Spatial heterogeneity and temporal changes of abiotic factors, in Lake Caçó, Maranhão state, Brazil

Heterogeneidade espacial e mudanças temporais de fatores abióticos no Lago Caçó, estado do Maranhão, Brasil

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Abstract: The present study aimed to characterize Lake Caçó limnologically, a tropical shallow lake located among ancient dunes in Maranhão State, Brazil. Sampling was carried out in April (rainy period) and November (dry period) in 1999, in order to verify possible seasonal variations in the physical and chemical characteristics of water and sediment, determined by the Intertropical Convergence Zone (ZCIT) displacement. A total of twenty sampling stations were established. Among these, 14 were in the littoral zone (7 in the right bank and 7 in the left) and 6 in the limnetic region. The results revealed thermal and chemical microestratifications, (pH, dissolved oxygen concentration and temperature) in both periods sampled, in the limnetic region. No differences were found among the stations located in the littoral region (both right and left bank) or among periods, revealing high spatial and temporal homogeneity. According to the trophic indices, Lake Caçó is a oligotrophic water body. The alternance between dry and wet periods, determined by the Intertropical Convergence Zone oscillation (ZCIT), was the main forcing function conducting the changes in physical and chemical characteristics of Lake Caçó in the year 1999.

Keywords: Lake Caçó, water physical-chemical variables, seasonality, intertropical convergence zone.

Resumo: O objetivo do presente trabalho foi apresentar uma caracterização limnológica do Lago Caçó, um lago tropical raso localizado entre dunas ancientes, no estado do Maranhão, Brasil. As coletas foram realizadas em abril (período chuvoso) e novembro (período seco) de 1999, visando verificar possíveis variações sazonais nas características físicas e químicas da água e do sedimento, em função dos deslocamentos da Zona de Convergência Intertropical (ZCIT). Foram amostrados 20 locais. Destes, 14 foram estabelecidos na região litorânea (7 na margem esquerda e 7 na margem direita) e 6 na região limnética. Foram observadas microestratificações térmicas e químicas (pH, oxigênio dissolvido e temperatura) nos pontos da região limnética em ambos os períodos amostrados, enquanto que na região litorânea (margem direita e esquerda) os resultados não evidenciaram diferenças significativas entre as estações de amostragem e entre os períodos, indicando elevada homogeneidade espacial e temporal. Os índices tróficos aplicados classificaram o lago do Caçó como oligotrófico. A alternância do período seco e chuvoso determinada pela oscilação da ZCIT atuou como a principal função de força condicionando as alterações nas condições físicas e químicas da água no ano de 1999.

Palavras-chave: Lago Caçó, variáveis físico-químicas da água, sazonalidade, zona de convergência intertropical.

1. Introduction

Freshwater ecosystems have been the subject of a great number of limnological studies for a better understanding of the whole system functions. Yet, in Brazil, a large number of water bodies have not been studied at all, owing to the large dimensions of the territory and the late development of the science Limnology in the country. Most limnological work has been focused in rivers and large reservoirs (Tundisi et al., 1995).

Comparatively, there have been much less studies in the Northeast states of Brazil, including Maranhão, than in other regions, despite the richness of freshwater systems. Among the lakes in the Maranhão State, the interdunal lakes of Lençóis Maranhenses present a unique feature in the Atlantic Coast of South America (Tundisi et al., 1995)

Lakes occurring near the Equator are, nevertheless, interesting sites to study from the limnological view point, because they are usually considered constant environments,

with very little seasonality. However a pseudo-seasonality could be produced by the strong periodicity of rainfall.

Rainfall patterns in the Northeast and in Maranhão State are very much influenced by the Intertropical Convergence Zone (ITCZ). The ITCZ (on Equatorial latitudes), is a belt of low pressure around the Earth, formed by rising wet air near the Equator and characterized by rainstorms and very light winds converging on the belt from both hemispheres. The zone oscillates to the North and South, according to the season, following approximately the position of the sun's zenith (Silva et al., 2000). It enters some parts of the Northeast region of Brazil, where it has a decisive influence on the climate in many areas of that region (Dias and Marengo, 1999).

Lake Caçó is located approximately 3 degrees South of the Equator and was selected for a Limnological and Paleoclimatological study in order to detect changes in the position of the Intertropical Convergence Zone during the last epoch of Quaternary (Sifeddine et al., 2003; Jacob et al., 2007). It is a lake placed among ancient dunes, around 50 km South of the Lençóis Maranhenses formation in Maranhão State, Brazil and on the zone of ITCZ influence and, therefore it could be subjected to an annual rhythm, provided by the occurrence of marked wet and dry periods.

The aim of the present study was to describe and characterize the physical and chemical properties of Lake Caçó. The hypothesis is that the abiotic environment of Lake Caçó changes considerably between the wet and dry periods as determined by the rainfall seasonality controlled by the ITCZ annual displacement.

2. Material and Methods

Lake Caçó (5 km long; 500 m average width) is situated to the North of Maranhão State (Brazil), in the rural district of Primeira Cruz, about 100 km from the Atlantic Ocean, at coordinates 2° 58′ S and 43° 25′ W. The lake was formed by a natural wall obstructing a valley cut by a river in an ancient area of dunes at a height around 80 m above sea level.

