Acta Limnologica Brasiliensia

Publication of the Brazilian Association of Limnology

Original Article
Acta Limnologica Brasiliensia, 2019, vol. 31, e22
https://doi.org/10.1590/S2179-975X12017
ISSN 2179-975X on-line version

Habitat, limnological signatures and spatial modeling: a zoning proposal for the Curuá-Una hydroelectric reservoir, Pará, Brazil

Habitat, assinaturas limnológicas e modelagem espacial: uma proposta de zoneamento do reservatório da hidrelétrica de Curuá-Una, Pará, Brasil

Juciley de Almeida Santos[1]*, Keid Nolan Silva Sousa[2], Paulo Roberto Brasil Santos[3], Joelson Leal de Lima[4] and Rivolo de Jesus Bacelar[5]

[1]Laboratório de Geoinformação Aquática – LAGIS, Programa de Pós-graduação em Recursos Aquáticos Continentais Amazônicos, Instituto de Ciência e Tecnologia das Águas, Universidade Federal do Oeste do Pará – UFOPA, Av. Mendonça Furtado, 2946, Fátima, CEP 68040-470, Santarém, PA, Brasil

[2]Laboratório de Geoinformação Aquática – LAGIS, Instituto de Ciência e Tecnologia das Águas, Universidade Federal do Oeste do Pará – UFOPA, Av. Mendonça Furtado, 2946, Fátima, CEP 68040-470, Santarém, PA, Brasil

[3]Universidade Federal do Oeste do Pará – UFOPA, Campus Monte Alegre, Tv. Major Francisco Mariano, s/n, CEP 68220-000, Cidade Alta, Monte Alegre, PA, Brasil

[4]Laboratório de Geoinformação Aquática – LAGIS, Instituto de Ciência e Tecnologia das Águas, Universidade Federal do Oeste do Pará – UFOPA, Av. Mendonça Furtado, 2946, Fátima, CEP 68040-470, Santarém, PA, Brasil

[5]Laboratório de Biologia Ambiental, Instituto de Ciência e Tecnologia das Águas, Universidade Federal do Oeste do Pará – UFOPA, Av. Marechal Rondon, s/n, Caranazal, CEP 68040-070, Santarém, PA, Brasil

*e-mail: juciley_stm@hotmail.com

Cite as: Santos, J.A. et al. Habitat, limnological signatures and spatial modeling: a zoning proposal for the Curuá-Una hydroelectric reservoir, Pará, Brazil. *Acta Limnologica Brasiliensia*, 2019, vol. 31, e22.

Abstract: Aim: The objective of this work is to characterize, spatially model and to perform the zoning of the aquatic environment in the Curuá-Una HPP reservoir, in the state of Pará, in the Brazilian Amazon. **Methods:** The data were collected from 77 sampling points distributed over 20 transects in the Curuá-Una reservoir, in November 2016. The data were obtained through descriptive templates of the landscape, and assessment of limnological, bathymetry and georeferencing variables. To describe and model spatial patterns for the limnological *Proxies*, geostatistical analysis was used with semivariogram fitting, and interpolation using Ordinary Kriging to generate the maps. To determine the degree of association of the landscape *Proxies*, Correspondence Analysis (CA) was chosen, and to relate the landscape *Proxies* with the limnological *Proxies*, Canonical Correspondence Analysis (CCA) was carried out. **Results:** The results of the analysis of the limnological *Proxies* showed that the variables presented normal distribution according to the Shapiro-Wilk test (5%) except for transparency and temperature. Most of the variables obtained well-defined, level and good geostatistical analysis. There was a prevalence of gaussian and spherical adjustment models. Different zones in the distribution of the limnological variables in the longitudinal axis of the reservoir were observed. The CA showed a short local gradient in the variables, which effectively characterizes the interface of landscape and human. In Figure 5, the first two axes of the CCA showed 61.17% of the data variability. The limnological signatures showed 42.3% of variability, with high correlation between the landscape Proxies and the environmental Proxies in both axes. **Conclusions:** This type of approach should be useful in managing Brazilian river basins, especially in the Amazon, a focus for the construction of numerous hydroelectric dams, as it can indicate the limnological and environmental state and provide a clearer view of these environments.

Keywords: Amazon; geostatistical; anthropic action; limnology; landscape.

Resumo: Objetivo: O objetivo deste trabalho é caracterizar, modelar espacialmente e realizar o zoneamento do ambiente aquático no reservatório da UHE de Curuá-Una, no estado do Pará, na Amazônia brasileira. **Métodos:** Os dados foram coletados em 77 pontos amostrais distribuídos em 20 transectos no reservatório de Curuá-Una, no mês de novembro de 2016. A obtenção dos dados ocorreu através de formulários descritivos da paisagem, aferição de variáveis limnológicas, batimetria e georreferenciamento. Para descrever e modelar os padrões espaciais para os *Proxies* limnológicos foi utilizada a análise geoestatística com o ajuste de semivariograma, e interpolação através da Krigagem ordinária para gerar os mapas. Para determinar o grau de associação dos *Proxies* de paisagem optou-se pela Análise de Correspondência (CA) e para relacionar os *Proxies* da paisagem com os *Proxies* limnológicos, realizou-se uma Análise de Correspondência Canônica (CCA). **Resultados:** Os resultados da análise dos *Proxies* limnológicos mostrou que as variáveis apresentaram distribuição normal pelo teste de Shapiro-Wilk (5%) exceto transparência e temperatura. A maioria das variáveis obteve patamar bem definido e boa análise geoestatítica. Houve prevalência dos modelos de ajustes gaussiano e esférico. Observou-se a existência de diferentes zonas na distribuição das variáveis limnológicas no eixo longitudinal do reservatório. A CA mostrou um gradiente local curto das variáveis que caracterizam efetivamente a paisagem e a interferência humana. Os dois primeiros eixos da CCA explicaram 61,17% da variabilidade dos dados. As assinaturas limnológicas explicaram 42,3% da variabilidade, com alta correlação entre os *Proxies* de paisagem e os ambientais em ambos os eixos. **Conclusões:** Este tipo de abordagem deve ser útil para o gerenciamento de bacias hidrográficas brasileiras, principalmente na Amazônia, foco para a construção de inúmeras hidrelétricas, pois pode indicar o estado limnológico e ambiental e proporcionar uma visão mais clara desses ambientes.

Palavras-chave: Amazônia; geoestatítica; ação antrópica; limnologia; paisagem.

1. Introduction

In a consensus among researchers, human actions at the landscape scale are the main threat to the ecological integrity of river ecosystems, impacting habitat, water quality, and biota in numerous and complex ways (Allan, 2004; Boscolo & Metzger, 2011). Human activity modifies, to a great extent, plant cover, hydrological functioning and biogeochemical cycles (Allan et al., 1997; Strayer et al., 2003; Agostinho et al., 2008; Fausch et al., 2012).

Among the stressors that may affect aquatic ecosystems, is the construction of Hydroelectric Power Plant (HPP) reservoirs, these developments change the landscape, which alters the heterogeneity and habitat availability within the ecosystem (Fearnside, 2005; Silva et al., 2010; Fearnside, 2015a). The abrupt change in habitat heterogeneity also affects the composition of species assemblages (Lassau & Hochuli, 2004; Durães et al., 2005). This process alters large areas of forest, reduces and fragments habitats, isolates areas that are conducive to species survival, and results in local, deterministic, and stochastic extinctions (Havel et al., 2005), mainly in small populations (Ouborg, 1993). In addition, excessive nutrient intake (nitrogen and phosphorous) through domestic and industrial dumping, decomposing organic material, raising livestock pastures among others, can cause eutrophication of the body and the waves of its physical and chemical properties (Junk et al., 1981; Pagioro et al., 2005; Fearnside, 2015b).

The damming of a river results in the disruption of an open transport system by a more closed, accumulation system (Junk & Mello, 1990; Agostinho et al., 2007). Therefore, the new configuration caused by the damming of the river generates a continuum along the longitudinal axis of the reservoir. This continuum begins in the area of river inflow up to where it reaches the dam, and in which three different zones are observed regarding the physical, chemical and biological properties: the fluvial zone (including the delta), the transition zone and the lacustrine zone (Thornton, 1990; Pagioro et al., 2005; Ribeiro-Filho et al., 2011).

The different zones mentioned above can be characterized on the basis of limnological variables, as these relate strongly to changes caused by the damming, and which directly impact their spatial distribution and the organisms in the water column (Pagioro et al., 2005). Among these variables, temperature, dissolved oxygen, pH, electrical conductivity, total dissolved solids and transparency can be cited (Tundisi, 1993; Almeida & Melo, 2009; Molozzi et al., 2012). The characterization of zones is important for management measures because the typology of a reservoir can vary along its longitudinal axis (Pagioro et al., 2005).

In the Amazon, this process of alteration of aquatic habitat is historical and worrying (Araújo et al., 2009; Castello et al., 2013). Faced with the impossibility of increasing the energy potential of the main hydrographic basins of the South and Southeast, the Amazon basin is currently a promising centre for the installation of more than 23 hydroelectric dams in its rivers (Brasil, 2005b; Fearnside, 2015a, b). However, examples of the construction of these power plants in the world's largest rainforest, such as Belo Monte, and prior to that Balbina, are showing that actually this enterprise is far from a clean and sustainable energy production method (Moretto et al., 2012; Fearnside, 2015c).

