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Inter-annual chemical stratification in Brazilian natural lakes: meromixis and hypolimnetic memory

Estratificação química em lagos naturais brasileiros: meromixia e memória hipolimnética

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Abstract: Aim: Chemical stratification and the patterns of light limitation and nutrients of two natural lakes, one shallow and the other one deep, were comparatively evaluated, both lakes located in the southeast Brazil. **Methods:** pH, electrical conductivity, dissolved oxygen, total dissolved solids and nutrients were monthly collected during 5 consecutive years at the vertical profile of the two lakes. **Results:** multivariate analysis indicated that the long thermal stratification period favored the occurrence of chemical stratification in the two lakes. However, in the deeper lake the stratified thermal profile with high hypolimnetic nutrient concentration, electrical conductivity, total dissolved solids and redox potential indicated that the mixing was not complete even during the annual circulation period, suggesting a slight meromixis and a high chemical stability at the hypolimnion. In the shallower lake, high light attenuation and high availability of nitrogen forms (mainly N-NH_4) and phosphorus was observed along the water column, even during stratification. In the deeper lake, N and P co-limitation and low light attenuation coefficients were detected. **Conclusion:** thermal and chemical stratification patterns indicated that the Carioca lake is a shallow, turbid, nutrient rich, whereas the Dom Helvecio lake is a deep, clear, oligotrophic system with a tendency towards meromixis and the isolation of solutes in the hypolimnion. Consequently, meromixis was compared to a "hypolimnetic memory", which was defined, in the case of the deeper lake, as the maintenance of the chemical stratification along the years, during the lake thermal circulation period.

Keywords: meromixis, chemical stratification, thermal stratification.

Resumo: Objetivo: A estratificação química e os padrões de limitação por luz e nutrientes foram avaliados comparativamente em dois lagos naturais, sendo um raso e o outro profundo no sudeste do Brasil. **Métodos:** as amostragens de pH, condutividade elétrica, oxigênio dissolvido, sólidos totais dissolvidos e nutrientes foram realizadas mensalmente, durante cinco anos consecutivos no perfil vertical dos dois lagos. **Resultados:** as análises multivariadas indicaram que o longo período de estratificação térmica favoreceu a ocorrência de estratificação química nos dois lagos. No entanto, no lago mais profundo, o perfil térmico estratificado, com elevadas concentrações hipolimnéticas de nutrientes, condutividade, sólidos totais dissolvidos e potencial redox indicaram que a mistura não foi completa mesmo durante o período de circulação anual, sugerindo uma leve meromixia e alta estabilidade química no hipolímnio. No lago mais raso, elevada atenuação de luz e alta disponibilidade das formas nitrogenadas (principalmente N-NH_4) e fosfatadas foram observadas em toda a coluna d'água, mesmo durante a estratificação. No lago mais profundo, foram observadas co-limitação por N e P e baixas coeficientes de atenuação da luz. **Conclusão:** os padrões de estratificação térmica e química indicaram que a lagoa Carioca é um lago raso, de rápida circulação com águas túrbidas, rico em nutrientes, enquanto o lago Dom Helvécio é um lago profundo, de águas claras, oligotrófico, com tendência à meromixia e ao isolamento de solutos no hipolímnio. Nesse contexto, a meromixia foi comparada a uma "memória hipolimnética" que foi definida, no caso do lago mais profundo, como a persistência da estratificação química ao longo dos anos durante o período de sua circulação térmica.

Palavras-chave: meromixia, estratificação química, estratificação térmica.

1. Introduction

Investigation on the heat contents and thermal and chemical stratification stability (meromixis) of lakes is abundant for the temperate zone (e.g. Birge, 1916; Hutchinson, 1957). However, references to meromitic lakes, i.e. lakes that have an incomplete mixture of the water column, are very scarce in Brazil (von Sperling, 1997).

Thermal structure directly affects biological, physical and chemical processes in lakes, including primary and secondary production, nutrient regeneration, oxygen depletion and planktonic organisms' migration patterns (Mazunder, 1990). Circulation and stratification dynamics as well as the thermocline depth are the main factors regulating the distribution of chemical substances and organisms along the water column, the mixture being many times induced by driving forces as the wind (Elci, 2008), rain precipitation and the dropping of the air temperature during the night (Barbosa et al., 2011).