The land around Lake Caçó is covered by a mosaic of vegetation, including various types of savannah-like forest cover (cerrado, palm stands, gallery forest), which apparently correspond to the types of soil occurring at each site. Despite the great diversity in vegetation, up to now the region has not been studied (Ceccatini and Ledru, 1999).

In the littoral zone of the whole lake, aquatic macrophytes are found, represented mainly by the families Juncaceae, Cyperaceae, Gramineae and Araceae (Volkmer-Ribeiro, 1999).

Water samples were colleted at 20 sites on 8 transects across the lake (Figure 1). Fourteen sites were chosen in the littoral zone (7 on the left bank and 7 on the right) and 6 in the limnetic region.The positions of the sites were fixed by referring to a GPS (Geographical Positioning System), model 130 Sounder (Garmin), and are the same in the two periods (April 12 and November 19, 1999, rainy and dry periods, respectively).

Rainfall data were obtained from the meteorological stations nearby Barreirinhas and refer to the months of January to December 1999.

At each site, water transparency, pH, electric conductivity and concentration of dissolved oxygen were measured with a Horiba multiprobe, model U-10. Total phosphorus concentrations were determined according to Valderrama (1981).

The trophic State of Lake Caçó, was identified using the trophic state index of Carlson (1977) modified by Toledo-Jr. et al. (1993) for tropical reservoirs and lakes, using the concentration of total phosphorus (TP, $\mu g.L^{-1}$) according to:

$$TSIc = 10 \times \left(6 - \frac{\ln\left(80{,}32/TP\right)}{\ln 2} \right) \quad (1)$$

Sediment samples were taken with the Ekman-Birge grab (225 cm^2) at all 20 sampling sites, in both periods and, the granulometric composition was determined according to Suguio (1973). Sediments texture was classified in accordance with Camargo et al. (1987).

Limnological variables (water column depth, transparency; temperature; dissolved oxygen concentration, electrical conductivity, pH, concentrations of nitrate, ammonium, total N and total P, organic and inorganic fractions of sediment) were included in a Multivariate Analysis of Variance used in order to reveal any influence of seasonal changes of the regional climate on the distribution of limnological data.

Principal Component Analysis (PCA) was also applied to limnological data (Manly, 1986) and the scores of the two components generated by PCA were used in a cluster over the 20 sites in the lake to define separate clusters (Zar, 1999).

3. Results

3.1. Climatic variables

Two distinct periods on precipitation can be distinguished in 1999, one from January to July (the rainy season) and the other from August to September (the dry season) (Figure 2). Each one of the two samplings performed corresponded to the highest and lowest precipitation months in the respective periods.

3.2. Limnological factors

There was a water level fluctuation around 0.5 m in the limnetic zone between two periods sampled. Water transparency was high in the littoral zone and light attained the bottom of the lake in both periods. In the limnetic zone the transparency values corresponded to half of water column. Thus, euphotic zone extended to the bottom at all sites, at both sampling times.