One of the pioneering developments in electricity generation in the Amazon was the HPP Curuá-Una. Built in the 1970s, it became the first hydroelectric power plant in Central Amazonia (Fearnside, 2005). As it is old (40 years old), and as it has been through all the post-installation processes, the hydroelectric plant can be an example for projections of impacts caused by these projects, as its physical, chemical and biological habitat structure is more consolidated (Junk & Mello, 1990; Fearnside, 2005).

In the Amazon, studies that characterize the aquatic environment of reservoirs through spatial modelling and longitudinal zoning are scarce. In general, studies that use geospatial and geosynthetic studies have focused on the production of monoculture systems (Machado et al., 2007; Lima et al., 2013) and agroforestry systems (Campos et al., 2013; Oliveira et al., 2013a).

The use of Geostatistics can contribute to these studies because this tool considers an important feature to evaluate the physical environment that is the spatial aspect of the natural phenomenon, different from the Classical Statistics (Matheron, 1963). For this characteristic, Geostatistics can describe and model patterns of spatial variability (semivariogram), predict values in non-sampled locations (Kriging), to generate uncertainty of estimates for non-sampled locations (standard deviation of Kriging) and to optimize sampling meshes (Cigagna et al., 2015). This allows a clearer view of the behavior of a variable in the environment (Yamamoto & Landim, 2013). Therefore, these techniques can estimate more reliably by associating to the evaluation a sense of quality of the estimate because it measures the existing uncertainty (Andriotti, 2003; Cigagna et al., 2015) and in addition it can make the monitoring of the environmental quality in reservoirs faster and cheaper.

In this respect, the current situation demonstrates the need for research that analyses the environmental and social impacts caused by reservoirs, generating databases that are key for future research comparative studies, because through this information it will be possible to interpret the ecological state of lakes with the presence of anthropogenic impacts (Tundisi, 2007; USEPA, 2007).

After the construction of the dam on the Curuá-Una River that occurred in the construction of the hydroelectric plant a new fluvial morphology was created. With this, the reservoir under lacustrine influence revealed a new phase of spatial and temporal heterogeneity of the river landscape. With these modifications, after 40 years of creation, it is not clear what spatial heterogeneity effects occur in the riparian zone and what their effect on the fluvial physiognomy of the reservoir. In this perspective, it is assumed that in this study the spatial and temporal complexity affect the reservoir to the level of provoking specific zones in the region.

In this context, this work aims to characterize, spatially model and perform longitudinal zoning of the aquatic environment in the Curuá-Una HPP reservoir, in the state of Pará, Brazil, seeking to understand the current limnological state of the reservoir and presents a spatial variation of the limnological signatures that make up its aquatic landscapes and that can determine a longitudinal zoning of this environment. From this, to generate information that may contribute to the management of Brazilian hydrographic basins, mainly in the Amazon, a target region for the construction of large dams.

2. Material and Methods

2.1. Study area

The study was carried out in the reservoir of the Silvio Braga Hydroelectric Power Plant, better known as Curuá-Una HPP, maintained and operated by ELETRONORTE S/A. The Curuá-Una HPP dam was built to supply electricity to the city of

Santarém in the state of Pará and its surroundings, and was inaugurated in the first half of 1977 (Figure 1). It is located on the Curuá-Una river, at the Palhão waterfall (54°18'55"W and 02°48'38" S), at 68 m above sea level and 70 km southeast of Santarém (Figure 2). It contains a shallow dam with an average depth of 5.2 m, and a maximum depth of 18 m. It covers an area of 102 km^2 and the volume, measured when at the 68 m depth level, is 472 million m^3, and its generation capacity is 30 MW (Junk & Mello, 1990; Fearnside, 2005). Eletronorte is working on a plan to expand the generation capacity of the Curuá-Una Hydroelectric Power Plant up to 40.3 MW (Vale et al., 2016).

The average annual rainfall in this region is 1750 mm, monsoon type, the first five months of which, from January to May are the rainiest, and between July and December, there is a dry season. The average temperature is 26 °C with little thermal amplitude, and a relative humidity of 85% (Vieira

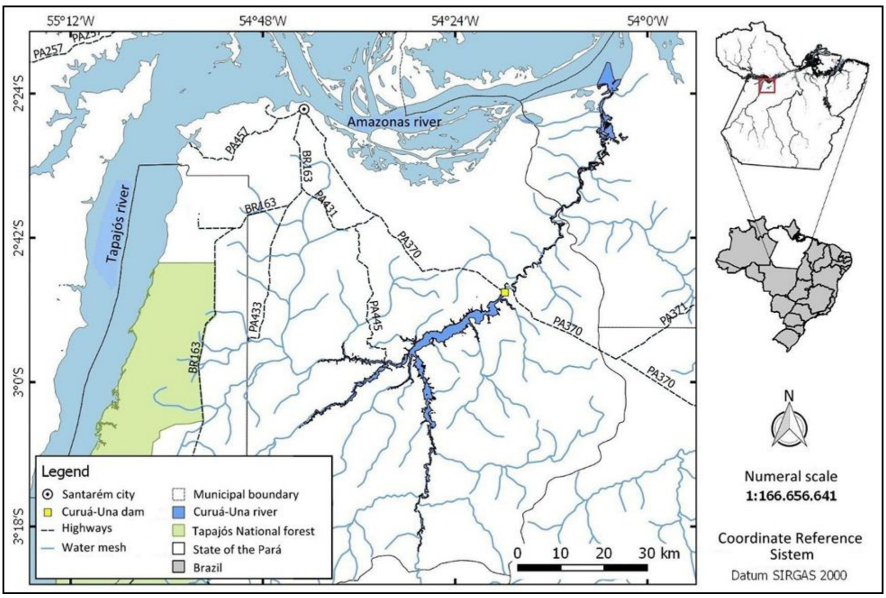

Figure 1. Geographical location of the Curuá-Una HPP, near the city of Santarém in Pará. Source: Water Geoinformation Laboratory – LAGIS.

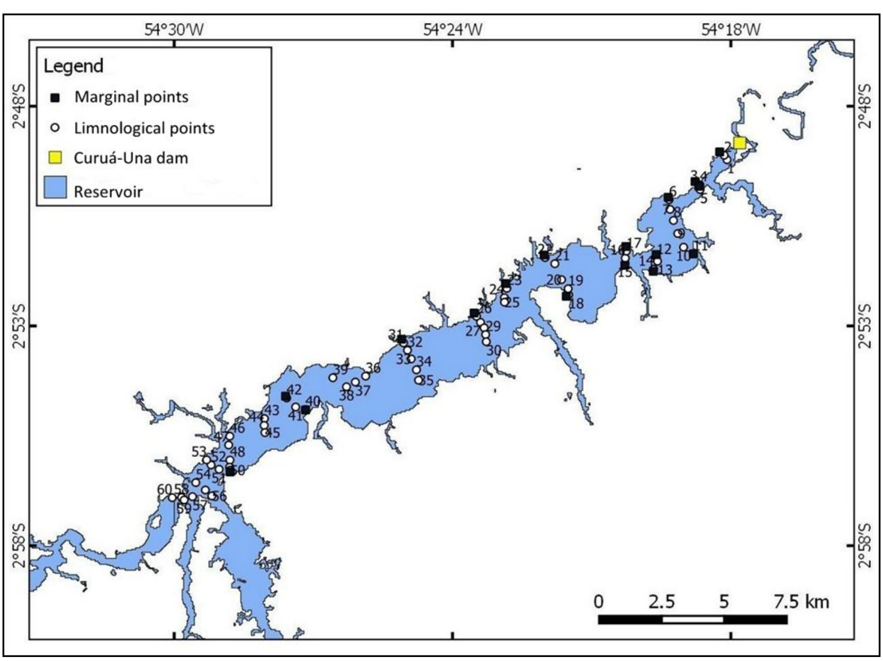

Figure 2. Locations of the sampling points in the Curuá-Una HPP reservoir. Source: Water Geoinformation Laboratory – LAGIS.

& Darwick, 1999). Lateral processes of weathering have contributed to the formation of yellow latosols with dense tropical vegetation (Gunkel et al., 2003). The areas surrounding the reservoir are occupied by riverside communities such as Corta Corda, Porto Novo, Porto Alegre, São Francisco do Puraquê, Castanheira, Sempre Verde, Tambor and Xavier. These communities subsist on small-scale fishing, agriculture and livestock farming (Almeida & Marín, 2014).

2.2. Design and procedures for data collection

Data collection took place using the following procedures and instruments:

- ***Descriptive templates***: For the data collection of landscape characterization in the Curuá-Una reservoir, forms with qualitatively measured variables were elaborated using the methodology proposed by USEPA (2007).

We considered two distinct areas, **the aquatic area** (corresponding to the river channel and the area where the area of water expanded due to the dam construction) and the **flood area** (considered the TATZ - Terrestrial aquatic transition zone, dry in November). To characterize the aquatic area, a template was used to register a number of variables, such as the presence of macrophytes, pallets, rocks, organic matter (leaves, branches), presence of anthropic activity (housing, commerce, waste, oil residues, grease, foams from household detergents). A template was developed to characterize the flooded area, based on the presence of a number of variables, such as evidence of erosion, silting, presence of macrophytes, drowned forests, undergrowth, decaying organic matter and the presence of anthropic activity within the above-mentioned reservoir.

