Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

New Water and Biotic Quality Assessment Indices for a tropical reservoir based on fuzzy logic

ARTICLES doi:10.4136/ambi-agua.2597

Received: 14 Jun. 2020; Accepted: 06 Aug. 2020

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ABSTRACT

The complexity of evaluating the quality of an aquatic environment with its numerous variables has resulted in several quality indexes to synthesize all information in a single value. However, most of these indexes are based on few environmental variables, losing information from other relevant variables. This article presents a new model capable of representing the quality level of a tropical oligo-mesotrophic reservoir on a numerical scale, considering the subjectivity implicit in the concept of quality, and involving several physical, chemical and biological variables. The proposed model, called "Fuzzy Indices for Water Quality Assessment and Biotics" (FUZZY-WBQAI), is based on fuzzy inference systems, providing a way to deal with the uncertainty between the quality categories. A computational tool was developed, which automatically assesses the quality of water, considering different methodologies that depend on the stratification conditions and the longitudinal zone of the reservoir. The model calculates two indices: one for water quality and one biotic that uses metrics from the fish assembly. The model was effective in revealing the decrease in water quality in summer months with higher temperature and precipitation. The effect of the mixture of the stratified reservoir in winter in decreasing the water quality in an area of fish cultivation was highlighted. The biotic index was sensitive to spatial changes in the environmental quality of the reservoir. The results were considered satisfactory, in agreement with the specialized knowledge, and can provide a rapid diagnosis of water conditions in oligo-mesotrophic reservoirs in the tropics.

Keywords: environmental index, fuzzy inference system, FUZZY-WBQAI model, hydropower reservoir, tropical reservoir, water quality index.

Novos índices de avaliação da qualidade da água e biótica de um reservatório tropical baseado em Lógica Fuzzy

RESUMO

A complexidade de avaliar a qualidade de um ambiente aquático com suas inúmeras variáveis resultou na criação de vários índices de qualidade para sintetizar todas as informações em um único valor. No entanto, a maioria desses índices é baseada em poucas variáveis, perdendo informações de outras variáveis relevantes. Este artigo apresenta um novo modelo capaz de representar o nível de qualidade de um reservatório oligo-mesotrófico tropical em escala numérica, considerando a subjetividade implícita no conceito de qualidade e envolvendo diversas variáveis físicas, químicas e biológicas. O modelo proposto, denominado "Índices Fuzzy de Avaliação da Qualidade da Água e Biótica" (FUZZY-WBQAI), é baseado em sistemas de inferência fuzzy, fornecendo uma forma de lidar com a incerteza entre as categorias de qualidade. Uma ferramenta computacional foi elaborada, a qual avalia automaticamente a qualidade da água, considerando diferentes metodologias que dependem das condições de estratificação e zona longitudinal do reservatório. O modelo calcula dois índices: um de qualidade da água e um biótico que utiliza métricas da assembleia de peixes. O modelo foi eficaz ao revelar a diminuição da qualidade da água nos meses de verão com temperatura e precipitação mais elevadas. Destacou-se o efeito da mistura do reservatório estratificado no inverno sobre a diminuição da qualidade da água em área de cultivo de peixes. O índice biótico foi sensível a mudanças espaciais na qualidade ambiental do reservatório. Os resultados foram considerados satisfatórios, concordando com o conhecimento especializado, e podem propiciar diagnósticos rápidos das condições da água em reservatórios oligo-mesotróficos nos trópicos.

Palavras-chave: índice ambiental, índice de qualidade da água, modelo FUZZY-WBQAI, reservatório de hidrelétrica, reservatório tropical, sistema de inferência fuzzy.

1. INTRODUCTION

Water is an indispensable natural resource for human survival, and is used in many human activities, including irrigation, food production, industrial processes, generation of energy, navigation, and landscaping. Hence, numerous countries have laws that specify strict limits for any water use, as well as treatment requirements according to the type of water use (Vargas *et al*., 2018). In Brazil, resolution 357/2005 of the National Environment Council (CONAMA, 2005) addresses the classification of water bodies, establishes environmental guidelines and sets the conditions and patterns for the discharge of effluents.

Therefore, for efficient management and control of water resources, it is imperative to continuously monitor water quality, in order to supply the information required for proper management of surface waters (Branco *et al*., 2019; Rocha *et al*., 2019) and groundwater (Gholami *et al*., 2015; 2020). A standard method for estimating water quality is to analyse features of several physical, chemical, and biological variables. Nevertheless, water quality indices are the preferred solution for integrated management, since they incorporate a large number of variables in a single value that can be easily understood. Current literature offers several quality indices for aquatic environments.

In 1965, Horton (1965) formulated the first water quality index based on a numerical scale to represent grades of water quality. Brown *et al*. (1970) developed a water quality index that is similar in structure to the Horton index, but substantially more rigorous in the selection of variables and the attribution of weights for the development of a common scale. Based on the research by Brown *et al.* (1970), the São Paulo State Environmental Company (Companhia de Tecnologia e Saneamento Ambiental - CETESB) in Brazil adapted and developed their own

Water Quality Index (Índice de Qualidade das Águas-IQA) (CETESB, 2006). This index was specifically designed for public water supply and incorporates nine variables considered relevant for water quality evaluations. Recently, Garcia *et al.* (2018) presented a review of water quality indices, discussing their evolution and future perspectives.

Most indices available in the literature, however, are formulated for running waters, having little to no applicability in lentic environments. Lakes and reservoirs are usually classified by trophic state, based on biomass of phytoplankton and on the content of total phosphorus, water transparency, and chlorophyll-*a* (Cunha *et al*., 2013; Klippel *et al.*, 2020).

The assessment of the water quality conditions in Brazilian reservoirs has been of paramount importance for establishing management strategies for stakeholders. The increase in efficiency and speed in environmental evaluation is crucial, since around 64% of the energy used in Brazil comes from hydroelectric power plants with reservoirs (ANEEL, 2020). Besides power generation, the waters of Brazilian reservoirs are used for domestic and industrial supply, recreation, fishing and agriculture. Considering this scenario, new and more efficient approaches using artificial intelligence techniques for environmental evaluation of these systems, are clearly welcome. Although trophic state indices have been used as a base for comparison of water quality in Brazilian reservoirs (Cunha *et al*., 2013; Klippel *et al.*, 2020), most of them are based on few environmental variables and may lose important information related to other monitored variables. Furthermore, they do not reflect the subjective aspects inherent to their qualitative counterparts, being less representative than quality indices.

The term quality implies a subjective judgment that is best kept separate from the concept of a trophic state. "The definition of trophic state and its index should remain neutral to such subjective judgments, remaining a framework within which various evaluations of water quality can be made" (Carlson, 1977). Therefore, to provide a quality index that naturally incorporates subjective aspects of environmental aspects, new indices should be developed considering the diversity of existing aquatic systems, which is a challenge especially for the tropical regions.