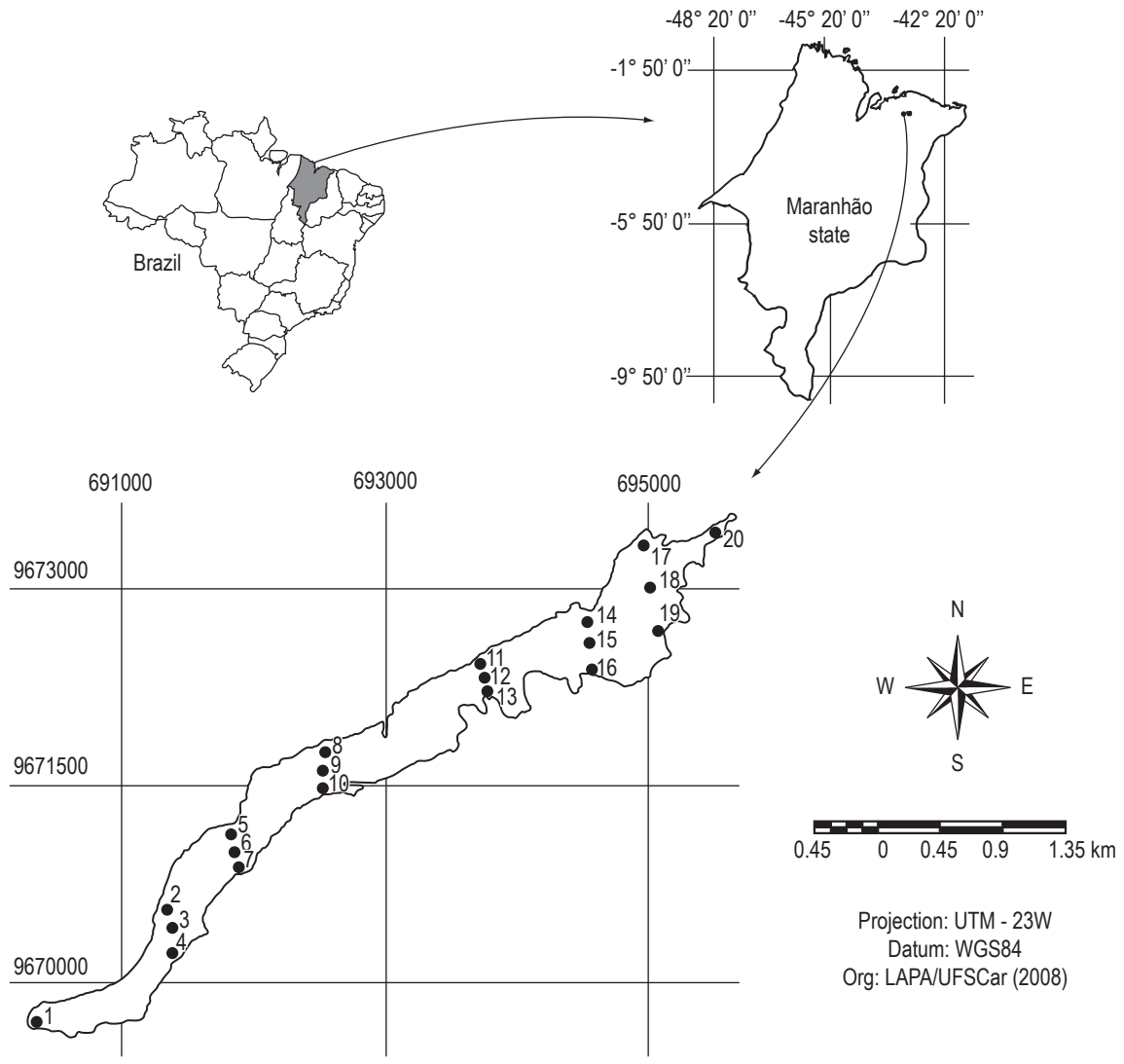

Figure 1. Localization of Lake Caçó (district of Primeira Cruz, MA), in Maranhão State, Brazil and map of the lake (2° 58' S and 43° 25' W), showing the sampling sites on eight transects.

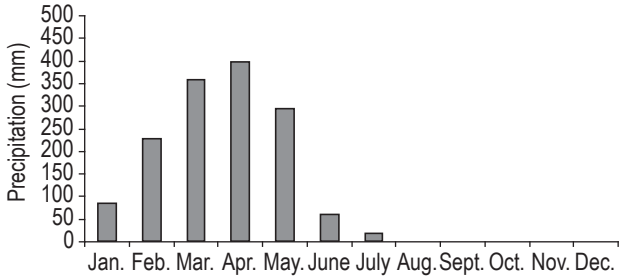

Figure 2. Monthly rainfall recorded at the meteorological station near Lake Caçó (Barreirinhas, Maranhão State) in 1999.

No significant changes were recorded between the two periods for pH, electrical conductivity, dissolved oxygen or water temperature (Table 1). Nutrient concentrations were low in both periods and mean values and standard deviation obtained for the trophic state index indicate that Lake Caçó is a oligotrophic system (Table 1).

Table 1. Mean values and standard deviations of pH, electrical conductivity, dissolved oxygen, temperature, nitrogen and phosphorus concentrations and calculated values of trophic state index and corresponding classification for Lake Caçó, Maranhão State, in April and November, 1999.

Abiotic	April/99	November/99
pH	5.03 ± 0.54	5.53 ± 0.51
Electrical conductivity ($\mu S.cm^{-1}$)	35.4 ± 1.06	35.1 ± 0.51
Dissolved oxygen ($mg.L^{-1}$)	6.67 ± 0.61	6.83 ± 0.46
Temperature (°C)	29.0 ± 0.27	29.0 ± 0.63
$N\text{-}NH^{+}_{3}$ ($\mu g.L^{-1}$)	35.69 ± 39.57	31.24 ± 25.01
$N\text{-}N0^{-}_{3}$ ($\mu g.L^{-1}$)	30.82 ± 11.75	60.27 ± 15.01
N total ($\mu g.L^{-1}$)	251.55 ± 36.62	281.74 ± 39.36
P total ($\mu g.L^{-1}$)	7.67 ± 2.18	6.65 ± 1.02
TSI	25.5 ± 4.21 (Oligotrophic)	24.1 ± 1.87 (Oligotrophic)

Great homogeneity on the electrical conductivity of water (Figure 3), temperature and dissolved oxygen (Figure 4), was observed in both periods. Nevertheless there was heterogeneity regarding the pH profiles in the rainy period, with a chemocline located at shallow depth in the superior part of the lake (stations 2, 3 and 4) and deepening towards the outlet (stations 6 and 7).