- ***Limnological data***: The variables of water temperature (°C), dissolved oxygen ($mg.L^{-1}$), pH, and transparency (m) were collected. For the latter variable, a Sechi Disk was used, and for the others, multiparameter equipment (AKSo-series ak88) was used for measuring;
- ***Bathymetric data***: collected using Sonar equipment (Fishfinder- *eco* 150 model);
- ***GPS data*** (*Global Positioning System*): The location of the points sampled for geostatistical modelling in the reservoir area of the Curuá-Una HPP were calibrated.

2.3. Selection of sampling points and data collection

The data were collected in the Curuá-Una HPP Reservoir, in November 2016. The river was at low levels and so was the reservoir. Data were collected from a total of 77 sampling points distributed along 20 transects of the reservoir. The layout of the points followed a zigzag pattern along the surface of the water body in two distinct areas (Figure 2). The minimum distance between samples was 500 meters and between transects was 1000 to 2000 meters.

In the aquatic area/limnological points (relating to the river channel), 60 points corresponding to the limnological *Proxy* and a characterization template per point (environmental *Proxy*) were sampled, and in the flooded area/marginal points (considered the TATZ - Terrestrial aquatic transition zone, dry in November), 17 points and a characterization template corresponding to each transect edge achieved were sampled. A motorboat was used for sample collection and a boatman to pilot the craft. This method was constructed based on the evaluation protocol (USEPA, 2007).

2.4. Process and data analyses

2.4.1. Spatial modelling of limnological descriptor variables

First, exploratory data analysis was performed to verify the central trend and dispersion measures in order to improve the efficiency of the spatial analysis through identifying discrepant values and *Outlier* removal. The descriptive statistics used in this analysis were: Maximum, Minimum, Mean, Standard Deviation and Coefficient of Variation (Guerreiro et al., 2017). The normality of the variables was also verified by the Shapiro-Wilk test at the significance level of 5% (Zar, 1999).

To describe and model spatial patterns for limnological *Proxies*, geostatistical analysis was used with semivariogram fitting, which is a mathematical tool that permits the study of spatial dispersion of a variable as a function of the distance (Isaaks & Srivastava, 1989; Vieira, 2000b; Guerreiro et al., 2017), by means of Equation 1:

$$\hat{y}(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[Z(x_i)-Z(x_i+h)\right]^2 \tag{1}$$

where: $\hat{y}$(h) = semivariance of the variable $Z(x_i)$; h = Distance; and N (h) = Number of pairs of measured points $Z(x_i)$ and $Z(x_i+ h)$, separated by a distance h(lag).

This function allows the generation of the experimental semivariogram that expresses the spatial dependence structure of the evaluated variables. For the experimental semivariogram generated by this function, a theoretical model must be fitted that provides the parameters 'Co' (nugget effect), C1 (contribution), 'Co + C1' and 'a' (reach). These parameters were estimated by the Ordinary Least Squares (OLS) fitting methods from the Spherical, Exponential, Gaussian and "the feeling" models, which is an empirical models adjustment. The adjusted geostatistical models follow the methodologies proposed by Isaaks & Srivastava (1989), Vieira (2000b) and Yamamoto & Landim (2013), and are defined in Equations 2, 3 and 4 below:

$$\hat{y}(h) = Co + C1\left[\frac{3h}{2a} + \frac{1}{2}\left(\frac{h}{a}\right)^3\right], Spherical \quad (2)$$

$$\hat{y}(h) = Co + C1\left[1 - e^{-\left(3\frac{h}{a}\right)}\right], Exponential \quad (3)$$

$$\hat{y}(h) = Co + C1\left[1 - e^{-3\left(\frac{h}{a}\right)^2}\right], Gaussian \quad (4)$$

In the Spatial Dependence Index (SDI) analysis of the variables under study, we used the classification by Cambardella et al. (1994) who proposed intervals to evaluate the percentage (%) of the semivariance of the Nugget Effect, in which values less than 25% are considered strong spatial dependence, 25% to 75% indicate moderate spatial dependence and values greater than 75% determine weak spatial dependence, shown in Equation 5 below:

$$IDE = \frac{Co}{Co + C1} x\, 100 \quad (5)$$

From each of the adjusted models, interpolation was carried out using ordinary Kriging, which allowed the mapping of all the limnological descriptor variables. Ordinary Kriging implicitly evaluates the mean in a sample space by area (Isaaks & Srivastava, 1989; Yamamoto & Landim, 2013). Therefore, the estimated value at any spatial position x_0 the interpolation expression of which is calculated by Equation 6:

$$\hat{z}(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \quad (6)$$

where: $\hat{z}(x_0)$ = is the estimated value for the point x_0; λ_i = are the Kriging weights defined according to the semivariogram parameters and $z(x_i)$ = are the values observed at the points sampled (sample space per area).

In order to select the best model, we used the cross-validation technique, which consists of predicting the known value $\hat{z}(x_0)$ of the random variable, and comparing it with the observed value Z (x_i). The errors of the observed and predicted values were analyzed using the following statistics: mean error (ME), mean square error (EQ), absolute error (AE) between observed and predicted values (Vieira, 2000b; Guerreiro et al., 2017).

The analyses were carried out in the computational environment R version 3.2.2 (R Development Core Team 2015), with *outliers* packages for identification and removal of outliers, *nortest* for the normality test, *geoR* (Ribeiro Júnior & Diggle, 2001) for the geostatistical analyses with semivariogram fitting and model selection (Cross-validation).

2.4.2. Multivariate model for landscape descriptor variables

To determine the degree of association of the Landscape *Proxies*, an exploratory technique to simplify the structure of variability of multivariate data was chosen, that uses categorical variables arranged in contingency tables, taking into account correlation measurements between the rows and columns of the data matrix (Krzanowski, 1993; Guedes et al., 1999). Thus, graphs are constructed with the main components of the rows and columns allowing the relation between the sets of landscape *Proxies* to be visualised, where proximity of points related to the line, column indicates relation and distance indicates a repulsion.

Non-biased Canonical Correspondence Analysis (DCCA) was used to investigate the size of the environmental gradient. Since this gradient was unimodal (> 4), it was chosen by the Canonical Correspondence Analysis (CA) and to relate the Curua-Una reservoir landscape Proxies (semiquantitative and categorical) with the limnological (quantitative) Proxies, performed a Canonical Correspondence Analysis (CCA). The limnological data was subject to *Ranging* standardization to remove the effect of the unit, so that they could all be analyzed at the same scale (Legendre & Legendre, 2012). The significance of the environmental variables was determined by the forward selection routine, using the Monte Carlo test (9999 random permutations).

To analyze the significant differences between spatial zones (Lake Zones and Trainers Zone) along the study area in relation to landscape *Proxies* and limnological signatures, the PERMANOVA test was applied in the Jaccard similarity matrix for landscape and Euclidean *Proxies* for limnological *Proxies*, and the data were permuted 9999 times.

PERMANOVA is a parametric test to prove a significant difference between two and more groups, based on any distance measure (Anderson, 2001). The CA and CCA analyses were performed with the help of the CANOCO program (version 4.5) (Ter Brak & Smilauer, 2002) and PERMANOVA was performed in the computational environment R version 3.2.2 (R Development Core Team, 2015).

3. Results

3.1. Spatial modelling and use of limnological Proxies (signatures)

The results of the descriptive statistics for the limnological *Proxies* studied are shown in Table 1. The values obtained for the variables showed normal distribution according to the Shapiro-Wilk test (significance of 5%), except for transparency and temperature.

The values of dissolved oxygen varied between 3.4 and 7.4 mg.L, obtaining an average of 5.6 mg.L ± 1.1 mg.L, with a variation coefficient of 19.64%, which is considered low. The water transparency was characterised by low values, ranging from 11.0 cm to 185.0 cm, with a mean of 143.7 ± 33.2 cm, and a relatively high variation of 23.11%. The pH results ranged between acid 5.0 and basic 8.7, with a mean value of 7.0 ± 0.8 and a variation coefficient of 12.31%. The surface temperature had little variation, between 29.9 and 32.4 °C, with a mean of 30.8 ± 0.4 °C and a very low variation rate of 1.54%. Depth values varied significantly (0.9 to 17.0 m) with a mean of 9.8 ± 4.6 m and a high variation of 47.18%.

The Geostatistical analysis showed a defined level (Table 2), which means that semivariogram fitting was possible for the gaussian, spherical

Table 1. Descriptive statistical analysis of the parameters of the limnological *Proxies* of water samples taken at the Curuá-Una HPP reservoir in November 2016.

Variables	Minimum	Average	Median	Maximum	Deviation Standard	CV (%)
DO ($mg.L^{-1}$)	3.4	5.6	5.7	7.4	1.1	19.64
Transparency (cm)	11.0	143.7	147.5	185.0	33.2	23.11
pH	5.0	7.0	7.3	8.7	0.8	12.31
Temperature (°C)	29.9	30.8	30.9	32.4	0.4	1.54
Depth (m)	0.9	9.8	12.0	17.0	4.6	47.18

DO = Dissolved Oxygen; pH = Hydrogenionic Potential; CV = Coefficient of Variation.