The natural environment must be analyzed as a complex system, and an integrated vision can promote a good understanding of the impacts occurring in water bodies, regarding the distinct nature of the factors and environmental quality legislation (Santos *et al*., 2019; Gholami *et al*., 2020). Under this perspective, fuzzy logic allows a flexible and realistic modeling system, and consists of a set of methods based on the concept of fuzzy sets and fuzzy operations (Salski, 2007). Recent studies have shown that fuzzy logic systems are universal surrogates for general non-linear functional relationships, to any degree of accuracy, making them a powerful tool for exploring complex, non-linear biological problems such as estimating and forecasting (Soyupak and Chen, 2004). The use of fuzzy logic as an environmental evaluation method began in the 1990s and has been used broadly for determining trophic status and water quality indices in rivers (Lee and Chang, 2005; Chang, 2008; Lermontov *et al*., 2009; Semiromi *et al.*, 2011; Ocampo-Duque *et al*., 2006; 2013; Mourhir *et al*., 2014), natural lakes (Chen and Mynett, 2003; Icaga, 2007), reservoirs (Lu *et al*., 1999; Soyupak and Chen, 2004; Liou and Lo, 2005; Taheriyoun *et al*., 2010) and in evaluation of groundwater quality (Gholami *et al*., 2017); but none of these uses involved tropical regions. The fuzzy approach has also been used in water quality and watershed evaluations combined with other techniques, such as self-organizing maps (Lu and Lo, 2002), and geographic information system (GIS) (Pinto *et al*., 2016; Gholami *et al*., 2017).

This research presents the proposal of a new intelligent model capable of representing the quality level of a tropical oligo-mesotrophic reservoir in a numerical scale, considering the implicit subjectivity in the concept of quality. The proposed model, named "Fuzzy Water and Biotic Quality Assessment Indices" (FUZZY-WBQAI), evaluates water and biotic quality of the reservoir based on fuzzy inference systems, providing a natural way to deal with uncertainty among quality categories. Fuzzy logic is conceptually simple, but the real power of the methodology comes from the ability to integrate different kinds of observations in a way that permits a balance between favourable and unfavourable observations, the information with more flexibility than discrete measures to ordinary sets, such as "acceptable versus unacceptable" (Silvert, 2000; Icaga, 2007). The proposed fuzzy model is capable of representing, in a more efficient form, the limits of the intervals of several quality variables, such as pH or dissolved oxygen. The range of the intervals for the variables was established based on water quality standards for Class 1, which according to resolution CONAMA 357/2005 (CONAMA, 2005) are waters that can be used as supply for human consumption, after simplified treatment, for primary contact recreation, such as swimming, water skiing, diving, and for the protection of aquatic communities. Additionally, the FUZZY-WBQAI provides a fish assemblage index in a set of subjective categories, e.g., low or poor, when those limits are imprecise or not well defined. The proposed FUZZY-WBQAI model is based on two hierarchical fuzzy inference systems developed for water and biotic quality assessment, respectively. A user-friendly computational tool was designed to easily evaluate the water and biotic quality of tropical reservoirs and can be very useful for hydroelectric power companies with the generator matrix supported by reservoirs.

2. MATERIALS AND METHODS

2.1. Study Area

The Lajes Reservoir was built in 1905 to generate hydroelectric power and belongs to a system of reservoirs operated by the Light Energy SA Company since 1940, which generates 612 MW of electricity and provided 96% of the water consumed by the municipalities of Rio de Janeiro (Guarino *et al.*, 2005; Soares *et al.*, 2008; Branco *et al.*, 2009). Currently, the Lajes Reservoir alone provides the domestic water supply for approximately one million people. The reservoir is also used for sports fishing and, recently, for fish farming in net-tanks in one of its bays.

The Lajes Reservoir (22°43’ S to 22°46’ S and 44°30’ W to 44°60’ W) is situated between the hills of Serra das Araras, in a protected area with tropical forests. The Lajes Reservoir is located 415 m above sea level, and has a surface area of 38.9 km^2, a maximum depth of 40 m, a mean depth of 15 m, and an accumulated volume of 450 x 10^6 m^3 (Soares *et al.*, 2008). The climate in the region of Lajes Reservoir is subtropical humid with rainfall between 1000 and 1700mm per year and presents two well-defined periods: a rainy season (November to March) and a dry season (April to October).

The reservoir has been considered as an oligo-mesotrophic system (Klippel *et al*., 2020). Nevertheless, the low values of chlorophyll-*a*, picocyanobacteria accounts for most of the phytoplankton abundance in this reservoir (Recknagel *et al.*, 2015). Regardless of phosphorus limiting conditions, picocyanobacteria can be influenced by water column stability and electrical conductivity (Rocha *et al*., 2019). Because of its high retention time of 300 days, the reservoir is considered vulnerable to eutrophication (Guarino *et al.*, 2005). Recent human activity, such as fish farming, can accelerate the growth of nutrient inputs in the reservoir, which has not occurred for decades.

According to Branco *et al*. (2009), the Lajes Reservoir is a monomictic reservoir with a tendency to mix the water column in the winter depending on the weather conditions. The prolonged stratification period leads to an anoxic hypolimnion that is rich in nutrients, which causes the reservoir to present poor water quality in its deepest part.

Two databases were used as sources of analytical information about the Lajes Reservoir. The first database (655 water samples from February 2000 to December 2009) is from Federal University of Rio de Janeiro State (UNIRIO). The second database (417 fish samplings from January 1994 to August 2012) is from Federal Rural University of Rio de Janeiro (UFRRJ). For the physical and chemical variables, the data were extracted from five sampling locations. For the fish assemblage metrics, data were obtained from twenty-four locations (Figure 1).

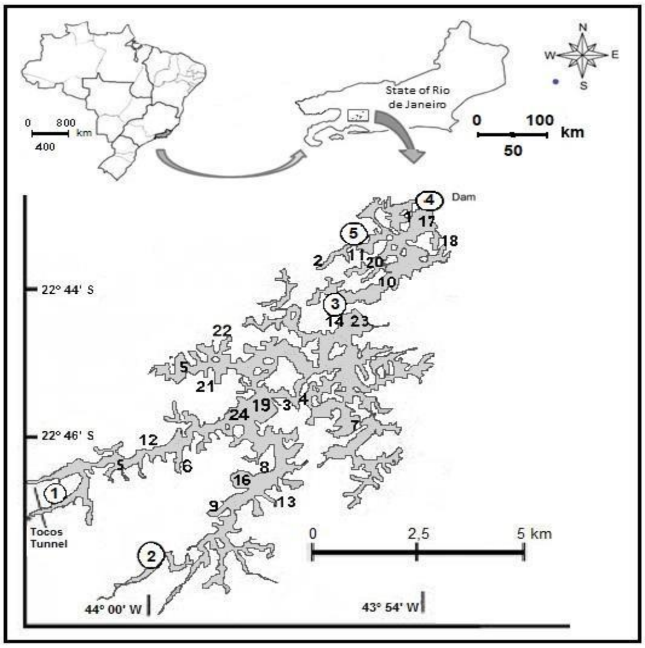


Figure 1. The geographic location of the physical, chemical and biological samples. The numbers in circles represent the sample locations of the physical and chemical samples; other numbers show sampling location of fish assemblage metrics.

2.2. Reservoir Fish Assemblage Index–RFAI

Multimetric fish-based indices of biological integrity (IBIs) have been developed for streams and rivers throughout the world (Roset *et al.*, 2007). However, few such indices have been developed for lakes (Appelberg *et al*., 2000; Drake and Pereira, 2002) and even fewer for reservoirs (Jennings *et al.*, 1995). The use of multimetric indices to monitor reservoir biological condition is an infrequently applied approach, which reflects the difficulty of implementing such indices to artificial systems relative to rivers. Jennings *et al.* (1995) were the first to propose an adaptation of the IBI for assessing reservoirs. They suggested a new name for the index, the Reservoir Fish Assemblage Index (RFAI).