3.3 Sediment characteristics in Lake Caçó

The grain composition of sediment at sites on the left bank, right bank and, in the limnetic region of Lake Caçó determined in April and November of the year 1999 is shown in Figure 5. Over the whole Lake silt represented a very small fraction (<1.98%) of sediment. On the left bank,

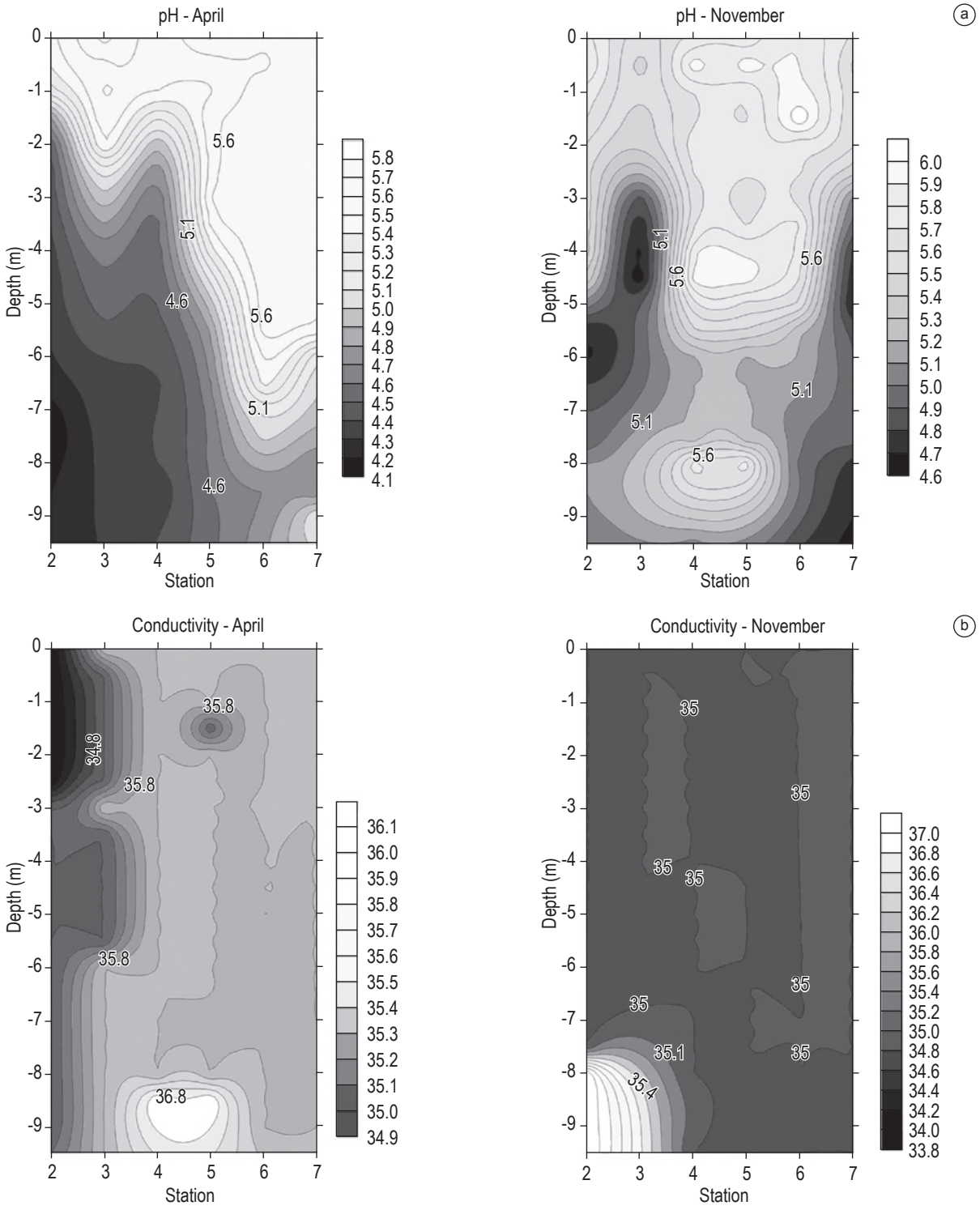

Figure 3. a) Vertical profiles of pH and b) electric conductivity of the water in the limnetic region (stations 2, 3, 4, 5, 6 and 7) in Lake Caçó, in April and November 1999.

clay predominated (mean 72.44% of the total sediment composition). In the limnetic region and in the right bank, sand was the major fraction representing 64.42 and 66.6%, of total composition respectively.

Seasonal changes on the relative amounts of organic matter and mineral fraction in Lake Caçó in both seasons are shown in Figure 6. The mineral component dominates at all sites, ranging in April from 70.1 (left bank) to 99.5% (limnetic region).

A statistical comparison of the limnological data obtained in April and November 1999 by analysis of variance revealed a significant difference between the two seasons. Therefore, the data were divided into two matrices, one for each sampling period.