Chemical stratification may be a consequence of long thermal stratification periods, when a well established thermocline promotes stratification of the abiotic variables and development of decomposition processes. Thus, primary production and nutrient consumption processes will dominate in the epilimnion, being nutrients limiting in this layer, whereas in the hypolimnion decomposition and oxygen consumption processes will dominate (Yu et al., 2010). Over the last years, several papers have treated chemical stratification associated both with the abiotic variables, nutrient vertical distribution and water quality (Larson et al., 2007; Elci, 2008; Yu et al., 2010), and the chemical indices calculated from variables to provide indication of the water quality, such as soluble phosphorus and chlorophyll-*a* (Yu et al., 2010).

Morphological differences between shallow and deep lakes may affect the thermal stability (Ambrosetti and Barbanti, 1999). The last ones may present a climate memory represented by a spatial and a temporal variation of their heat contents. The present study aimed at evaluating and comparing differences of chemical stratification between the two lakes.

2. Material and Methods

2.1. Study area

The Rio Doce State Park is the largest remnant of the Atlantic Forest in Minas Gerais, comprising *c.* 50 natural lakes, which represent one third of the lakes forming the middle Rio Doce Lake District, southeastern Brazil (19° 29' S and 42° 28' W). Located in a humid tropical forest area nowadays completely disconnected from the River Doce, the ecology of the two lakes is closely related to the geomorphological processes that originated them (Meis and Tundisi, 1997). Recent stratigraphic analyses indicate that the beginning of the lacustrine sedimentation in the area occurred about 9,000 years AP, i.e. simultaneous to the regional alluvial sedimentation in the area (Mello et al., 1999).

Lake Carioca is a shallow, more or less round-shaped, nutrient-rich system (Bezerra-Neto et al., 2010), with a surface area of approximately 0.14 km^2 and maximum depth of 11.8 m. In contrast, Dom Helvécio is a deep, oligotrophic, dendritic lake, with a surface area of 5.27 km^2 and a maximum depth of 39.2 m (Bezerra-Neto and Pinto-Coelho, 2008) (Figure 1). Both lakes are warm-monomictic and stratified between September and April, and nearly isothermal from May to August (Henry and Barbosa, 1989).

2.2. Sampling and data analyses

Temperature, dissolved oxygen, pH, electrical conductivity, total dissolved solids and redox potential were measured "*in situ*" at 0.5 m intervals from surface to bottom of the two systems using a Horiba, model U-22, multi-parameter probe.

Water transparency (m) was calculated using the disappearance depth of the Secchi disk (Z_{ds}) (Cole, 1994). Euphotic zone (Z_{eu}) was empirically calculated multiplying the value obtained from the Secchi disk (10% of incidence of light) by 2.7 (Cole, 1994). Light attenuation vertical coefficient (k) was calculated using the equation $k = 1.7 \times Z_{DS}^{-1}$ (Poole and Atkins, 1929). Mixing zone (Z_{mix}) was calculated on the basis of the water temperature differences, considering the layer above in which the temperature gradient first exceeded 0.2 °C (Coche, 1974). Z_{eu}:Z_{mix} ratio was used as an evaluation index for light availability in mixing layer (Jensen et al., 1994).