The RFAI may be an efficient tool to monitor reservoirs; however, it needs to be adapted for transitional river and reservoir zones. A river-reservoir RFAI (RRFAI) would enable environmental managers to monitor river-reservoir systems and to assess the impact of reservoirs on what previously were entirely lotic systems. Such monitoring programs for transitional river-reservoir systems are necessary for Brazil, where almost all electricity and urban water supplies are generated by/from dammed rivers. A preliminary RRFAI from fish assemblage data was proposed by Terra and Araújo (2011). Based on the values of these metrics and using the criteria for assigning grades detailed in Table 1, the RRFAI is formulated by adding the grades attributed to each metric following the applied fishing effort. The standardized sampling unit, the fishing effort, was defined as the total number of fishes caught during each sampling occasion at each site, using three gillnets of different mesh sizes (25, 50, and 75 mm stretched mesh) encompassing 150 m^2. The nets were set up at sunset and retrieved the following morning, remaining for 15 h.

Thus, the value of the RRFAI is reflected in the biotic quality of a reservoir. Accordingly, RRFAI <25 corresponds to a Bad biotic quality, 25 – 50 to a Regular, and > 50 to a Good (Terra and Araújo, 2011).

Table 1. Criteria for the attribution of grades–RRFAI (Terra and Araújo, 2011).

Attributes	Criteria for attribution of grades		
	0	**5**	**10**
Number of native species	<5	5 to 8	>8
Number of native Siluriformes	0	1 to 3	>3
Number of native Characiformes	0	1 to 3	>3
Percentage of non-native species biomass	>75	50 to 75	<50
Dominance	>0.6	0.3 to 0.6	<0.3
Shannon index H´	<1	1 to 1.5	>1.5
Astyanax N	<50	50 to 100	>100
Hypostomus affinis	<4	4 to 8	>8

As can be noted, this biotic quality index considers crisp boundaries between each quality category, which hinders a more detailed analysis close to the borders. Those crisp boundaries are the main drawback of most water and biotic quality indices available in the literature, since they do not consider the intrinsic imprecision of the limits imposed between quality categories boundaries.

2.3. FUZZY-WBQAI: Proposed Intelligent Model

The proposed FUZZY-WBQAI was developed for the tropical oligo-mesotrophic Lajes Reservoir. Therefore, the model considers thermal stratification as well as mixing of the water column in the formulation of its indices. This characteristic is significant, since vertical gradients of temperature in the water column of a lake influence numerous physical and chemical variables, which, in turn, determine the basic features of its function. This aspect is further substantiated in the case of reservoirs with long retention time, which is particularly true for the Lajes Reservoir. In other words, the FUZZY-WBQAI model attempts to differentiate quality calculations among the epilimnion, metalimnion, hypolimnion, and possible mixing of water. Note that the intrusion effect was not considered in the proposed model.

As a function of the horizontal location of a sample, the FUZZY-WBQAI also aims to differentiate the quality calculation between river zones, transition zones, and lake zones. These three zones of a reservoir possess their own biological, physical, and chemical properties (Thorton, 1999), providing another reason for their relevance in the model. By differentiating between vertical zones and longitudinal zones in the quality calculation, the FUZZY-WBQAI aims to capture the features of each sampling point of the reservoir. The possible combinations between zones are as follows: 1. Lake zone – Epilimnion; 2. Lake zone – Metalimnion; 3. Lake zone – Hypolimnion; 3. Lake zone – Mixture; 4. Transition zone – Epilimnion; 5. Transition zone – Metalimnion; 6. Transition zone – Hypolimnion; 7. Transition zone – Mixture, and 8. River zone.

However, according to the limnological characteristics of the reservoir, the transition zone and lake zone may be regarded as homogeneous, due to the horizontal spatial heterogeneity (Guarino *et al.*, 2005). Therefore, the two zones were treated as one. This deliberation reduces the number of possible heterogeneous regions to five: 1. Epilimnion zone; 2. Metalimnion zone; 3. Hypolimnion zone; 4. Mixture zone; 5. River zone.

The FUZZY-WBQAI model, therefore, comprises five distinct methodologies, each one applicable to a specific zone. The proposed model is based on the hierarchical fuzzy inference system approach, which is known to reduce the complexity of a fuzzy inference system when the number of input variables increases (Jin, 2000), improving its interpretability. Depending on the zone, two hierarchical fuzzy inference systems are developed, providing water and biotic quality indices, respectively.

All fuzzy inference systems were developed using the following steps:

• *Choice of input variables for each index*: first, the quality indicators and metrics considered decisive in the implementation of each index were selected;

• *Definition of the universes of the discourse of each input variable*: then, the universes of discourse (range of possible values) were specified for each input variable, i.e., quality indicators and fish assemblage metrics;

• *Definition of the membership functions*: the membership functions of each fuzzy set, with their respective linguistic labels, for each input variable, were defined;

• *Determining the sub-indices*: the hierarchical nature of the fuzzy inference systems proposed in this work produces intermediate results, or quality sub-indices. So, the most suitable sub-indices for the water quality index and biotic index, their universes of discourse, and their membership functions must be determined;

• *Construction of the rule bases*: finally, the fuzzy rule base, with their antecedents and consequents, for each sub-index and for the final indices must be established.

The five methodologies (one for each considered reservoir region) use the same selection of input variables and the same structure of sub-indices. However, the universes of discourse for each variable, their membership functions and their associate rule base are specific for each methodology.

The FUZZY-WBQAI model was developed based on the knowledge of specialists from the Laboratory of Limnology of the UNIRIO and from the Animal Biology Department of the UFRRJ that, for several years, have been conducting research in the Lajes Reservoir. Additionally, the limits for each variable established by the resolution CONAMA 357/2005 (CONAMA, 2005) for waters of Class 1 were considered. Therefore, all steps were developed through discussions with those specialists in water and environmental quality and were based on the notion that "expert judgment is the key for any environmental assessment, evaluation, or diagnosis" (Scardi *et al.*, 2008). The selection of relevant environmental variables is a common problem in ecological modelling, and the selection by expert decreases model complexity and the amount of data required to estimate model parameters efficiently (D'heygere *et al.*, 2003; Forio *et al.*, 2017).

2.3.1. General View of the Indices Calculation Methodology

In evaluating the water and biotic quality of a reservoir, the proposed model considers the following:

• Ten environmental indicators (or physical, chemical and biological indicators) for water quality calculation: water temperature, dissolved oxygen, pH, chlorophyll-*a*, nitrate, total phosphorus, nitrite, ammonium, conductivity, and turbidity;

• Eight metrics of fish community assemblies for the calculation of biotic quality: number of native species, number of native Siluriformes, number of native Characiformes, percentage of non-native species biomass, dominance (D), Shannon index (H), number of *Astyanax* fish (N), and number of *Hypostomus affinis*;

• Stratification and possible mixing of the water column;
• Horizontal location of the sample: river zone, transition, or lake;
• Vertical location of the sample;
• Date of sampling.

The model evaluates the water and biotic quality of a sample according to its horizontal and vertical locations in the reservoir, and considers possible thermal stratification at the sampling time. The ten water quality indicators and eight fish assemblage metrics are considered inputs to the system.

Since the reservoir used as the basis for the design of the proposed model is the Lajes Reservoir, the entire process of designing and programming this tool considered limnological information obtained from previous studies of the reservoir. The proposed model is based on the limnological characteristics described in Guarino *et al*. (2005), Soares *et al.* (2008) and Branco *et al.* (2009). Other environmental variables included were shown as important for phytoplankton increases in this aquatic ecosystem, such as nitrogen and phosphate compounds (Recknagel *et al.*, 2015), water column stability and electrical conductivity (Rocha *et al.*, 2019). It must be emphasized, however, that although the proposed FUZZY-WBQAI model was developed using Lajes Reservoir as the basis, it can be applied to any other tropical oligo-mesotrophic reservoir with similar limnological characteristics.