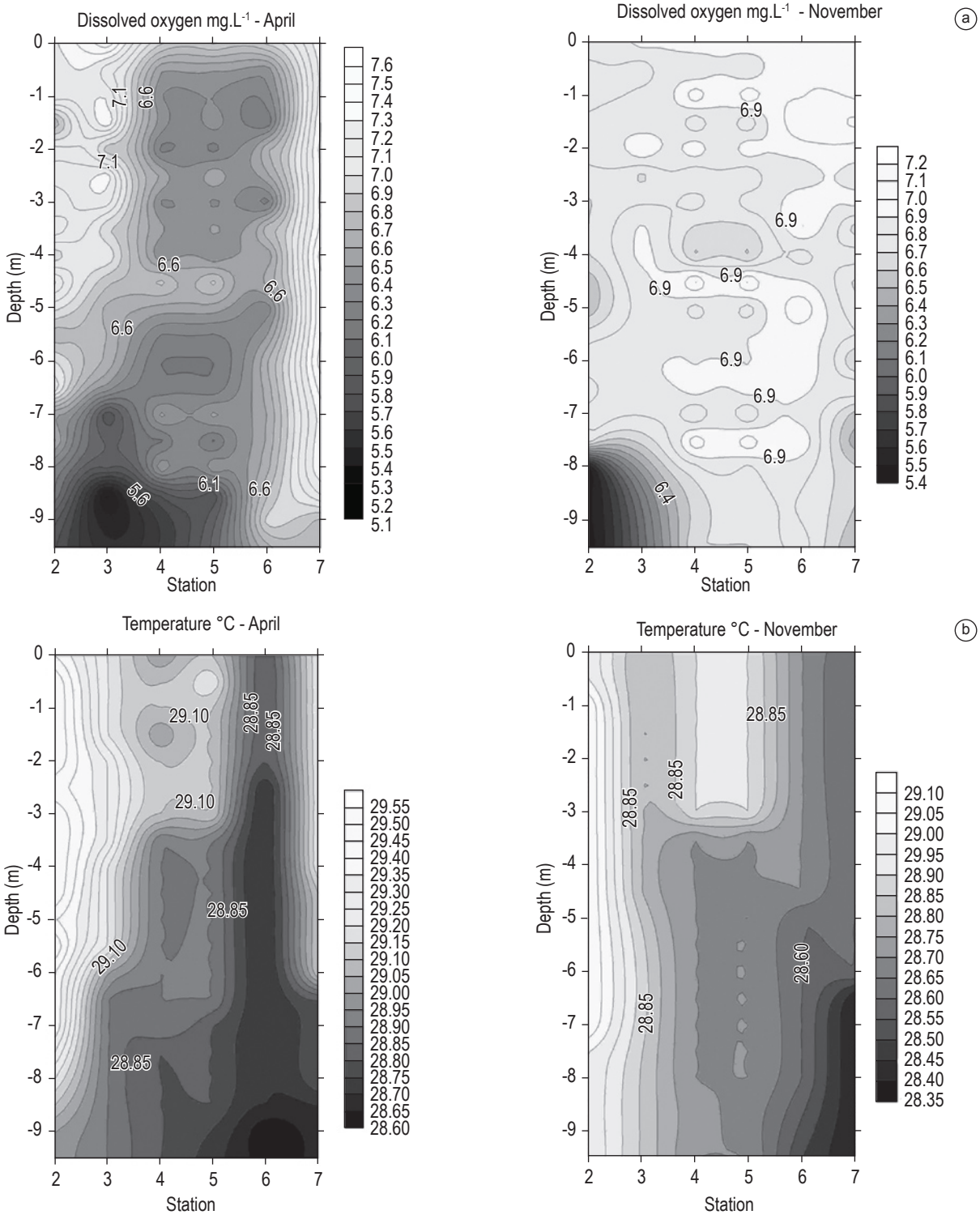

Figure 4. a) Vertical profiles of dissolved oxygen and b) water temperature in the limnetic region (stations 2, 3, 4, 5, 6 and 7) in Lake Caçó in April and November 1999.

