Eco-Exergy) and the Margalef and Shannon–Wiener indices and tested differences in their responses to change in benthic communities across reservoirs characterised by different degrees of anthropogenic disturbance. Indices were estimated based on biotic descriptors (macrofauna biomass, composition, and abundance) and their values analysed against abiotic descriptors (pH, conductivity, transparency, turbidity, nutrients concentration, dissolved oxygen, chlorophyll *a*, and total dissolved solids). The Margalef index showed significant differences between reference and impacted sites, with the highest values in the former type of sites, (Pseudo $F_{2.719} = 24{,}506$, $p = 0.001$), while the Shannon–Wiener index values showed no significant differences between reference and impacted sites. Eco-Exergy values were significantly higher at stations located in more disturbed sites (Pseudo $F_{2.719} = 80.319$, $p = 0.001$), but Specific Eco-Exergy did not show really significant differences between disturbed and non-disturbed sites, although values were higher in the non-disturbed sites type. This might be explained by the fact that opportunistic tolerant species present high biomass values in polluted sites, since Eco-Exergy values may vary due to changes in biomass or information. On the other hand, differences in information between disturbed and non-disturbed sites were more subtle (although the number of species was higher in the less disturbed sites, it was not clearly reflected in Specific Eco-Exergy values). Our results suggest that thermodynamic oriented indicators can capture coherent structural changes in biological communities, highlighting its indicator potential for assessing the ecological condition/integrity of highly modified water bodies, such as reservoirs.

1. Introduction

Reservoirs are highly modified ecosystems, built to meet the demands of economic growth. These systems caused significant changes in the prevailing hydrological and ecological conditions of rivers and watersheds (Tundisi, 2006). The impact of impoundment coupled with perturbations induced by urbanisation, agricultural and industrial activities result in higher instability and lower resilience of the aquatic communities (Fore et al., 1994; Klemm et al., 2003).

Large river reservoir systems are some of the most difficult aquatic ecosystems to assess because they are essentially artificial and, consequently, it is hard to find minimally disturbed sites that can be used to determine as comparable reference conditions. This reservoir type, characterised by a low retention time is essentially a transitional system between rivers and lakes (Terra and Aráujo, 2011).

To evaluate the ecological condition of these aquatic ecosystems, a panoply of ecological indicators has been used in environmental assessment studies. Nevertheless, most ecological indicators take into consideration only a few ecosystem components and result from non-universal theoretical approaches. Some

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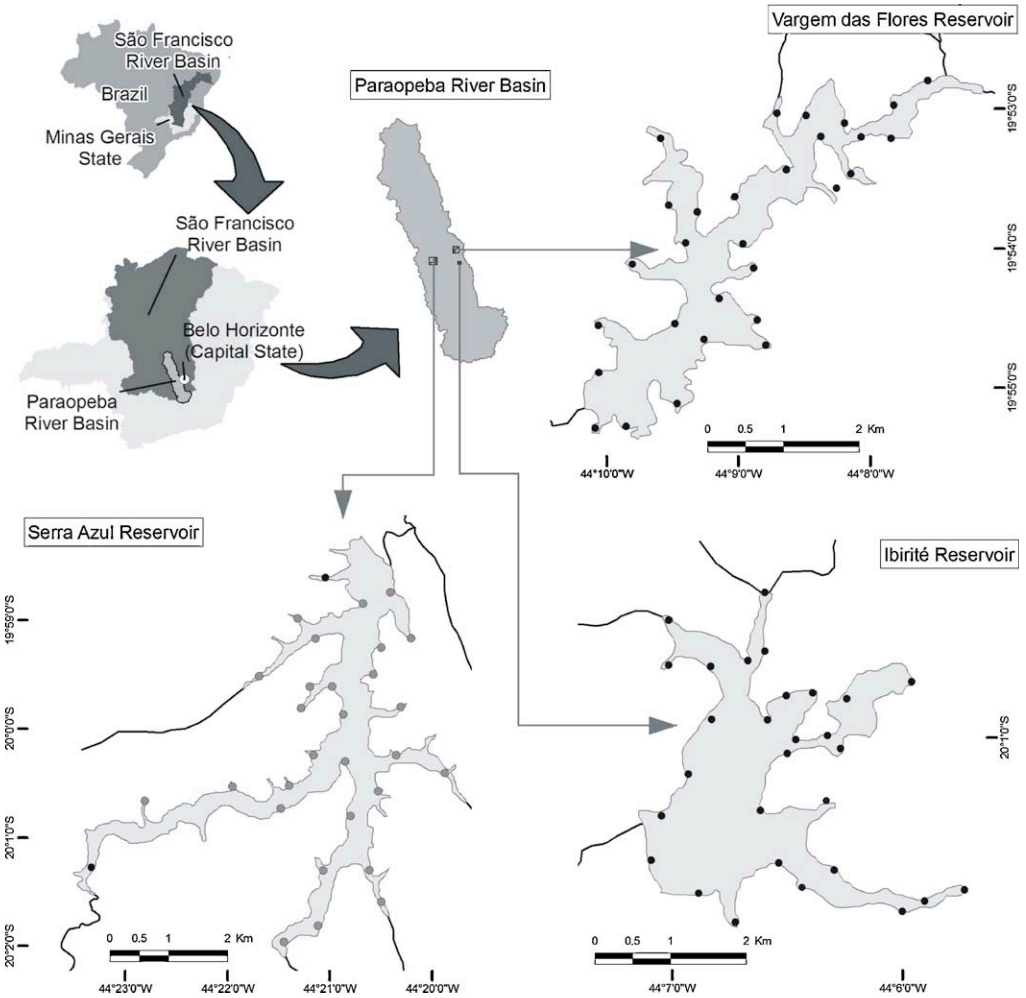

