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Categorization of the trophic status of a hydroelectric power plant reservoir in the Brazilian Amazon by statistical analyses and fuzzy approaches

Tarcísio da Costa Lobato [a,*], Rachel Ann Hauser-Davis [b], Terezinha Ferreira de Oliveira [a], Marinalva Cardoso Maciel [a], Maria Regina Madruga Tavares [a], Antônio Morais da Silveira [a], Augusto Cesar Fonseca Saraiva [c]

[a] *Universidade Federal do Pará (UFPA) Instituto de Ciências Exatas e Naturais, Faculdade de Estatística and Faculdade de Ciências da Computação, Rua Augusto Correa 01, CEP: 66075–110, Belém, PA, Brazil*

[b] *Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Departamento de Química, Laboratório de Bioanalítica, Rua Marquês de São Vicente, 225 Gávea, CEP: 22453–900, Rio de Janeiro, RJ, Brazil*

[c] *Centro de Tecnologia da ELETRONORTE, Rodovia Arthur Bernardes, s/n – Miramar, Telégrafo sem Fio, CEP: 66.115-000, Belém, PA, Brazil*

HIGHLIGHTS

- New Water Quality (WQI) and Trophic State (TSI) indices were constructed
- They were then applied to a fuzzy system for trophic status categorization
- When compared to other TSIs the fuzzy results were more reliable
- Results show that other TSI tend to over or underestimate trophic status
- The model is relevant to categorize ecological status of reservoirs

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ABSTRACT

The Amazon area has been increasingly suffering from anthropogenic impacts, especially due to the construction of hydroelectric power plant reservoirs. The analysis and categorization of the trophic status of these reservoirs are of interest to indicate man-made changes in the environment. In this context, the present study aimed to categorize the trophic status of a hydroelectric power plant reservoir located in the Brazilian Amazon by constructing a novel Water Quality Index (WQI) and Trophic State Index (TSI) for the reservoir using major ion concentrations and physico-chemical water parameters determined in the area and taking into account the sampling locations and the local hydrological regimes. After applying statistical analyses (factor analysis and cluster analysis) and establishing a rule base of a fuzzy system to these indicators, the results obtained by the proposed method were then compared to the generally applied Carlson and a modified Lamparelli trophic state index (TSI), specific for trophic regions. The categorization of the trophic status by the proposed fuzzy method was shown to be more reliable, since it takes into account the specificities of the study area, while the Carlson and Lamparelli TSI do not, and, thus, tend to over or underestimate the trophic status of these ecosystems. The statistical techniques proposed and applied in the present study, are, therefore, relevant in cases of environmental management and policy decision-making processes, aiding in the identification of the ecological status of water bodies. With this, it is possible to identify which factors should be further investigated and/or adjusted in order to attempt the recovery of degraded water bodies.

1. Introduction

Eutrophication, or nutrient enrichment in water bodies, is one of the main processes that causes water deterioration in lentic environments (Harremoes, 1998; Vieira et al., 1998). The most prevalent causes of eutrophication are anthropogenic activities, such as the releases of industrial and domestic effluents into water bodies, while some natural causes have also been reported, including macronutrient-rich soils lixiviated to water bodies due to changes in rainfall volume caused by local hydrological regimes (Aubert et al., 2013; Fletcher et al., 2013; Lai et al., 2013; Merten and Minella, 2002; Oenema and Roest, 1998; Rebouças

* Corresponding author. Tel.: +55 92 3201 7000.
E-mail address: tarcisiolobato@yahoo.com.br (T. da Costa Lobato).

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et al., 2002). Eutrophication can lead to serious consequences for aquatic ecosystems, such as exacerbated vegetation growth, which in turn decreases dissolved oxygen levels in the water, leading to the death of many aquatic organisms, increased toxicity caused by ammonia and, finally, the appearance of cyanobacteria and microalgae that can release deadly to toxins to humans and aquatic biota (Esteves and Barbosa, 1986; Recknagel et al., 1998).

In order to understand and, when possible, mitigate anthropogenic impacts and remediate degraded water bodies, the investigation, categorization and discussion of the trophic status of lakes and reservoirs is paramount. Water physico-chemical parameters typically related to eutrophication processes are chlorophyll, water transparency, nutrients, electrical conductivity, fecal coliforms, water residence time and dissolved oxygen levels. In addition, light and water temperature are external factors that also act in the control of this phenomenon (Cunha et al., 2013; Haydée, 1997; Toledo and Nicolella, 2002; Tundisi et al., 1988; Wetzel, 1993).

The trophic status of lakes and reservoirs is generally given by the Carlson trophic state index, as recommended by the United States Environmental Protection Agency (USEPA) (Besse-Lototskaya et al., 2011; Chaves and Kojiri, 2007; Cunha et al., 2013; Liou and Lo, 2005; Naumoski et al., 2012; Pereira et al., 2009; USEPA, 2007). However, according to the US EPA, this index should only be used with lakes that have relatively few rooted plants and non-algal turbidity sources (USEPA, 2007). This limits the use of this index to areas with these characteristics, since it does not take into account other physicochemical variables which might be present in other ecosystems. Other indices, such as the Indiana trophic state and Lamparellis's trophic status index, have been constructed for application in certain specific ecosystems. The former takes into account Secchi depth, total phosphorous, soluble reactive phosphorous, nitrogen, nitrate, ammonia, dissolved oxygen, total plankton count and percentage of blue-green algae (Indiana, 1986) while the latter, built specifically for tropical areas, takes into account total phosphorus (TP), chlorophyll a (Chl a) and cyanobacteria density (Cunha et al., 2013). However these indices do not include the hydrological regime to which Amazon reservoirs go through annually.