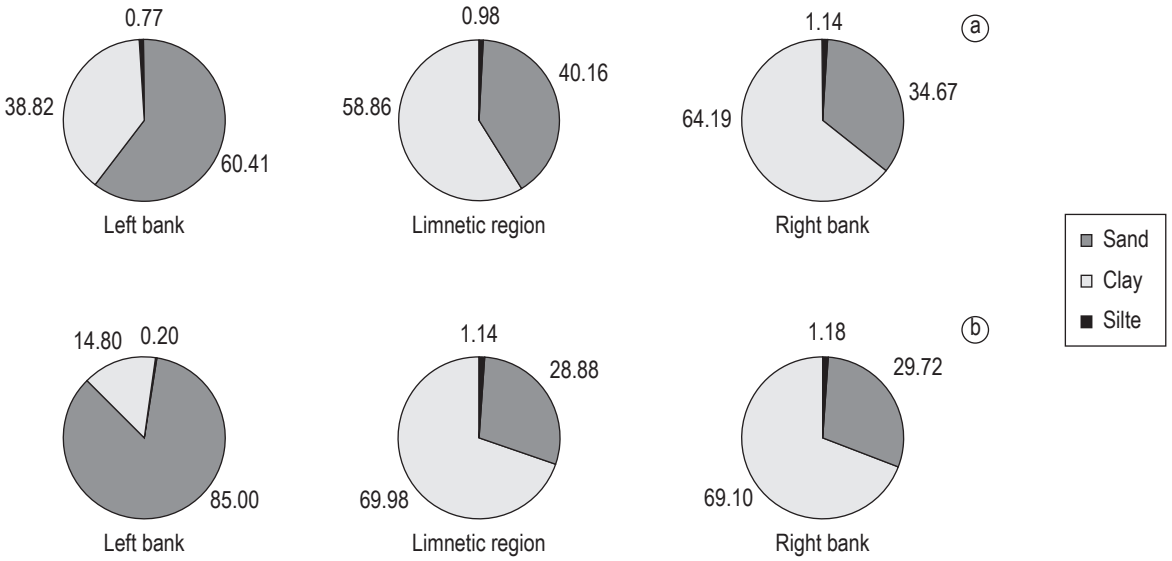

Figure 5. Mean values (in %) for inorganic fractions of sediment in the littoral (right bank, left bank), and limnetic region in Lake Caçó, Maranhão State, a) April 1999 and b) November 1999.

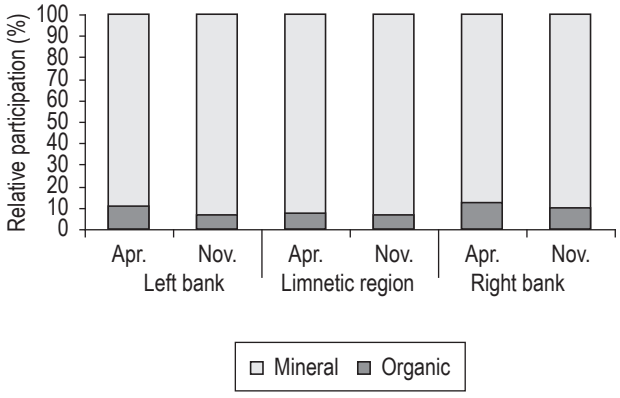

Figure 6. Mean values of mineral and organic fractions of the sediment of Lake Caçó (Maranhão State, Brazil) at the right bank, left bank and limnetic region in April and November 1999.

3.4. Principal component analysis (PCA): April 1999

After a preliminary analysis, two variables (electrical conductivity and total N) with low correlation coefficients were discarded from the data matrices. Significant variables and respective correlation coefficients with first and second principal components are listed in Table 2.

The two components explain 58.93% of the total variance in April. Total sand and, silt and clay were positively and negatively correlated with the first factor, respectively. pH was positively and, depth and transparency negatively correlated with the second factor.

The limnetic sites, with greater depths and transparencies, were associated with negative values of factor 2, while sites near the banks (left or right) being shallow and less transparent, were associated with positive values (Figure 7a).

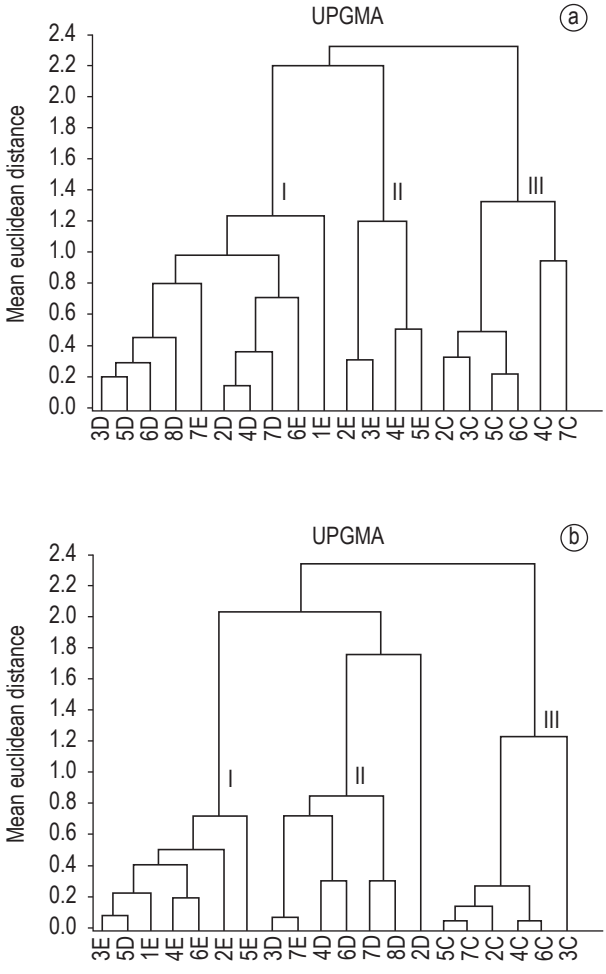

Figure 7. Dendrogram of clusters of sampling sites based on the values of principal components for the limnological variables measured in Lake Caçó (Maranhão State, Brazil) in a) April 1999 and b) November 1999.

Table 2. Values of the correlation coefficients (>0.7) between limnological variables and principal components (factors) 1 and 2 and percentages of variance explained by these factors for data obtained in April and November 1999.