Table 2. Results of the geostatistical analysis of the physical-chemical parameters of the water sampled in the reservoir of the Curuá-Una HPP, Brazil, in November 2016.

Variables	Model	C_0	C	A	SDI	ME	AE	EQ
DO ($mg.L^{-1}$)	Spherical	0.18	1.58	9214.92	10.24	0.0051	0.3104	0.1720
	Exponential	0.08	1.88	4776.73	4.17	0.0077	0.4640	0.1772
	Gaussian	0.37	1.39	4480.15	21.40	0.0012	0.0734	0.1748
	“At feelings”	0.16	1.62	10489.45	8.98	0.0049	0.2993	0.1821
Transparency (m)	Spherical	436.07	896.78	10534.51	32.71	0.0052	0.3135	29.6591
	Exponential	416.21	1170.32	7182.77	26.23	-0.012	-0.713	29.8847
	Gaussian	494.73	810.79	4341.14	37.89	-0.002	-0.084	28.8232
	“At feelings”	347.93	1043.80	6455.05	16.0	-0.136	-8.176	31.7258
pH	Spherical	0.1098	4.7403	138134.82	2.26	0.0002	0.0149	0.4799
	Exponential	0.0390	1.0607	11941.84	3.55	-0.001	-0.065	0.4899
	Gaussian	0.1866	0.8197	11147.53	18.54	-0.001	-0.087	0.4823
	“At feelings”	0.18	1.06	15330.74	14:51	-0.001	-0.067	0.4784
Temperature (°C)	Spherical	0.15	0.05	2388.36	72.55	-2.225	-1.335	0.4383
	Exponential		-	-	-	-	-	-
	Gaussian	PNE	-	-	-	-	-	-
	“At feelings”	0.13	0.09	4975.76	59.09	1.7831	-1.335	0.4383
Depth (m)	Spherical	PNE	-	-	-	-	-	-
	Exponential	PNE	-	-	-	-	-	-
	Gaussian	PNE	-	-	-	-	-	-
	“At feelings”	20.27	1.40	12506.66	93.53	6.4605	-3.40	-2.0401

DO = Dissolved Oxygen; pH = Hydrogenionic Potential; C_0 = Nugget Effect; C = Level; A = Scope; SDI = Spatial Dependency Index (%); ME = Medium Error; AE = Absolute Error; EQ = Square Error Root; PNE = Pure Nugget Effect.

and exponential models; the choice of model was determined by best fit of the line to the points located in the contribution range of the semivariogram, using the lower value of the errors obtained (by means of the relationship: predicted/observed). Among the variables studied, depth was the only one that showed a pure nugget effect for all the applied models, making it impossible to interpolate using Kriging, so the use of another interpolation method is recommended.

For dissolved oxygen and transparency (Figure 3), there was a predominance of fit to the Gaussian semivariogram model, and this model had a lower nugget effect and greater contribution, its range values for the variables were 4,480.15 metres and 4,341.14 metres for dissolved oxygen and transparency respectively. The Gaussian model showed the best fit with the least errors obtained, and showed strong spatial dependence (SDI < 25%).

For the variables of pH and temperature (Figure 3), there was a predominance of fit to the spherical model, however the spherical model was obtained by manual fitting ("at feelings"). These models showed lower nugget effect and higher contribution, their range of values for the variables were 1,38134.82 metres and 4,975.76 metres for pH and temperature, respectively. The spherical model shows the best fit with the least errors obtained, showing strong spatial dependence

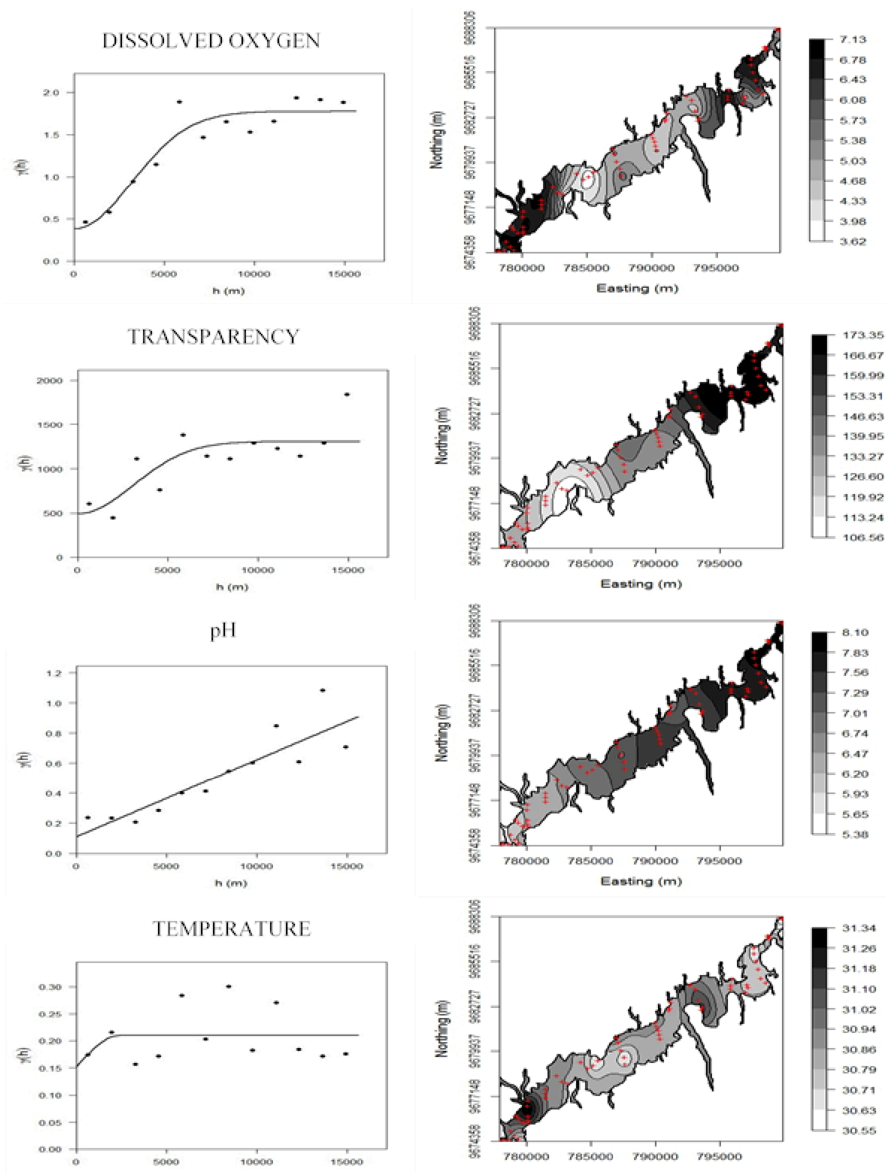

Figure 3. Semivariograms adjusted for the Gaussian model (Dissolved Oxygen and Transparency) and spherical (pH and Temperature) and their respective maps and scales of values obtained by the Kriging method for the Curuá-Una reservoir, in November 2016. Legends: Red cross (+) - each georeferenced point; Sequence of red crosses (+ + +) - transects; $\gamma(h)$ - Semivariance; h (m) - distance.

for pH (SD < 25%) and weak spatial dependence for temperature (25%<SD>75%).

Using ordinary Kriging one can estimate the limnological *Proxies* for the entire sampling area of the reservoir (Figure 3). It can be seen that the highest concentrations of dissolved oxygen are in the areas of fluvial influence due to its tributaries, and near the HPP dam. Transparency forms a gradient, its lowest values are located in the region of fluvial influence with its value increasing towards the dam. A similar behavior was observed with pH, in as much as the environment is more acidic in the area of fluvial influence and tends to alkaline when approaching the dam. The temperature shows some nuclei with higher temperature values, these higher values are associated with the lower values for depth observed in these areas.

3.2. Multivariate models and water zoning of the reservoir

The Correspondence Analysis (CA) is an indirect gradient analysis technique (Figure 4), by which we can observe a short local gradient of the variables that effectively characterize the landscape and human interference, this gradient is 19.48%. While the second axis is a gradient of areas where waste material was observed and this gradient is 18.18%. Transects T15, T10, T9 and T8 are strongly associated with areas where pasture, waste, harbours, housing, commerce and aquiculture were observed. In other words, these transects are strongly associated with environments of human interference and waste material of these anthropic activities. Transects T17, T18, T19 and T20 that characterize the area of fluvial influence are strongly associated with deforested areas, with the presence of fishermen, rocks and boulders and organic debris, whereas the others are strongly associated with the presence of pallets, macrophytes and sediment in suspension. However, T7 did not show any association with the landscape *Proxies*.

The first two axes of the CCA explained 25.9% of the variability of the data (Figure 5). However, the amount of explanation of the association between landscape *Proxy* and limnological signatures was 42.3%. Nevertheless, the significance of pseudo-canonical relations (environment-landscape) was not impaired, as the CCA produced significant correlations ($p < 0.05$) in the first two axes indicated by the Monte Carlo test (0.9264 and 0.8256 for axes 1 and 2), respectively (Table 3).

The first axis of the CCA of Figure 5 forms a gradient of pH, oxygen and temperature and this gradient explains 16.05%. The transparency in the sorting diagram is a complementary variable that correlates with temperature. The highest values of dissolved oxygen are located in the zone of trainers, a more preserved area, which is strongly associated with the *Proxy* of landscape fisher, boulder, stone and organic matter.