First, the model locates the sample longitudinally in the reservoir using Cartesian coordinates in degrees, minutes, and seconds. The tool identifies whether the sample is located in the river, transition, or lake zone. According to the limnological characteristics of the reservoir, the transition zone and lake zone may be considered homogenous because of their horizontal spatial homogeneity (Busch and Sly, 1992). Therefore, the quality calculation methodology for those zones in the Lajes Reservoir is the same.

If the sample is located in the transition or the lake zone, the model will determine whether there is any presence of stratification or mixture. If there is stratification, the computational tool then identifies the stratification layer to which the sample belongs. The model analyses the presence of stratification or mixture using a temperature vs. depth curve based on the temperature and depth of the water column. Once the sample is located, and horizontal zone and layer (epilimnion, metalimnion or hypolimnion) to which it belongs are identified, the model uses one of the available calculation methodologies to evaluate the water quality.

As previously explained, five calculation methodologies were created: one methodology for the river zone and four methodologies for the transition and lake zones. These methodologies correspond to the stratification layers of the epilimnion, metalimnion, hypolimnion, and a possible mixture of water. Figure 2 shows the flowchart for selecting the appropriate calculation methodology. If the sample is located in the epilimnion or river zone (methodologies #1 and #2), the model calculates two indices: a water quality index, and a biotic index that utilizes the fish assemblage metrics. In the metalimnion and hypolimnion zones, only the water quality index is calculated, as the number of fish collected in these layers is limited.

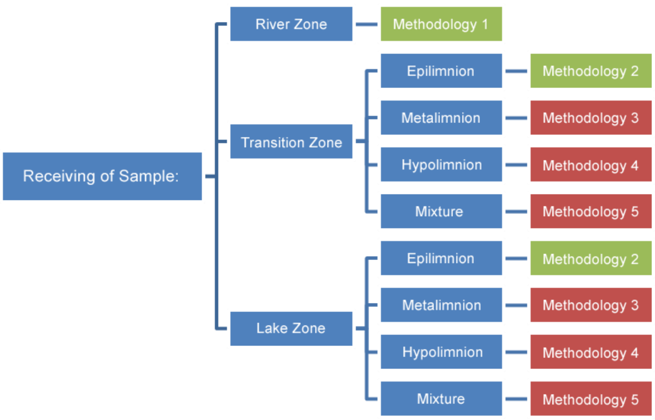
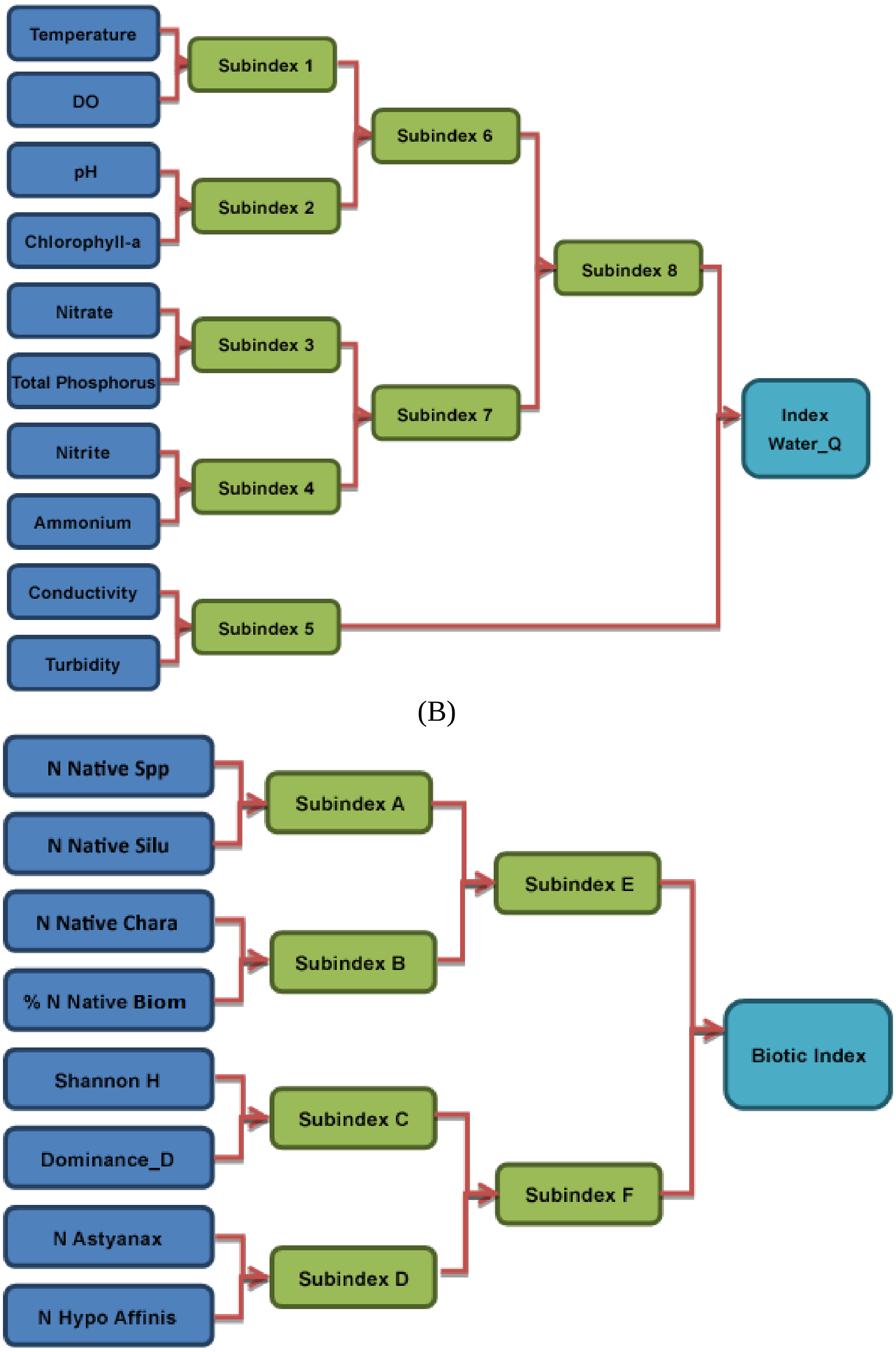


Figure 2. Selection of the calculation methodology for the evaluation of the water and biotic quality.
Source: authors.

2.3.2. Hierarchical Fuzzy Inference System: Quality Sub-indices

The development of fuzzy inference systems with more than four input variables becomes a significant challenge, with the exponential growth of the number of rules and interpretability reduction (Gonçalves *et al.*, 2006). Thus, input variables are usually divided into intermediate fuzzy systems, where their outputs are used as inputs to the final system. In the proposed FUZZY-WBQAI model, the ten water quality variables and eight biotic quality variables are divided into groups of two, originating quality sub-indices, which in turn are used as inputs to the final indices (Figure 3).

(A)



(B)

Figure 3. a) Flowchart of the sub-indices that compose the Water Quality Index; b) Flowchart of the sub-indices that compose the Biotic Quality Index.

2.3.2.1. Fuzzy Sets Definition

The universe of discourse for each variable and the support of each fuzzy set were defined by limnology specialists (co-authors of this study) and adjusted during the evaluation of the proposed model. All input variables were partitioned into five fuzzy sets: Low, Average-Low, Average, Average-High and High. Figure 4 presents an example of the fuzzy sets of the linguistic variables used in water and biotic quality indices, respectively, for temperature, dissolved oxygen, pH and chlorophyll-*a* in Methodology #2 (Epilimnion region).