Limnological variable	April		November	
	Factor		Factor	
	1	2	1	2
Total sand	0.939	-	-	-
Silt	–0.907	-	0.933	-
Clay	–0.944	-	0.928	-
pH	-	0.819	-	-
Depth	-	–0.921	-	–0.868
Transparency	-	–0.925	-	–0.870
Dissolved oxygen	-	-	–0.775	-
Temperature	-	-	–0.929	0.741
Variance explained (%)	32.75	26.190	36.460	23.500
Total Variance explained (%)	58.93		59.96	

3.5. Principal component analysis (PCA): November 1999

No variable was discarded after the preliminary analysis of data by PCA. Relevant variables and respective correlation coefficients with the two principal components are listed in Table 2.

Total variance explained by these two components was 59.96%. First component (factor 1) was correlated positively with silt and clay and, negatively with total sand and dissolved oxygen, while the second component (factor 2) was correlated positively with water temperature and, negatively with depth and water transparency (Table 2).

Regarding Factor 1, it is worth noting that the central sites (except 3C) were associated with low dissolved oxygen (DO) values, indicating the fall in the O_2 concentration at greater depths. Moreover, there was a clear association between the central and right bank sites (except 3C; 4D and 5D) and silt and clay, in contrast to left-bank sites, which showed higher proportions of total sand.

Considering Factor 2, it can be seen that all the limnetic sites, where depth and transparency are greater, presented a negative value. Conversely the sites in the littoral zone (left and right banks), which are shallow, are positively associated with Factor 2. The ordering of the sampling sites with respect to the two axes is displayed in Figure 7b.

3.6. Cluster analysis of the sites based on PCA coefficients

The scores of individual sites for the two principal components derived by PCA of limnological variables sampled in April 1999 were used in a cluster analysis (cophenetic correlation coefficient: 0.8034) of the sites resulting in the dendrogram in Figure 8a.

Three distinct clusters are discernible for the limnological data of April 1999: Cluster I contains all sites on the right bank plus 1E, 6E and 7E on the left; cluster II consists of the remainder of the left bank sites and cluster III is made up of all sites in the limnetic region. The sites scores for the two principal components for November abiotic factors are shown in Figure 8b. The cophenetic correlation coefficient was 0.8437. In the November 1999, three main clusters of sites can be distinguished: Cluster I contains most of the left-bank sites, plus 5D and 4C; cluster II consists of most of the right-bank sites, plus 7E and cluster III is entirely made up of sites in the limnetic regional of the lake.

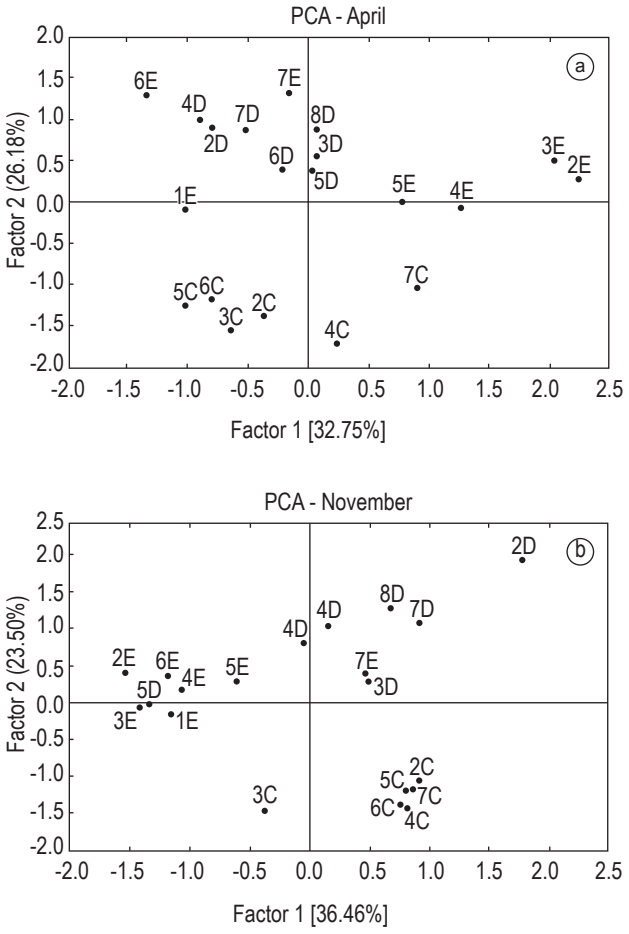

Figure 8. Ordering of sampling sites with respect to the two principal components obtained from PCA of limnological variables, measured in a) April 1999 and b) November 1999, in Lake Caçó, Maranhão.

Both PCA and cluster analysis revealed significant differences in the physical and chemical characteristics of the water and sediment, between sites in the littoral and limnetic regions. In both seasons, the main feature discriminating site clusters was sediment granulometry.

4. Discussion

Distinct climatic regions, with different patterns of rainfall, can be recognized within the continental size of Brazil. The drought–prone Northeast Region, and Amazonia with its rainforest, for example, clearly have very different climates especially in relation to precipitation. In the Northern Region, where Lake Caçó is found, the rainy season (with more than 60% of the annual rainfall) runs from March

to May, while the period of drought is normally from September to December (Dias and Marengo, 1999).