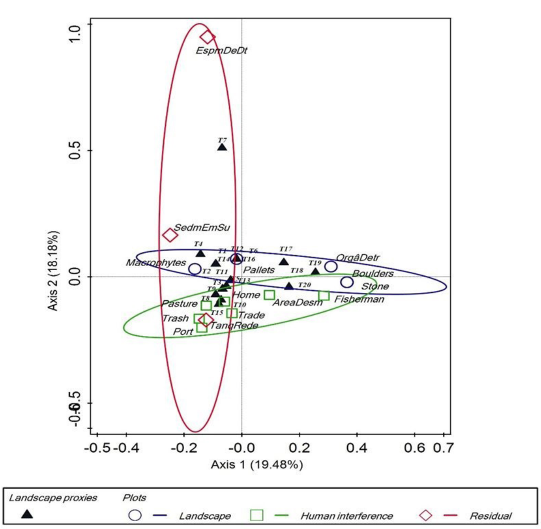

Figure 4. Ordering Diagram of the Correspondence Analysis (CA) of the qualitative variables of the landscape distributed in 20 transects along the Curuá-Una reservoir, in November, 2016. Legend: T = Transects; SedmEmSu = Suspended sediment; TanqRede = Cage fish farming; Area Desm = Deforested area; OrgâDetr = Organic matter/debris; EspDeDet = Foam from household detergent.

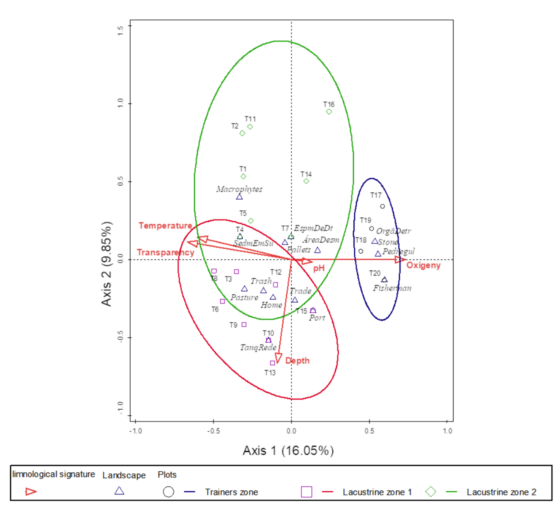

Figure 5. Ordering diagram of the Canonical Correspondence Analysis (CCA) showing the sample transects, limnological signatures and the *Proxy* of the landscape in the Curuá-Una reservoir, in November 2016. Legend: T = Transects; SedmEmSu = Suspended sediment; TanqRede = Tank network; AreaDesm = Deforested area; OrgâDetr = Organic matter/debris; EspDeDet = Foams for household detergents; Pedregul = boulders.

Table 3. Results of the statistical analysis of the eigenvalues, percentages of the variance explained by the relation *Proxy* of the landscape and limnological signature of the significant axes of the Correspondence Analysis Canonic in the reservoir of the UHE of Curuá-Una, in the month of November, 2016.

statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eingenvalues	0.474	0.2912	0.2287	0.1857
Variation explained (acumulative)	16.05	25.9	33.65	39.93
Correspondence Analysis Canonic	0.9264	0.8256	0.8514	0.8147
Result of the test of permutation: all axes		pseudo-F=2.1; P=0.006		
Result ***Forward Selection***	**Explanation %**	**F**	**P**	
Oxygen	11.9	2.4	0.047	
Depth	8.2	1.7	0.068	
pH	8.7	2	0.024	
Temperature	8.3	2	0.05	
Transparency	5.2	1.3	0.255	
Total of Explanation	42.3			

The lacustrine zone 2 is an area that suffered the anthropic action by the construction of the dam so it is strongly associated with the deforested areas, paliteiras. In addition, the presence of detergent foams where the highest pH values are located is observed.

The second axis is a depth gradient and it explains 9.85%. The highest values are located in the lacustrine zone 1, which is strongly associated with the presence of tank-net and port. This zone correlates environmental parameters with the lacustrine zone 2, a similarity is observed between the landscape, house, commerce and pasture parameters, this similarity is related to the higher values of temperature and depth in the reservoir and it is where there is a great human presence.

When testing the three zones formed by the transects in relation to the landscape proxies, PERMANOVA showed that there is a significant difference between the zones ($F = 4.24$, $p = 0.0002$) and in the comparison with each other there was a high dissimilarity, that is, the zones formed by the landscape proxies are distinct. As for the limnological proxies, there was a difference with marginal significance between the zones ($F = 2.92$, $p = 0.065$), and in the same comparison lacustrine zones 1 and 2 showed a significant similarity with the results of Figure 5.

4. Discussion

4.1. Spatial modeling and use of limnological Proxy (signatures)

The limnological *Proxy* analysis from geostatistical modeling showed with efficiency the gradients formed by the variables studied along the reservoir of the Curuá-Una HPP. This reveals the need to use geostatistical modeling as an effective tool for water zoning studies. As regard to the Amazon and reservoirs built and in planning, this type of analysis is essential to indicate the limnological and environmental state because it provides a clearer view of the typology of these environments.

Most of the analyzed variables obtained a well-defined level and provided good geostatistical analysis. The prevalence of the gaussian and spherical adjustment models is common in the literature, presenting a good fit of the data (McBratney & Webster, 1986; Gomes et al., 2007; Guerreiro et al., 2017). Temperature and transparency did not show normality at the 5% level of significance, however according to Isaaks & Srivastava (1989), normality is not the determining factor for the accomplishment of the geostatistical study, being more important the existence of well-defined thresholds in semivariograms.

As regards kriging used in this work as a geostatistical method of estimating values of variables distributed in space, the most fundamental difference was observed in relation to other traditional methods, kriging presents non-biased estimates and the minimum variance associated with the estimated value, this creates greater reliability to the results (Yamamoto & Landim, 2013; Cigagna et al., 2015).

Through the results it is possible to observe the existence of different zones along the longitudinal axis of the reservoir. Each studied variable behaves in a distinct way, presenting, in some cases, well established standards. However, there are no studies using this methodology in the Curuá-Una reservoir and in the Amazon, which makes a comparison difficult. In this way, it was searched for works that have a similarity with the data and results obtained.

The hypothesis of longitudinal zoning was tested in 6 reservoirs in the state of Paraná and São

Paulo and it was concluded that these environments presented regions with very different limnological characteristics (Pagioro et al., 2005). Thornton (1990) had observed the existence of three different zones regarding the physical-chemical and biological properties the fluvial zone, the transition zone and the lacustrine zone. The characterization in zones is important in management measures since the typology of a reservoir can vary along its longitudinal axis (Pagioro et al., 2005).

The pattern of dissolved oxygen (DO) was different from the found standard by other authors. In the present study, the DO was higher in the fluvial influence areas and near the HPP dam with a maximum of 7.13 $mg.L^{-1}$. However, another study, after conducting a limnological analysis in the Curuá-Una reservoir, found that the dissolved oxygen decreased as it approached the dam, from 4 mg.L-1 at the station near the fluvial area to less than 0.5 mg .1 near the dam (Junk et al., 1981). This pattern was similar to that found by Vieira (2000a) who observed that in the area near the dam the concentration of oxygen was low and a strong odor similar to sulfuric gas impregnated the air. In addition, large amounts of organic plant matter were still decomposing in their waters.

In the present study, the higher DO values found near the dam (7. 13 $mg.L^{-1}$) may be related to the lower amount of phytoplanktonic organisms that use oxygen to perform their aerobic processes and the low vegetation in that zone. And the great amount of oxygen dissolved in the fluvial area is related to the influence of the Moju and Mojuí tributaries in well-oxygenated running waters, even in the driest season when these data were collected. In rainy season, from December to May, the flow increases (Vieira, 2000a).

This study occurred in a post El Nino period and the limnological condition may have been influenced by this event. Vale et al. (2016) in his work in Curuá-Una, showed that the years of 1983, 1992, 1997 and 1998 corresponded to years of lower rains. These years are related to years of strong El Nino events, according to the NOAA classification. Therefore, it was concluded that the years of lower rainfall also presented effects on the flow of the Curuá-Una reservoir.

The behavior of the variable transparency was considered normal, the increase of this variable in the river-dam direction is related to the high sedimentation of suspended particulate matter in the upper section of the reservoirs (Pagioro et al., 2005). This behavior corroborates what was found in other works in this reservoir where the water transparency varied between 0.6 m entrance of the Curuá-Una River in the dam, maintaining in the dam itself values between 1.6 and 2.0 m (Junk et al., 1981; Vieira & Darwick, 1999), values close to what was found in this work, but this analysis occurred in the rainy season where the water level is higher. In general, the transparency variable followed the pattern of zoning that was found in previous works.

The pH followed the longitudinal behavior being more alkaline the closer to the dam. The rivers of clear water have the characteristic of having more acidic waters, the Curuá-Una river and its tributaries present this characteristic, therefore the more acidic pH at the entrance of the river in the reservoir is justified. However, the levels found within the reservoir were higher (5.6-8.4) than those found by Junk et al. (1981), (5.2-5.4) and Vieira & Darwick (1999), (5.0-6.5) demonstrating that an alkalinization of this water body may have occurred over time.