Fig. 1. Location of the reservoir Vargem das Flores, Ibirité and Serra Azul in the Paraopeba River catchment, Minas Gerais, Brazil and distribution of the sampling sites: maximum ecological potential (reference sites) (◍) and impacted sites (●) in the reservoirs.

of these approaches are based on the presence/absence of indicator species, and others take into account the ecological strategies of different organisms while diversity measures consider communities composition, abundance and equitability. Another group of ecological indicators is either thermodynamically oriented or based on network analysis, capturing information on the ecosystem from a more holistic perspective (Salas, 2002; Salas et al., 2006; Marques et al., 2009).

The characteristics that define a good ecological indicator are easy handling, a unimodal response to small variations of specific types of pollution, independence of reference states, and applicability across extensive geographical areas (Salas, 2002).

Salas et al. (2005) and Marques et al. (2009) considered that excellent indicators are those that are based on the more general properties of populations, communities and processes involved in ecosystem function. Eco-Exergy (Jørgensen et al., 1995; Marques et al., 1997, 2003) is one of the mathematical functions that has been proposed as a holistic ecological indicator over the last two decades: (a) to express emergent properties of ecosystems arising from self-organisation processes as part of their development and (b) to act as a goal function in model development (Marques et al., 1998). Such proposals have resulted from a wider application of theoretical concepts, based on the assumption that it is possible to develop a theoretical framework able to explain ecological observations, rules and correlations based on an accepted pattern of ecosystem theories (Marques and Jørgensen, 2002; Patrício et al., 2006).

Eco-Exergy is a concept derived from thermodynamics, a measure of the maximum amount of work that an ecosystem can perform when it is brought into thermodynamic equilibrium with their environment. Eco-Exergy is a measure of the distance between the ecosystem in its present state and what it would be if it was at equilibrium with the surrounding abiotic environment, i.e. a measure of its thermodynamic potential. Eco-Exergy of an ecosystem at thermodynamic equilibrium would be zero. This means that, during ecological succession, Eco-Exergy is used to build up biomass, which in turn stores Eco-Exergy; Eco-Exergy therefore represents a measure of the structural biomass and the information embedded in the biomass (Jørgensen and Mejer, 1979; Jørgensen, 2002; Xu et al., 2005).

If the total biomass in the system remains constant then Eco-Exergy variations will rely upon its structural complexity. Specific Eco-Exergy is defined as total Eco-Exergy divided by total biomass. Both Eco-Exergy and Specific Eco-Exergy may be used as indicators in environmental assessment and management and it is advisable to use them complementarily (Marques et al., 1997, 2003).

Salas et al. (2005) indicated that higher values of Eco-Exergy and Specific Eco-Exergy are concordant with higher biodiversity, higher functional redundancy, higher buffer capacity and resilience and more complex systems. This is the reason why the Eco-Exergy