Sub-indices and indices' variables were also partitioned into five fuzzy sets, with the following labels: Poor, Average-Poor, Average, Average-Good and Good, as shown in Figure 4. The same fuzzy partitioning is used in all methodologies (Epilimnion, Metalimnion and Hypolimnion).

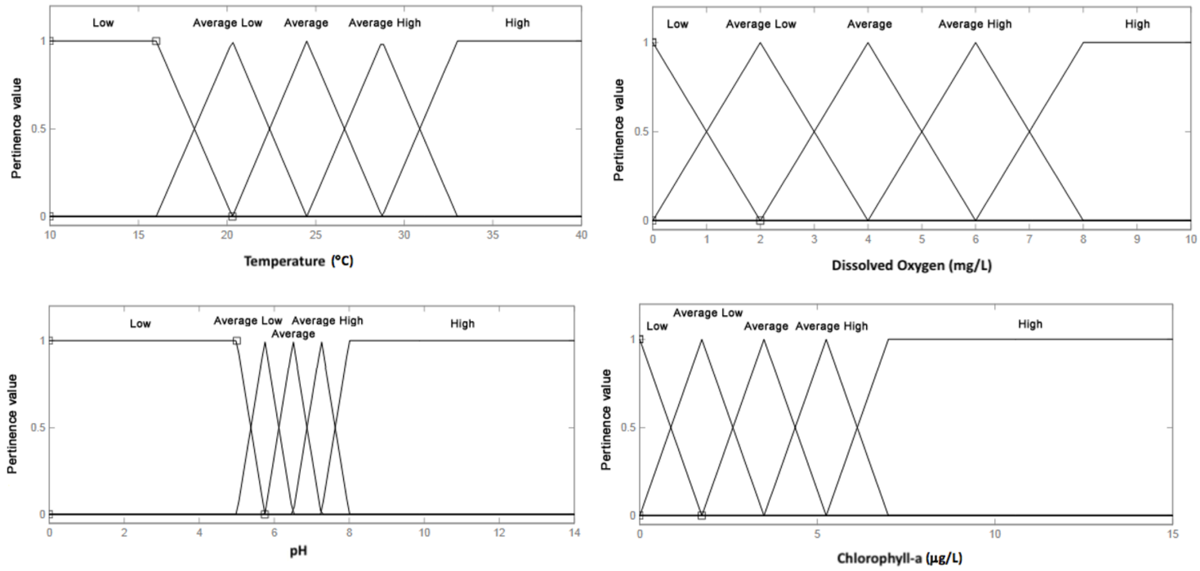


Figure 4. Example of fuzzy sets of water quality index for the variables water temperature, dissolved oxygen, pH and chlorophyll-*a*.

2.3.2.2. Rule Bases

The fuzzy rule bases for all sub-indices and final indices were provided by the specialists mentioned above. It is important to emphasize that the rule bases are dependent on the characteristics of the body of water for which the system is originally designed or on limits recommended in the legislation for that class of water. Thus, the rule base can only be extended to other reservoirs that share similar limnological characteristics or are included in the same type of water. The features of a reservoir act directly on the vertical and horizontal structures of the lake, which in turn directly influence the water quality. Consequently, when considering the use of the proposed model for the evaluation of a reservoir other than the Lajes Reservoir, the following limnological characteristics must be similar to those of the Lajes Reservoir:

- Reservoir size, geographic region, and climate
- Hydrographical characteristics
- Water retention time
- Class type of water (according to the legislation CONAMA 357/2005)

For reservoirs that significantly differ from the Lajes Reservoir, in addition to altering the rule base, the calculation methodologies might also require modification.

The fuzzy rule bases for all methodologies (epilimnion, metalimnion and hypolimnion), as well as for all sub-indices related to each methodology, can be found in Andrade (2013). Each fuzzy inference system is developed using the Mamdani inference system (Jang and Sun, 1995). The intersection and implication operators can be configured by the user (min or prod), so as the defuzzification method, as described in the next section.

The values of all sub-indices, as well as the final FUZZ-WBQAI index, vary between 0 and 100.

2.3.3. FUZZY-WBQAI: The computational Tool

The proposed FUZZ-WBQAI model was implemented in a user-friendly computational tool, programmed using C# programming language together with Microsoft Visual Studio and Microsoft Excel. The final tool was developed as a Windows application for ease of use and then synchronized with an Excel file. To further simplify the application, the tool's configuration, processing control and results presentation are configured through the software interface. On the other hand, to facilitate data entry, the complete database is provided through an Excel file, containing the required information for tool operation, i.e., the values of all input variables: sample depth; sample geographic coordinates; rule bases and membership functions of each methodology; and temperature vs. local water column depth. According to the description of the model, to determine the calculation methodology, the application imports and analyses all the required information from the Excel file before proceeding with the calculation of the sub-indices and indices.

3. RESULTS AND DISCUSSION

3.1. The computational program

The development of a software tool for decision support, based on the application of fuzzy logic techniques and considering the support of experts has been already applied with success in water quality monitoring (Angulo *et al.,* 2012). In the present study, the interface is organized in four subdivisions: Controls, Fuzzy Inference System, Spatial Characteristics, and Indices, which can control, supervise, and visualize the state of the reservoir and results of the sub-indices and final indices. The Controls subdivision includes the only four command buttons of the application. The excel button opens the Excel file that contains the database to feed the program. The load button loads the data from the Excel file. The calculate button starts the calculation of the sub-indices and final indices using the calculation methodology chosen by the program. The close button closes the application.

In the Fuzzy Inference System subdivision, specific characteristics of the fuzzy inference system (FIS) of each sub-index and final index are easily configured, including the fuzzy t-norm operator that is used in the antecedent (min or prod) and defuzzification method (area centroid or half of the maxima). The complete graphical interface of the application is shown in Figure 5.

In contrast to the Controls and Fuzzy Inference System subdivisions, spatial characteristics is a visualization subdivision, and not a control or configuration subdivision. This subdivision presents the thermal stratification curve, temperature vs. reservoir depth, and the horizontal zone where the sample was collected (river, transition or lake zone). The depth of the sample, the temperature at this depth, and thermal stratification layer attributed by the tool to the specified depth are presented on the left side; the beginning and end of each layer are shown on the right side with their respective estimated temperatures. Figure 6 presents the spatial characteristics before and after the indices calculation.

Finally, the Indices subdivision presents the Water and Biotic Quality Indices, as well as the value of their respective sub-indices. As specified in Section 2.3, the calculation methodology used in the evaluation of the sub-indices and final indices is selected by the tool, according to the horizontal location (river, transition and lake zone) and the thermal stratification layers to which the sample belongs. The thermal stratification layer is automatically calculated by the same tool using the depth data of the sample as specified in the Excel file.