Temperature, in turn, presented very specific nuclei with higher values of temperature, located in areas with less depth. The temperature tends to increase in shallower places because the solar radiation affects that area more quickly, causing this difference in temperature (Silva et al., 2010). The average temperature found in this work (30.8 °C), compared to the highest value found by Junk et al. (1981), (x = 29.3 °C) and Vieira & Darwick (1999), (x = 29.4 °C) shows that there was an increase of about 1.5 °C, which may show a possible influence of El Nino in this water body (Vale et al., 2016) and global warming on a larger scale.

Changes in temperatures in these environments alter water density as well as dissolved oxygen content, affecting many aquatic organisms. Water temperature establishes standards of physiological behavior, limits, accelerates the growth of organisms (productivity) and interferes in the reproductive processes. With the increase in water temperature, intense reproduction of phytoplanktonic organisms occurs, which will lead to a great absorption of dissolved nutrients (Tundisi, 2006).

4.2. Multivariate models and water zoning of the reservoir

The results of the Canonical Correspondence Analysis (CCA) evidence the strong influence of the anthropic action on the aquatic ecosystem of the reservoir. These results show the occurrence of a complex system that links limnology, human interference and the landscape. Moreover, they reaffirm the existence of longitudinal zones that differ according to the characteristics of each gradient with the results of PERMANOVA.

It is know the existence of factors that can affect the stability and limnological distribution of a body of water. Among these factors are the construction of the reservoir itself, responsible for altering the ecosystem dynamics through the hydroelectric plant implantation process with the flooding of the area and the modification of the morphometric conditions of the river (Boscolo & Metzger, 2011; Allan et al., 1997; Strayer et al., 2003; Fausch et al., 2012). Beyond the post-implantation factors such as deforestation of the riparian zone around the reservoir, decomposing organic material, pollution by household detergents, cattle grazing among others, may influence the dynamics of the abiotic components and consequently reflect on the associated biota (Junk et al., 1981; Agostinho et al., 2007, 2008; Fearnside, 2015b).

In this study, the transects most associated with human interference are those close to the existing communities around the reservoir (Figure 4) located in the lacustrine zone 1 / intermediate zone (Figure 5). Generally, members of these communities use water from the reservoir for their own consumption (to prepare food and drinking), in cleaning activities (washing clothes, cleaning the house, personal hygiene) to irrigate their plantations and crops of vegetables. Oliveira et al. (2013b) analyzing the socioeconomic profile of fishermen in the Coaracy Nunes hydroelectric power plant in Amapá, found that 3.77% used river water as a source of supply and 15.10% of the household waste was directed to streams or lakes.

Therefore, the disposal of human waste such as bottles and plastic bags, as well as domestic detergent foams, directly interfere in the quality of water consumed by these communities (Silva et al., 2010; Oliveira et al., 2013b). It is essential a awareness project of the communities around the reservoir for the non-disposal of those residues that are harmful to humans. The high investments in the construction of reservoirs, over time, cause concern about the quality of the dammed water, generating the need to monitor the resource, mainly against the importance of water quality for the use, both for human consumption, animal and agricultural (Souza et al., 2014; Fearnside, 2015a).

The fauna and flora existing in the aquatic ecosystem are directly affected by the waste disposal because the increase of the nutrients supply and organic compounds generated by this discarded linked to the residues generated by the compounds of cattle pastures, leached into the reservoir become bases for the establishment of a eutrophication process as can be observed in a recent study in the Amazon (Faria et al., 2015). This process renders water unsuitable for several species of fish and reduces quality for consumptive uses (Silva et al., 2010; Fearnside, 2015b). A study of the chemical analysis of water revealed that the Curuá-Una river contained large concentrations of Fe and phosphorus (P) mainly due to increased land use and that the eutrophication of the Curuá-Una reservoir was also happening, since these activities leading to increased erosion and high sediment load for rivers flowing into the reservoir (Gunkel et al., 2003).

The CCA of Figure 5, although presenting a low amount of explanation, showed a correlation gradient between pH, dissolved oxygen and temperature variables, which shows that the landscape has a significant effect on limnological signatures.

The temperature, among the parameters, is one of the most important characteristics of the aquatic environment, because it influences much of the other physical and chemical parameters of water such as density, viscosity and vapor pressure (Tucci, 2004; Cunha et al., 2011). The dissolved oxygen is another important parameter of water quality, being influenced by the deposition of organic matter in the water, that is, the higher the amount of organic matter in the reservoir, the greater the retraction of the amount of DO in the aquatic environment, thus damaging, the natural stability. The main sources for oxygen renewal in water are coming from atmosphere and photosynthesis process (Braga, 2005; Cunha et al., 2011).

According to Braga (2005), pH is a measure of the acidity or relative alkalinity of a certain solution, varying from 0 to 14. Being, therefore, the value for pure water is equal to 7. Thus, in relation to the element water, according to the CONAMA resolution (Brasil, 2005a), the data of the pH must vary between 6 and 9. The amount of available light in the aquatic ecosystem has a direct influence on its metabolism. The increase of suspended sediments in the water can promote the reduction of the euphotic zone that interferes in the primary production process.

The Curuá-Una reservoir is considered small, however with a long existence time, almost 40 years, it is the oldest of the reservoirs of Central Amazon (Junk et al., 1981; Vieira & Darwick, 1999). Smaller reservoirs should be more influenced by external factors than larger area and volume reservoirs, in other words, in smaller reservoirs, external events of reduced magnitude should provide greater changes in the physical, chemical and biological characteristics of the mass of water than this same event acting in larger reservoirs (Tundisi, 2006).

Therefore, this work shows that the reservoirs present a dynamic that reflects both the influence of external and internal factors. Over time, there must be alternation in the order of importance of these factors (Straškraba & Tundisi, 1999; Pagioro et al., 2005). This reinforces the need for work that reveals the influence of external and internal factors on reservoir dynamics as a crucial factor for the management of these systems, especially in the Amazon region and government projects to build countless hydroelectric power plant that if badly planned can extinguish many species and cause an irremediable imbalance in the ecosystem.

5. Conclusion

The limnological *Proxy* analysis from geostatistical modeling effectively showed the gradients formed by the variables studied along the reservoir of the Curuá-Una HPP. It reveals the need to use geostatistical modeling as an effective tool for water zoning studies, as well as being useful for faster and cheaper monitoring in reservoirs.

The longitudinal zonation within the Curuá-Una reservoir was evident, corroborating with the idea of the existence of horizontal and vertical gradients and of a continuous flow of water towards the zone of the dam. Due to the continuous flow of water towards the dam and the variation of the residence time, the reservoirs can be considered transition systems between rivers and lakes, with specific operating mechanisms, depending on the basin and the uses of the system. Its morphometric characteristics and its position in the river basin make it function as an accumulator of information processed along its watershed.

With regard to the Amazon and reservoirs built and in planning, this type of analysis is essential to indicate the limnological and environmental state because it provides a clearer view of the typology of these environments, mainly in the Amazon, a focus for the construction of numerous hydroelectric power plant.

Therefore, this work can serve as a data base for the management of reservoirs and areas of its surroundings, since from this can be realized an integrated management with the communities around the reservoir and to take measures with regard to the influence of anthropic action on the aquatic ecosystem, to make them aware of the importance of this resource and to preserve them for their own benefit and of any biota associated with that water body.

Acknowledgements

We thank all the people who have helped in the field work, Universidade Federal do Oeste do Pará/UFOPA, to the Programa de Pós-Graduação em Recursos Aquáticos Continentais Amazônicos/PPGRACAM, CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), ELETRONORTE (Centrais Elétricas do Norte do Brasil S/A), to the Laboratório de Geoinformação Aquática /LAGIS and to the PRÓ-AMAZÔNIA PROGRAM: BIODIVERSITY AND SUSTAINABILITY, Announcement 047/2012 that supported the execution of the analyzes as well as the work of data collection.

References

AGOSTINHO, A.A., GOMES, L.C. and PELICICE, F.M. *Ecologia e manejo de recursos pesqueiros em reservatórios do Brasil*. Maringá: EDUEM, 2007, 502 p.

AGOSTINHO, A.A., PELICICE, F.M. and GOMES, L.C. Dams and the fish fauna of the Neotropical region: impacts and management related to diversity and fisheries. *Brazilian Journal of Biology = Revista Brasileira de Biologia*, 2008, 68(4), 1119-1132, Supplement. http://dx.doi.org/10.1590/S1519-69842008000500019. PMid:19197482.

ALLAN, J.D. Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annual Review of Ecology Evolution and Systematics*, 2004, 35(1), 257-284. http://dx.doi.org/10.1146/annurev.ecolsys.35.120202.110122.

ALLAN, J.D., ERICKSON, D.L. and FAY, J. The influence of catchment land use on stream integrity across multiple spatial scales. *Freshwater Biology*, 1997, 37(1), 149-161. http://dx.doi.org/10.1046/j.1365-2427.1997.d01-546.x.

ALMEIDA, A.W.B. and MARÍN, R.E.A. *Mapeamento social como instrumento de gestão territorial contra o desmatamento e a devastação: processo de capacitação de povos e comunidades tradicionais*. Manaus: UEA Edições, 2014. Boletim Informativo, no. 3.