In this context, the present study aimed to investigate the use of a combined approach of statistical analyses in the creation and application of a novel water quality index (WQI) and trophic state index (TSI) and a fuzzy solution using these indices to aid in the categorization of the trophic status of a tropical Amazon reservoir. These approaches considered different regional characteristics than those taken into account by the generally applied Carlson TSI and the Lamparelli TSI, such as the hydrological regime of the study area and the location of the water sampling stations. Comparisons between the Carlson TSI, the Lamparelli TSI and the proposed fuzzy solution were conducted. As the Amazon region and adjacent areas, such as the Pantanal, are considered areas of world interest by UNESCO due to their unique flora and fauna and great biodiversity, this approach is even more important, since identifying man-made changes to this ecosystem can aid in environmental management and policy decision-making processes. Even more importantly, the proposed approach may be applicable in other environments with different hydrological characteristics, demonstrating possible global applicability.

2. Methodology

2.1. Study area and sampling stations

The Tucuruí Hydroelectric Plant reservoir is located in the Brazilian Amazon area of the state of Pará (Fig. 1). Its construction has produced several environmental impacts in the Amazon region, including loss of biodiversity of terrestrial and aquatic fauna and flora, high concentrations of organic matter and loss of water quality (low dissolved oxygen, high conductivity, low pH). This reservoir has a total area of approximately 2,850 m^2 flooded with approximately 50.8 million m^3 of water and approximate water residence time of 46 days (CETESB, 2009; Deus et al., 2013; Eletronorte, 1998). The area is characterized by well defined rainy (December to May) and dry (June to November) seasons, with annual precipitations between 2250 and 2500 mm. The rainiest month is March and the driest is September (Fisch et al., 1990).

The water sampling considered the regional hydrological regime and, consequently, the upstream water levels of the reservoir. The reservoir water levels were classified into four categories: dry, filling, full and emptying. Water was sampled from eleven the sampling stations (C1, C2, M1, M3, MR, MBB, MBL, MP, MIP, ML and MJV), distributed upstream of the reservoir, representing the specific characteristics of each different reservoir area.

2.2. Determination of water physicochemical parameters and major ion concentrations

Water physicochemical parameters and chemical elements and compound concentrations were determined in samples collected from the reservoir surface from 2009 to 2012. The following physicochemical parameters were determined: temperature – T (°C), Transparency – S (m), electrical conductivity – EC (μS/cm), pH, total suspended solids – TSS (mg/L), chlorophyll *a* – CL*a* (mg/L), turbidity – Turb (NTU) and dissolved oxygen – DO (mg/L). The following chemical compounds were determined: chloride _ Cl (mg/L), ammonium – NH_4 (mg/L), nitrate – NO_3 (mg/L), phosphate – PO_4 (mg/L) and total phosphorus – TP (mg/L). Major ion concentrations (Ca, total iron – TFe, K, Mg and Na) were determined by inductively coupled plasma optical emission spectrometry (ICP-OES). Samples for major ion determinations were stored in 50 ml polypropylene vials and acidified with nitric acid. The vials were initially washed with ultrapure water to remove dirt and plastic remnants, and then were left in a solution of 10% nitric acid for 24 hours. Sample preservation was performed according to the Standard Methods norms (Standard Methods, 2013). The certified reference material used for quality control was SLRS-4, River Water Reference Material for Trace Metals (National research Council, Canada) (Table 1).

2.3. Construction of the Water Quality Index (WQI)

The reservoir water quality index (WQI) was constructed using two multivariate statistical techniques: a factor and cluster analysis (Hair et al., 2005; Johnson and Wichern, 2007; Lin and Wang, 2006).

The factor analysis used the factor extraction method of a principal component analysis with Varimax rotation to select the relevant variables for the WQI construction, taking into account upstream water level and, consequently, the hydrological regime.

The cluster analysis was then applied to separate the position of the sampling stations at high and low upstream locations from the water quality of the reservoir. The applied clusterization criteria was the Ward method, which minimizes the square of the Euclidean distance of the means of the groups (Hair et al., 2005; Johnson and Wichern, 2007).

The construction of the water quality index (WQI) of the reservoir was conducted based on the National Sanitation Foundation report (Brown et al., 1970), the SEMAD study (SEMAD, 2005) and on water quality indicator and limits established by the Brazilian CONAMA (CONAMA, 2005) for class 2 freshwater bodies.

The data processing of the results of the factor and cluster analyses based on fuzzy logic rules was implemented using the Matlab 7.0 Fuzzy Logic Toolbox (Mathworks, 2009).

2.4. Trophic State Index (TSI)

The TSI was constructed based on the modified index proposed by Lamparelli for tropical regions, more specifically, for the Brazilian southeastern region of São Paulo (Cunha et al., 2013). Lamparelli applied the same procedure as Carlson (Carlson, 1977), creating equations that