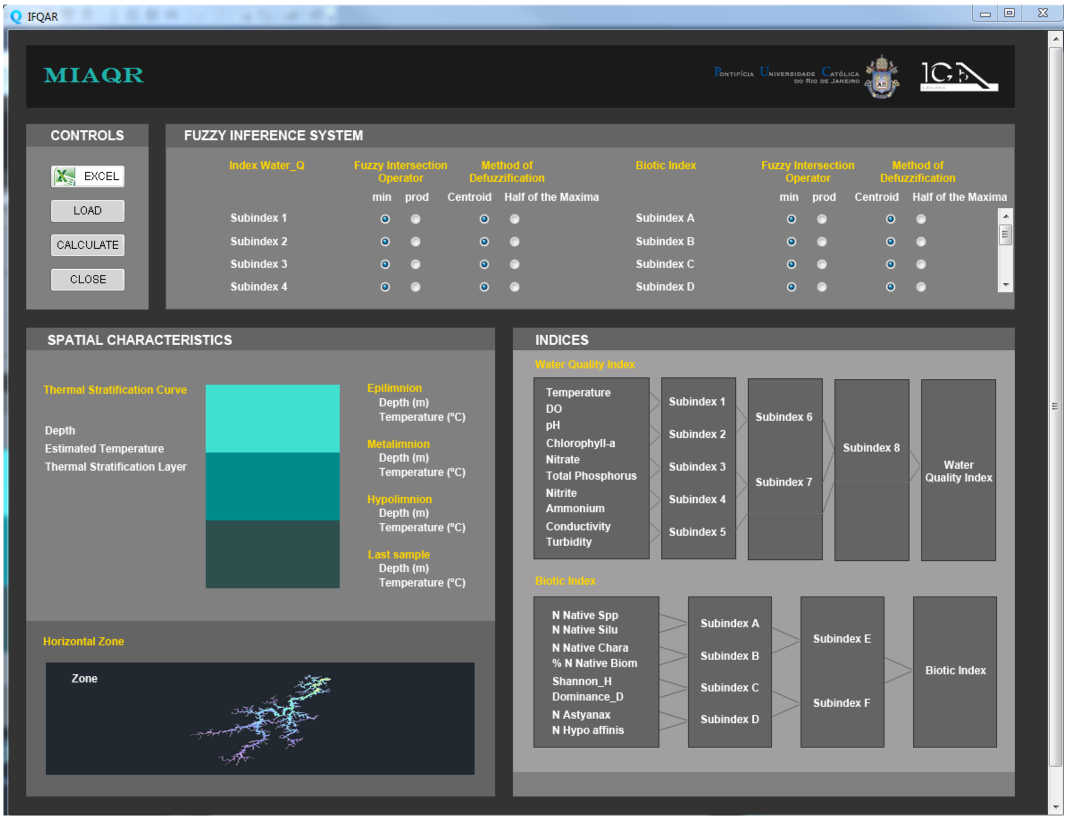


Figure 5. The graphical interface of the application.

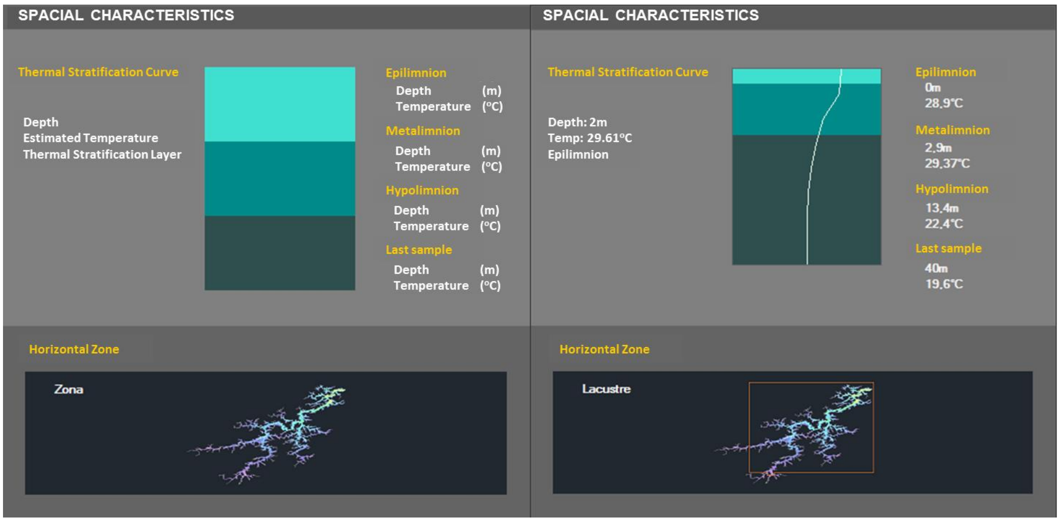


Figure 6. Spatial Characteristics of a sample, before and after indices calculation.

3.2. Evaluation of the FUZZY-WBQAI for Water Quality Analysis

3.2.1. Response analysis of the model for each variable

For all the inference systems, ten variables in the water quality index and seven in the biotic index were used. They were chosen based on their importance, taking into account the legislation for water quality (CONAMA, 2005) and metrics from the fish assemblage index

(Terra and Araújo, 2011). The variables were configured as follows:

- Minimum t-norm as fuzzy operator AND of the antecedents. No rule was implemented with the operator OR;
- Minimum as implication operator;
- Maximum in the aggregation of the consequents;
- Area Centroid in the defuzzification.

With the purpose of testing each variable in its complete range of variation, simulated data as input values were used. Two different evaluation databases were created: a database for the water quality index and another for the biotic index. The data in the databases consisted of values that were proportionally separated inside the most extensive variation range of each indicator or metric. The ranges were obtained from the UNIRIO and UFRRJ databases, and 21 values were considered sufficient to represent the entire variation range of each input variable satisfactorily.

The behaviour of the model for the ten water quality indicators was analysed. The behaviour test consisted of varying the input value of a single indicator along with the entire interval, while all other indicators remain fixed. Consequently, the final index and sub-indices reflect only the variations of the tested indicator.

The chosen values of the other indicators that were not part of the test and remained fixed were the average of the amounts of all of the collections among the five sampling locations L1, L2, L3, L4, and L5, performed in the year 2009.

Because the final index is the result of intermediate fuzzy systems, and only the subsystems with two input variables were used in this study, the sub-indices with both input constants were also constant. Some comments about the behaviour analysis for the following variables water temperature, dissolved oxygen, pH, nitrate, nitrite, ammonium, total phosphorus, chlorophyll-*a*, electrical conductivity and turbidity are provided below:

- *High temperatures exerted a negative influence on water quality*. The remarkable influence of the temperature variable was easily observed in the result of sub-index 1. Thus, we infer that for temperature values above 24.5°C, the result of the sub-index shows an inversely proportional trend. Water temperature directly influences dissolved oxygen saturation in the water; additionally, in the tropical regions oxygen values can show an overall downward trend during high temperature in the summertime, which can be a threat for aquatic life (Souza *et al.*, 2011).
- *A directly proportional relationship occurs between the water quality and dissolved oxygen variable.* A directly proportional relationship was observed between the values of dissolved oxygen and results of sub-index 1; the corresponding influence of the indicator on sub-indices 6 and 8 up to the final index was also observed.
- *There is a marked influence of the dissolved oxygen on the final index.* Besides being essential for aquatic life, the dissolved oxygen has a concentration limit for water used for human consumption supply with disinfection, such as the waters of Lajes Reservoir. According to the CONAMA 357/2005 (CONAMA, 2005), dissolved oxygen, in any sample, cannot be less than 6 $mg.L^{-1}$.
- *Better water quality was indicated by pH values close to 6.5.* In Lajes Reservoir, pH presented values around this value at sampling sites without human influence across years of studies (Guarino *et al.*, 2005; Soares *et al*., 2008; Rocha *et al*., 2019).
- *An inversely proportional relationship occurs between the water quality and increments in the nitrogen series, total phosphorus and chlorophyll-a.* As an oligo-mesotrophic reservoir,

the increase of nutrients can mean a change in trophic conditions, especially in a reservoir with a high retention time (Klippel *et al.*, 2020). The differentiated condition of an oligo-mesotrophic system used for domestic water supply was shown by the importance of maintaining chlorophyll-*a* values below 5 µg.L^{-1} for better water quality. This value is lower than that recommended by the CONAMA 357/2005 (CONAMA, 2005), which is 10 µg.L^{-1}.