ALMEIDA, F.F. and MELO, F. Considerações limnológicas sobre um lago da planície de inundação amazônica (lago Catalão - Estado do Amazonas, Brasil). *Acta Scientiarum. Biological Sciences*, 2009, 31(4), 387-395.

ANDERSON, M.J. A new method for non-parametric multivariate analysis of variance. *Austral Ecology*, 2001, 26, 32-46.

ANDRIOTTI, J.L.S. *Fundamentos de estatística e geoestatística*. São Leopoldo: Unisinos, 2003, 165 p.

ARAUJO, R.A., COSTA, R.B., FELFILI, J.M., GONÇALVEZ, I.K., SOUSA, R.A.T.M. and DORVAL, A. Floristics and structure of a forest fragment at a transitional zone at the Amazon in Mato Grosso State, Municipality of Sinop. *Acta Amazonica*, 2009, 39(4), 865-878. http://dx.doi.org/10.1590/S0044-59672009000400015.

BOSCOLO, D. and METZGER, J.P. Isolation determines patterns of species presence in highly fragmented landscapes. *Ecography*, 2011, 34(6), 1018-1029. http://dx.doi.org/10.1111/j.1600-0587.2011.06763.x.

BRAGA, V. *Introdução à engenharia ambiental*. 2. ed. São Paulo: Pearson Prentice Hall, 2005, 336 p.

BRASIL. Ministério do Meio Ambiente. Agência Nacional de Águas – ANA. *Avaliação de programas nacionais. Versão final: síntese, comentários e recomendações* [online]. Brasília: ANA, 2005a [viewed 10 June 2017]. Available from: www.ana.gov.br/pnrh_novo/docs/Avaliação_Programas_Nacionais.pdf

BRASIL. Ministério das Minas e Energia. *Plano decenal de expansão de energia 2020* [online]. Brasília: Empresa de Pesquisa Energética, 2005b. vol. 2 [viewed 10 June 2017]. Available from: www.epe.gov.br/pdee/20111229_1.pdf

CAMBARDELLA, C.A., MOORMAN, T.B., PARKIN, T.B., KARLEN, D.L., NOVAK, J.M., TURCO, R.F. and KONOPKA, A.E. Field scale variability of soil properties in central Iowa soils. *Soil Science Society of America Journal*, 1994, 58(5), 1501-1511. http://dx.doi.org/10.2136/sssaj1994.03615995005800050033x.

CAMPOS, M.C.C., SOARES, M.D.R., OLIVEIRA, I.A., SANTOS, L.A.C. and AQUINO, R.E. Spatial variability of physical attributes in Alfissol under agroforestry, Humaitá region, Amazonas state, Brazil. *Revista de Ciências Agrárias*, 2013, 56(2), 149-159. http://dx.doi.org/10.4322/rca.2013.023.

CASTELLO, L., MCGRATH, D.G., HESS, L.L., COE, M.T., LEFEBVRE, P.A., PETRY, P., MACEDO, M.N., RENÓ, V.F. and ARANTES, C.C. The vulnerability of Amazon freshwater ecosystems. *Conservation Letters*, 2013, 6(4), 217-229. http://dx.doi.org/10.1111/conl.12008.

CIGAGNA, C., BONOTTO, D.M., STURARO, J.R. and CAMARGO, A.F.M. Geostatistical techniques applied to mapping limnological variables and quantify the uncertainty associated with estimates. *Acta Limnologica Brasiliensia*, 2015, 27(4), 421-430. http://dx.doi.org/10.1590/S2179-975X3315.

CUNHA, A.C., BRITO, D.C., CUNHA, H.F.A. and SCHULZ, H.E. Dam effect on stream reaeration evaluated with QUAL2KW model: case study of the Araguari River, Amazon Region, Amapá State/Brazil. In: C. BILLIBIO, O. HENSEL and J. SELBACH, eds. *Sustainable water management in the tropics and subtropics: and case studies in Brazil*. Jaguarão: Universidade Federal do Pampa, 2011, pp. 153-157.

DURÃES, R., MARTINS, W.P. and VAZ-DE-MELLOS. Dung beetle (Coleoptera: Scarabaeidae) assemblages across a natural forest-cerrado ecotone in Minas Gerais, Brazil. *Neotropical Entomology*, 2005, 34(5), 721-731. http://dx.doi.org/10.1590/S1519-566X2005000500003.

FARIA, F.A.M., JARAMILLO, P., SAWAKUCHI, H.O., RICHEY, J.E. and BARROS, N. Estimating greenhouse gas emissions from future Amazonian hydroelectric reservoirs. *Environmental Research Letters*, 2015, 10(12), 124019. http://dx.doi.org/10.1088/1748-9326/10/12/124019.

FAUSCH, K.D., TORGERSEN, C.E., BAXTER, C.V. and LI, H.W. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. *Bioscience*, 2012, 52(6), 483-498. http://dx.doi.org/10.1641/0006-3568(2002)052[0483:LTRBTG]2.0.CO;2.

FEARNSIDE, P.M. Do hydroelectric dams mitigate global warming? The case of Brazil's Curuá-Una Dam. *Mitigation and Adaptation Strategies for Global Change*, 2005, 10(4), 675-691. http://dx.doi.org/10.1007/s11027-005-7303-7.

FEARNSIDE, P.M. Brazil's São Luiz do Tapajós Dam: the art of cosmetic environmental impact assessments. *Water Alternatives*, 2015a, 8(3), 373-396.

FEARNSIDE, P.M. Hidrelétricas e hidrovías na Amazônia: Os planos do governo brasileiro para a bacia do Tapajós. In: P.M. FEARNSIDE, ed. *Hidrelétricas na Amazônia: impactos ambientais e sociais na tomada de decisões sobre grandes obras*. Manaus: Instituto Nacional de Pesquisas da Amazônia, 2015b, pp. 85-98. vol. 2.

FEARNSIDE, P.M. A hidrelétrica de Balbina: o faraonismo irreversível versus o meio ambiente na Amazônia. In: P.M. FEARNSIDE, ed. *Hidrelétricas na Amazônia: impactos ambientais e sociais na tomada de decisões sobre grandes obras*. Manaus: Instituto Nacional de Pesquisas da Amazônia, 2015c, pp. 97-125. vol. 1.

GOMES, N.M., SILVA, A.M., MELLO, C.R., FARIA, M.A. and OLIVEIRA, P.M. Métodos de ajuste e modelos de semivariograma aplicados ao estudo da variabilidade espacial de atributos físico-hídricos do solo. *Revista Brasileira de Ciência do Solo*, 2007, 31(3), 435-443. http://dx.doi.org/10.1590/S0100-06832007000300003.

GUEDES, T.A., IVANQUI, I.L., MARTINS, A.B.T. and COCHIA, E.B.R. Seleção de variáveis categóricas utilizando análise de correspondência e análise procrustes. *Acta Scientiarum*, 1999, 21(4), 861-868.

GUERREIRO, Q.L.M., OLIVEIRA JÚNIOR, R.C., SANTOS, G.R., RUIVO, M.L.P., BELDINI, T.P., CARVALHO, E.J.M., SILVA, K.E., GUEDES, M.C. and SANTOS, P.R.B. Spatial variability of soil physical and chemical aspects in a Brazil nut tree stand in the Brazilian Amazon. *African Journal of Agricultural Research*, 2017, 12(4), 237-250. http://dx.doi.org/10.5897/AJAR2016.11766.

GUNKEL, G., LANGE, U., WALDE, D. and ROSA, J.W.C. The environmental and operational impacts of Curuá-Una, a reservoir in the Amazon region of Pará, Brazil. *Lakes and Reservoirs: Research and Management*, 2003, 8(3-4), 201-216. http://dx.doi.org/10.1111/j.1440-1770.2003.00227.x.

HAVEL, J.E., LEE, C.E. and VANDER ZANDEN, M.J. Do reservoirs facilitate invasions into landscapes? *Bioscience*, 2005, 55(6), 518-525. http://dx.doi.org/10.1641/0006-3568(2005)055[0518:DRFIIL]2.0.CO;2.

ISAAKS, E.H. and SRIVASTAVA, R.M. *In the introduction to applied geostatistcs*. New York: Oxford University Press, 1989, 561 p.

JUNK, W.J. and MELLO, J.A.S.N. Impactos ecológicos das represas hidrelétricas na bacia amazônica brasileira. *Estudos Avançados*, 1990, 4(8), 126-143. http://dx.doi.org/10.1590/S0103-40141990000100010.

JUNK, W.J., ROBERTSON, B.A., DARWICH, A.J. and VIEIRA, I. Investigações limnológicas e ictiológicas em Curuá-Una, a primeira represa hidroelétrica da Amazônia Central. *Acta Amazonica*, 1981, 11(4), 689-717. http://dx.doi.org/10.1590/1809-43921981114689.

KRZANOWSKI, W.J. Attribute selection in correspondence analysis of incidence matrices. *Applied Statistics*, 1993, 42(3), 529-541. http://dx.doi.org/10.2307/2986330.

LASSAU, S. and HOCHULI, D.F. Effects of habitat complexity on ant assemblages. *Ecography*, 2004, 27(2), 157-164. http://dx.doi.org/10.1111/j.0906-7590.2004.03675.x.