The climate in the States of Maranhão and Piauí is usually influenced by the phenomenon of El Niño, which normally has the effect of diminishing the rainfall in affected areas. In the year of this study (1999), El Niño was moderate and above–average amounts of rain were recorded in the region, during March and April, according to data from INPE/CPTEC (2000). This was confirmed by the precipitation recorded near Lake Caçó during the April sampling. The clearly–defined seasonal variation in the vicinity of this lake is a consequence of the annual oscillatory movement of the ITCZ and the associated wind pattern. Dias and Marengo (1999) have shown the great importance of the shifting position of the ITCZ in determining the pattern of rain in the North and Northeast regions of Brazil. Thus, the climatic zone is responsible for the seasonal changes in these regions and probably influences the temporal profile of all the environmental variables.

In Lake Caçó the water was totally transparent in the littoral zone at both sampling times, and the seasonal variation in the visibility of the Secchi disk was small. In the limnetic region of the lake, the disk was visible at depths greater than 4.5 m at all sites and the temporal difference in transparency of the water column, was only 0.3 m. Araujo (2000) recorded similar Secchi disk readings in Lake Azul, located at the Lençóis Maranhenses National Park (MA), whose water–column reaches comparable depths to those found in Lake Caçó. Conversely, Barbieri et al. (1989) found that Lake Açu (MA), a large, shallow lake on the Baixada Maranhense coastal plain had very low transparency.

In the case of Lake Caçó, the extent of the euphotic zone reached the bottom indicating no light limitation. Dellamano-Oliveira et al. (2003) showed that the phytoplankton was evenly distributed along the water column in this lake, as algal densities were similar near the surface, in the middle and on the bottom.

In Lake Caçó, the pH was found to be rather acid at both sampling times, a pH common in lakes occurring inside the Brazilian savanna vegetation, the so-called cerrado. Similar pH values were reported by Bozelli (1990) and Huszar (1994) in Lake Batata in the Amazon region (PA) by Tundisi et al. (1998) and Pereira (1999) in interdunal Lakes of the Lençóis Maranhenses formation and by Barbieri et al. (1989) in Lake Açu (MA).

Stratification on pH was a special feature in Lake Caçó, especially in the rainy season sampling. Dellamano-Oliveira et al. (2003) did not find differences in the vertical distribution of the phytoplankton in the water column and the euphotic zone extends down to the bottom. Possible explanation for the observed pattern would be a more intense photosynthesis in the superior part of the water column, and a predominance of decomposition in deeper waters, liberating acid compounds.

Low seasonal variation was found regarding electrical conductivity in Lake Caçó a trend similar to what was already identified by Aranha et al. (1997) and by Pereira (1999) in other aquatic ecosystems in the State of Maranhão.

Chemical properties in the water of Lake Caçó were changed in the rainy period indicating that the rain is a relevant forcing function to the system, as shown by Bormann and Likens (1967) for small hydrographic basins. Bozelli (1990) recorded electrical conductivities in Lake Batata (PA) of similar magnitude to the Lake Caçó, even though the soil geology around the two lakes and vegetation differ widely. Lake Batata is in a region of Amazon rainforest growing on dystrophic yellow latosol (Radambrasil. 1976. in: Callisto and Esteves 1996) whereas lake Caçó is surrounded by sandy soils covered with cerrado forest.

No marked variation in the dissolved oxygen concentration between sampling seasons was recorded in Lake Caçó and, the water column is always well oxygenated. Thus this variable is not a limiting factor. In Lake Caçó the water temperature presents small temporal variations. The spatial variation of temperature recorded in the water column (difference surface bottom) was 1.9 °C in the rainy period and 1.1 °C in the dry period, characterizing a typical tropical lake. Similar values were reported by Huszar and Sophia (1996), Aranha et al. (1997), Pereira (1999) and Araujo (2000) in other water bodies located in Maranhão State and in the Amazon region.

Both nitrogen and phosphorus concentrations were low, indicating the oligotrophic condition of Lake Caçó. On the whole oligotrophic lakes are characterized by a low concentration of inorganic matter coming from outside sources (e.g. leached by rain), despite the marked climatic change between the wet and dry periods.

In the littoral zone of Lake Caçó, on the left bank, the sand fraction predominated at most sites in both sampling periods, whereas on the right bank and in the limnetic region, the clay predominated, also in the two periods. The physical heterogeneity of the substrate in this lake must have an influence on the distribution of benthic invertebrates.

There was an appreciable seasonal difference in some properties of the water. The changes are related to the water level fluctuations, and reflect the influence of the oscillation of the ITCZ across the equator and in the vicinity of the lake.

It was also found that sites in the littoral zone tended to differ from those in the limnetic region, in both sampling periods, especially in relation to depth and transparency. With respect to sediment particle size and more specifically the fraction of clay particles, the littoral sites on the left and right banks were clustered into two separated groups.

In conclusion, data from Lake Caçó in April and November, 1999, showed that the alternation of wet and dry seasons acts as the principal driving force on limnological conditions.

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