• *Regarding turbidity and conductivity: no significant variations in water quality were observed by varying conductivity and turbidity.* Lajes Reservoir characteristically presents low values of these two variables throughout the years. The surroundings protected by rainforest and the control of human activities in the creeks entering the reservoir explain the good water conditions of the reservoir (Branco *et al.*, 2009; Rocha *et al.*, 2019).

More generally, it can be observed that there was a predominance of one sub-index over the others. Sub-index 8 had a strong influence, while sub-index 5 exhibited a weak impact on the final water quality index. Furthermore, a predominance of one variable over the others was shown since the influence of oxygen in sub-index 1 was clearly more significant than the influence of temperature.

3.2.2. Water Quality analysis using real data

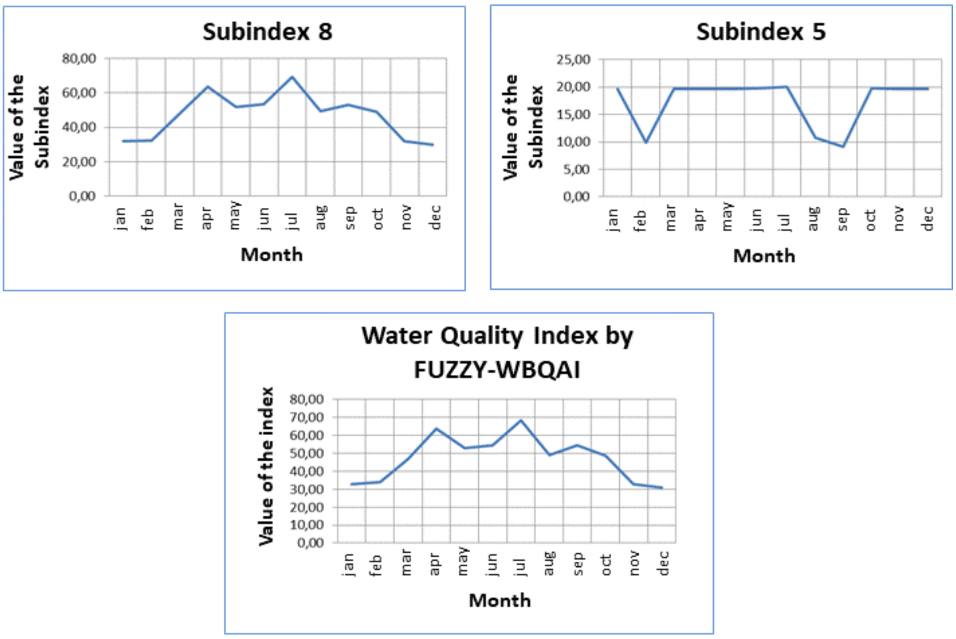
Unlike the previous test, real sample data were used in this trial. Due to the lack of samples at low depths, the index was evaluated at the surface of the reservoir. This test used only superficial samples collected in the year 2009 and from sampling locations L1, L2, L3, L4, and L5. A detailed analysis of the behaviour of the sub-indices and final index was performed for locations L1 and L5 (Figure 7a and b), respectively, near the main tributary of the reservoir and near an area of fish cage aquaculture.

As a result of the test, at sampling location L1, formulation of the sub-indices followed the complete logic used in the formulation of the rules. For example, in sub-index 1, average temperatures between 15 and 20°C and high values of dissolved oxygen between 8 and 10 mg.L^{-1} generated good water quality values. In sub-index 2, the average pH value of 6.56 and high chlorophyll-*a* value of 7.4 µg.L^{-1} in January generated a relatively low sub-index 2 score of 8.38, which represents poor water quality for the Lajes Reservoir at L1. However, in October, the average pH of 6.3 can be characterized as good and low average chlorophyll-*a* of 2.2 µg.L-1 resulted in an average sub-index 2 of 58.42, which indicates intermediate quality. In this example, the predominance of one variable over another was observed. A higher chlorophyll-*a* value had greater weight in the evaluation of water quality for human consumption than did a good pH value. In sub-index 3, low values of nitrate of approximately 0.1 mg.L^{-1} and low values of total phosphorus of around 0.05 mg.L^{-1} generated good quality results. Considering the final FUZZY-WBQAI water index, the worst values are among the months from November to February (Figure 7a), which are related to months with higher average temperature, and increase of nutrients input by rains. Augmentation of the content of phosphate and nitrate in water due to more intense rainfall in summer has been shown for other Brazilian reservoirs (Brandimarte *et al.*, 2008; Branco *et al.*, 2019).

The results from sampling location L5 (Figure 7b), exhibited the same tendencies as found in the previous tests. Furthermore, in the final index, a decrease in the water quality was noticeable in May and June. Differently from location L1, L5 is not influenced by rainfall. The mixture of the water column at the beginning of the dry season increasing values of ammonium and nitrite in May and June influenced a decrease in sub-index 4. The result was transmitted by sub-indices 7 and 8 to the final index. Guarino *et al.*, (2005) and Branco *et al.*, (2009) reported the increase of nitrogen content in the water surface in Lajes Reservoir caused by the winter mixing of the water column, consequently decreasing water quality.

For the sites L2, L3, and L4, only the results for the last index are shown (Figure 8). All these locations have a decline of water quality in the months at the end and at the beginning of the year (except for L4 whose deterioration was not so marked), which correspond to the rainy season in summer. Higher water temperature in this period corresponded to a decrease of dissolved oxygen (decreasing subindex 1) and a rise in chlorophyll-*a* values (decrease of subindex 2). A positive association between water temperature and chlorophyll-*a* has been shown in several Brazilian reservoirs (Silva *et al.*, 2014). Further, the washing of surrounding soils by rainfall meant an increase of nutrients carried into the waters, especially nitrogen compounds and total phosphorus (decreasing subindex 3 and 4). These scenarios provided by the rainy season helped to explain a lower final FUZZY-WBQAI water index in November and December in most sites.

(A)



(B)

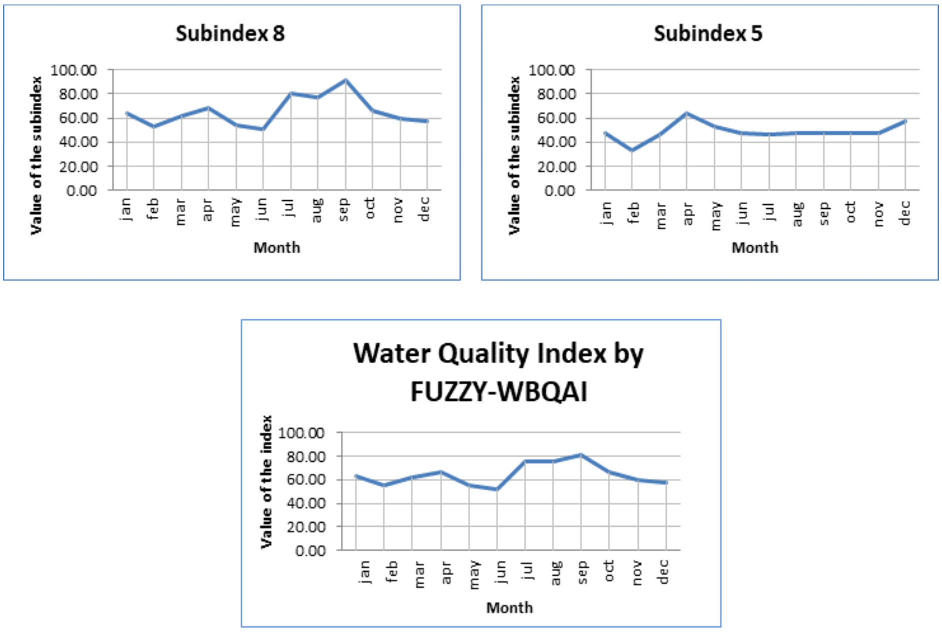


Figure 7. Water Quality Index by FUZZY-WBQAI using real data – sampling location L1 (a) and sampling location L5 (b) - Final index's behaviour.