LEGENDRE, P. and LEGENDRE, L. *Numerical ecology*. 3rd ed. Amsterdã: Elsevier, 2012, 1006 p. vol. 24.

LIMA, J.S.S., SILVA, A.S. and SILVA, J.M. Variabilidade espacial de atributos químicos de um Latossolo Vermelho-Amarelo cultivado em plantio direto. *Ciência Agronômica*, 2013, 44(1), 16-23. http://dx.doi.org/10.1590/S1806-66902013000100003.

MACHADO, L.O., LANA, Â.M.Q., LANA, R.M.Q., GUIMARÃES, E.C. and FERREIRA, C.V. Variabilidade espacial de atributos químicos do solo em áreas sob sistema plantio convencional. *Revista Brasileira de Ciência do Solo*, 2007, 31(3), 591-599. http://dx.doi.org/10.1590/S0100-06832007000300019.

MATHERON, G. Principles of geoestatistics. *Economic Geology and the Bulletin of the Society of Economic Geologists*, 1963, 58(8), 1246-1266. http://dx.doi.org/10.2113/gsecongeo.58.8.1246.

MCBRATNEY, A.G. and WEBSTER, A.G. Choosing functions for semi-variograms and fitting them to sampling estimates. *Journal of Soil Science*, 1986, 37(4), 617-639. http://dx.doi.org/10.1111/j.1365-2389.1986.tb00392.x.

MOLOZZI, J., FEIO, M.J., SALAS, F., MARQUES, J.C. and CALLISTO, M. Development and test of a statistical model for the ecological assessment of tropical reservoirs based on bentic macroinvertebrates. *Ecological Indicators*, 2012, 23, 155-165. http://dx.doi.org/10.1016/j.ecolind.2012.03.023.

MORETTO, E.M., GOMES, C.S., ROQUETTI, D.R. and JORDÃO, C.O. Histórico, tendências e perspectivas no planejamento espacial de usinas hidrelétricas brasileiras. *Ambiente & Sociedade*, 2012, 15(3), 141-164. http://dx.doi.org/10.1590/S1414-753X2012000300009.

OLIVEIRA, I.A., CAMPOS, M.C.C., SOARES, M.D.R., AQUINO, R.E., MARQUES JÚNIOR, J. and NASCIMENTO, E.P. Variabilidade espacial de atributos físicos em um Cambissolo Háplico, sob diferentes usos na região Sul do Amazonas. *Revista Brasileira de Ciência do Solo*, 2013a, 37(4), 1103-1112. http://dx.doi.org/10.1590/S0100-06832013000400027.

OLIVEIRA, J.C.S., VASCONCELOS, H.C.G., PEREIRA, S.W.M., NAHUM, V.J.I. and TELES JUNIOR, A.P. Caracterização da pesca no Reservatório e áreas adjacentes da UHE Coaracy Nunes, Ferreira Gomes, Amapá - Brasil. *Biota Amazônia*, 2013b, 3(3), 83-96. http://dx.doi.org/10.18561/2179-5746/biotaamazonia.v3n3p83-96.

OUBORG, N.J. Isolation, population size and extinction: the classical and metapopulation approaches applied to vascular plants along the dutch rhine-system. *Nordic Society Oikos*, 1993, 66(2), 298-308. http://dx.doi.org/10.2307/3544818.

PAGIORO, T.A., ROBERTO, M.C., THOMAZ, S.M., PIERINI, S.A. and TAKA, M. Zonação longitudinal das variáveis limnológicas abióticas em reservatórios. In: L. RODRIGUES, S.M. THOMAZ, A.A. AGOSTINHO and L.C. GOMES, eds. *Biocenoses em reservatórios: padrões espaciais e temporais*. São Carlos: RiMa, 2005, pp. 39-46.

R DEVELOPMENT CORE TEAM. *R: a language and environment for statistical computing* [online]. Vienna: R Foundation for Statistical Computing, 2015 [viewed 10 Mar. 2017]. Available from: https://www.R-project.org/

RIBEIRO JÚNIOR, P.J. and DIGGLE, P.J. GeoR: a package for geostatistical analysis. *R-News* [online], 2001, 1(2), 14-18 [viewed 10 June 2017]. Available from: http://www.R-project.org

RIBEIRO-FILHO, R.A., PETRERE-JUNIOR, M., BENASSI, F.S. and PEREIRA, J.M.A. Itaipu Reservoir limnology: eutrophication degree and the horizontal distribution of its limnological variables. *Brazilian Journal of Biology = Revista Brasileira de Biologia*, 2011, 71(4), 889-902. http://dx.doi.org/10.1590/S1519-69842011000500010.

SILVA, J.J.L.S., MARQUES, M. and DAMÁSIO, J.M. Impactos do desenvolvimento do potencial hidroelétrico sobre os ecossistemas aquáticos do Rio Tocantins. *Revista Ambiente & Água*, 2010, 5(1), 189-203. http://dx.doi.org/10.4136/ambi-agua.129.

SOUZA, J.R., MORAES, M.E.B., SONODA, S.L. and SANTOS, H.C.R.G. A importância da qualidade da água e os seus múltiplos usos: caso Rio Almada, Sul da Bahia, Brasil. *Revista Eletrônica do Prodema*, 2014, 8(1), 26-45.

STRAŠKRABA, M. and TUNDISI, J.G. Reservoir ecosystem functioning: theory and application. In: J.G. TUNDISI and M. STRAŠKRABA, eds. *Theoretical reservoir ecology and its applications*. São Carlos: ABC, IIE, Backhuys Publishers, 1999, pp. 565-597.

STRAYER, D.L., BEIGHLEY, R.E., THOMPSON, L.C., BROOKS, S., NILSSON, C., PINAY, G. and NAIMAN, R.J. Effects of land cover on stream ecosystems: roles of empirical models and scaling issues. *Ecosystems*, 2003, 6(5), 407-423. http://dx.doi.org/10.1007/PL00021506.

TER BRAK, C.J.F. and SMILAUER, P. *CANOCO: manual and CanoDraw for Windows user's guide, software for canonical community ordination (version 4.5)*. Ithaca: CANOCO, 2002, 500 p.

THORNTON, K.W. Sedimentary processes. In: K.W. THORNTON, B.L. KIMMEL and F.E. PAYNE, eds. *Reservoir limnology: ecological perspectives*. New York: John Wiley & Sons, 1990, pp. 43-69.

TUCCI, C.E.M. *Hidrologia: ciência e aplicação*. 3. ed. Porto Alegre: ABRH, 2004, 943 p.

TUNDISI, J.G. Represas do Paraná Superior: limnologia e bases para o gerenciamento. In: A. BOLTOVSKOY and H.L. LÓPEZ, eds. *Conferencias de límnologia*. La Plata: Instituto de Limnologia, 1993, pp. 40-52.

TUNDISI, J.G. Gerenciamento integrado de bacias hidrográficas e reservatórios: estudos de caso e perspectivas. In: M.G. NOGUEIRA, R. HENRY and A. JORCIN, eds. *Ecologia de Reservatórios: impactos potenciais, ações de manejo e Sistemas em cascata*. São Carlos: RIMA, 2006.

TUNDISI, J.G. Reservatórios como sistemas complexos: teoria, aplicação e perspectivas para usos múltiplos. In: R. HENRY, ed. *Ecologia de reservatórios: estrutura, função e aspectos sociais*. Botucatu: FUNDIBIO, 2007, pp. 19-38.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY – USEPA. *Evaluation of the nation's lakes: field operations manual*. Washington: E.S. Environmental Protection Agency, 2007, 104 p.

VALE, R.S., GOMES, A.C.S., SANTANA, R.A.S., TÓTA, J., MILLER, S.D. and SOUSA, R.A.F. Hydroclimatic variables associated with El Nino and La Nina events at the Curuá-Una hydroelectric reservoir, Central Amazonia. *Acta Amazonica*, 2016, 46(3), 303-308. http://dx.doi.org/10.1590/1809-4392201600083.

VIEIRA, I. and DARWICK, A.J. Sinecologia da ictiofauna de Curuá-Una, Amazônia: características hidroquímicas, climáticas, vegetação e peixes. *Acta Limnologica Brasiliensia* [online], 1999, 11(2), 41-64 [viewed 10 June 2017]. Available from: http://repositorio.inpa.gov.br/handle/123/1215

VIEIRA, I. Frequência, constância, riqueza e similaridade da ictiofauna da bacia do rio Curuá-Una, Amazônia. *Revista Brasileira de Zoociências*, 2000a, 2(2), 51-76.

VIEIRA, S.R. Geoestatística em estudos de variabilidade espacial do solo. In: R.S. NOVAES, V.V.H. ALVAREZ and C.E.G.R. SCHAESER, eds. *Tópicos em ciências do solo*. Viçosa: Sociedade Brasileira de Ciência do Solo, 2000b, pp. 1-54.

YAMAMOTO, J.K. and LANDIM, P.M.B. *Geoestatística: conceitos e aplicações*. São Paulo: Oficina de Textos, 2013, 215 p.

ZAR, J.H. *Biostatistical analysis*. 4th ed. New Jersey: Prentice Hall, 1999, 663 p.

Received: 26 October 2017
Accepted: 01 August 2019