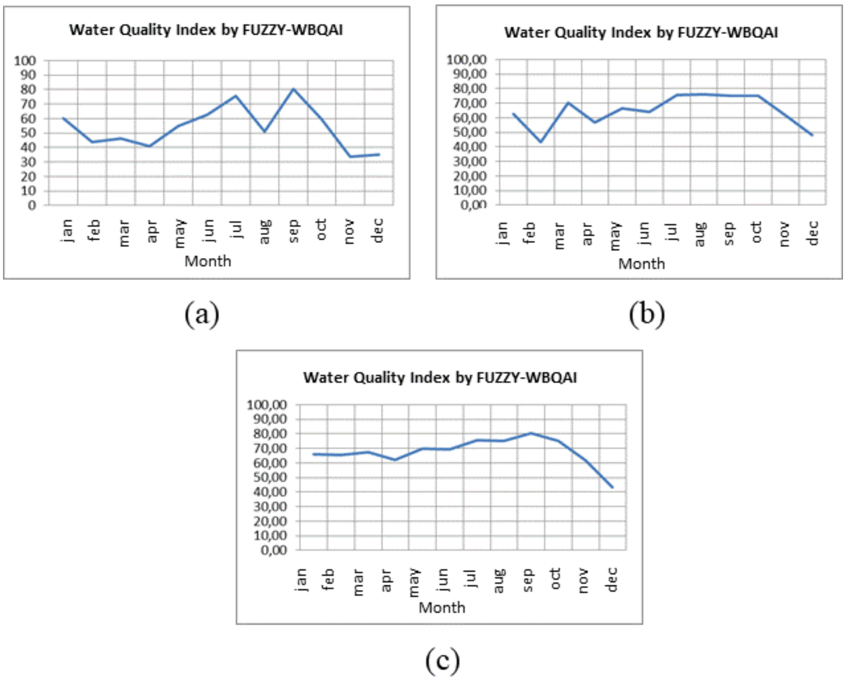


Figure 8. Water Quality Index by FUZZY-WBQAI using real data – sampling locations L2 (a), L3(b) e L4(c) (Final index's behaviour).

3.3. Evaluation of the FUZZY-WBQAI for Biotic Quality Analysis

To evaluate the biotic index, a sampling location was selected from the 24 locations used for fishing and listed in Figure 1. The position number 6 was chosen due to the abundant quantity of data compared to the other sampling locations. All the samples collected from that location between the years 1994 and 2011 were used, producing a total of 19 samples.

Similar to the results of the FUZZY-WBQAI for water quality analysis, the behaviour of the FUZZY-WBQAI for biotic quality sub-indices followed the complete logic used in the formulation of the rules. For example, in sub-index B, the combination of a low biomass percentage of non-native species with a high number of native Characiformes generated good biotic quality levels in the first samples. Also, a decrease in the number of native Characiformes and an increase of the biomass percentage produced a reduction in the quality value; as the Shannon index decreased and dominance increased, the value of sub-index C decreased.

A comparison of the RRFAI (Terra and Araújo, 2011) and FUZZY-WBQAI (Figure 9) shows that both indices followed the same pattern of variation for the samples. The FUZZY-WBQAI biotic quality index presents quality values that are slightly higher than those of the RRFAI.

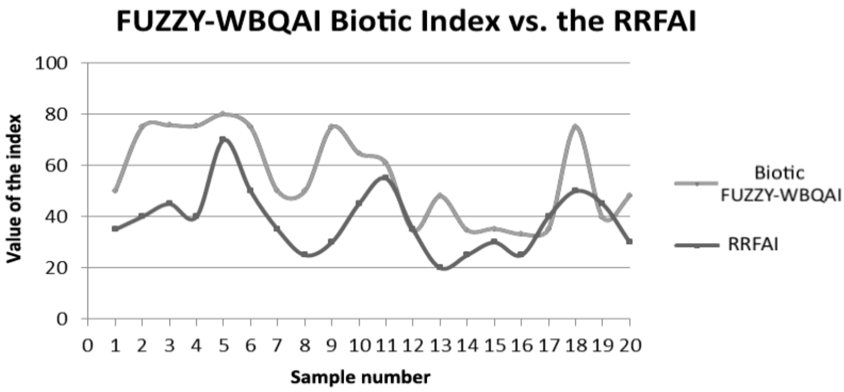


Figure 9. Results of the FUZZY-WBQAI Biotic Index vs. the RRFAI.

4. CONCLUSIONS

FUZZY-WBQAI is a new evaluation model for environmental quality of a tropical reservoir, and a friendly computer tool to implement; it effectively represents advances in water quality evaluation on a numerical scale, in addition to considering the inherent subjectivity of the concept of quality. In the model, the oligo-mesotrophic conditions, morphometric features, long retention time, and stratification and mixture of the water column were considered the main forces acting on the Lajes Reservoir. The peculiar condition of an oligo-mesotrophic system used for domestic water supply was shown by the importance of maintaining chlorophyll-*a* values below 5 $\mu g.L^{-1}$ for better water quality. This condition complies with the environmental legislation.

Most variables included in previous limnological studies performed in this reservoir were included in the model, which was sensible to track water quality decrease in summer months (November to February) with higher temperature and pluviosity. Also, the mixing in winter was highlighted as decreasing water quality at sampling location 5 near the fish aquaculture. In this location, the accumulation of nutrients in the hypolimnion has been enhanced due to the long-time aquaculture activities.

The performance of the proposed model, FUZZY-WBQAI, was validated and found to be satisfactory when different quality indicators were combined in the formulation of the indices. The good performance was possible due to the ability of fuzzy logic to expand and easily combine quantitative data with qualitative information. Additionally, the model demonstrated efficiency equal to that of the RRFAI in characterizing biotic quality.

The computational tool developed possesses the following features: it can configure the defuzzification method of each FIS directly in the user interface without requiring additional configuration in the program; and it has a dynamic and user-friendly interface, with a configurable database that is uploaded into the application. Although the proposed model was specifically developed for tropical oligo-mesotrophic reservoirs, it can be adapted to reservoirs with different characteristics. Since this methodology considers the uncertainties involved in several steps of an integrated system, a robust collection of data and experts availability are of primary importance as well as limiting factors for practical use. Imprecise and heterogeneous data variations and expertise can be integrated more effectively using the fuzzy approach.

Given the wide variety of uses of Brazilian reservoirs, and considering that several reservoirs are being planned or constructed throughout the country, new and more efficient approaches to evaluate environmental quality are clearly welcome. This tool can be especially useful for energy production companies whose generating matrix is based on hydroelectric power plants with reservoirs.

5. ACKNOWLEDGEMENTS

The authors would like to thank the National Council for Scientific and Technological Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq), the Brazilian Federal Agency for the Support and Evaluation of Graduate Education (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - CAPES) and Light S.A. for their financial support.

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