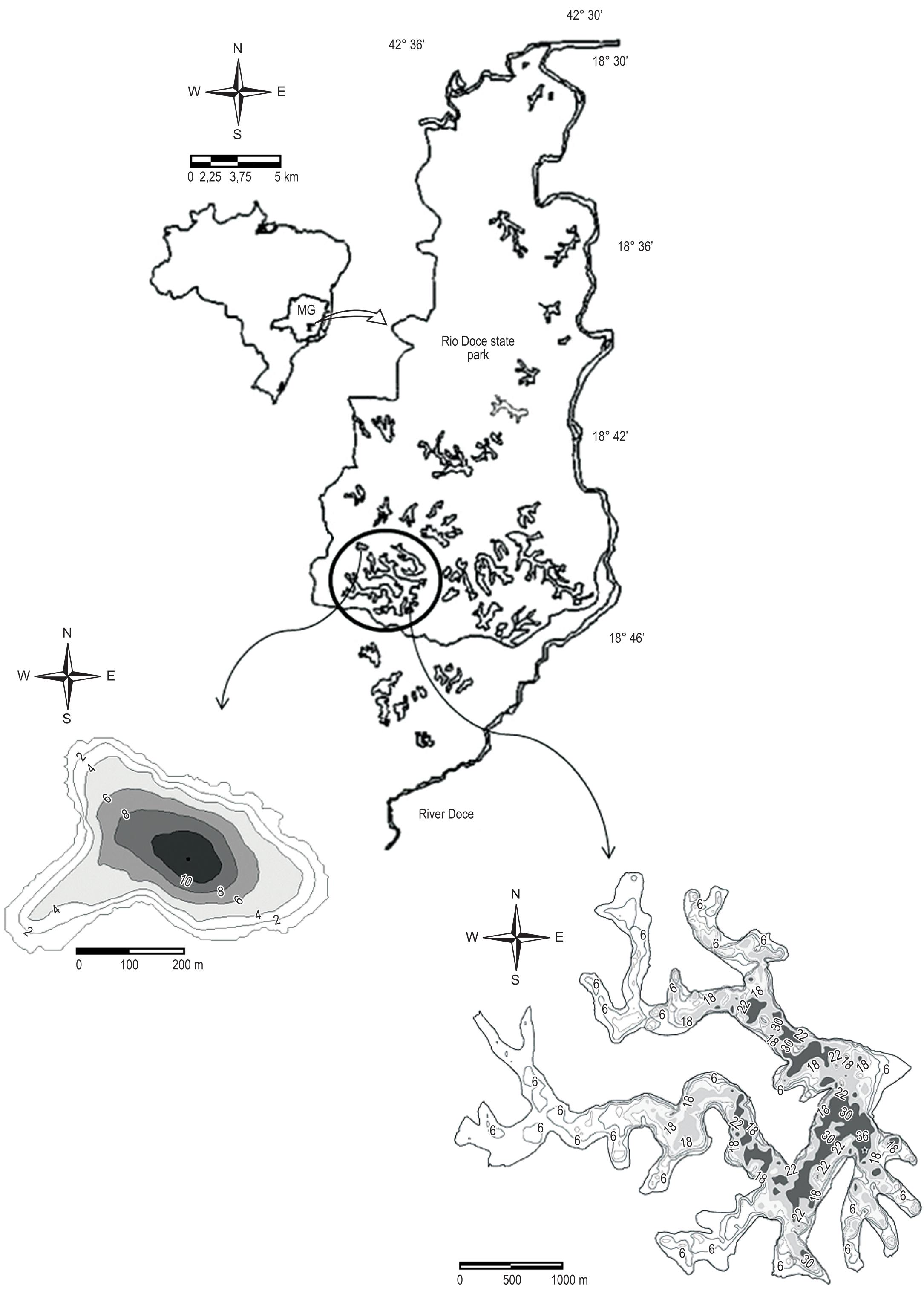

Figure 1. The Rio Doce State Park, showing lakes Carioca and Dom Helvécio.

Heat content (in cal cm^{-2}) was calculated according to Cole (1994), and thermal stability (g-cm cm^{-2}) according to equation in Idso (1973). Thermocline was identified as the greatest difference (°C) between one layer and the one immediately preceding in the thermal profile, and was considered in the present study >0.3 °C.

Total phosphorus (TP), soluble reactive phosphorus (SRP = P-PO_4^{-3}), total nitrogen (TN), dissolved inorganic nitrogen (DIN = N-NO_3, N-NO_2 and N-NH_4^+) and soluble reactive silica (SRSi) were measured according to Golterman et al. (1978), Koroleff (1976) and MacKereth et al. (1978), respectively. For chlorophyll-*a* concentration determination, pigment was extracted with 90% acetone (Lorenzen, 1967). Trophic State Index used was Carlson's modified by Toledo et al. (1983).

Comparison between depths and periods was performed using analysis of variance factor-1 (ANOVA one way) Statsoft Inc. version 4.2 program. For multivariate descriptive analysis of the 5-year abiotic variable (dissolved oxygen, electrical conductivity, pH) series, principal component analysis (PCA) from the covariance matrix with data transformed by log (x + 1) was used. Statistic programs used were FITOPAC (Shepherd, 1996) and PC-ORD for Windows, version 3.0 (McCune and Mefford, 1997).

For descriptive multivariate analysis at a monthly scale for variables stability, Z_{mix}, Secchi disk (as a measure of water transparency) and light attenuation coefficient, a single value was generated. Nutrients (dissolved and total) were included (100%, 10%, 1% incident light, and Z_{aph}) and integrated arithmetically.

3. Results

Analysis of the climatic variables indicated inter-annual repetitive patterns, with rainy periods characterized by high precipitation (maximum 117.3 mm) and high air temperature (maximum 23.7 °C) that alternate with dry periods with low precipitation (12.7 mm) and low air temperature (18.8 °C). Wind speed values ($m.s^{-1}$) were considered low according to Beaufort's anemometric scale during both climatic seasons, and were not considered, therefore, the conclusive factor for the identification of the thermal stratification patterns (Table 1). Air temperature maximum value (28 °C) over the lake during the rainy season may have influenced the great thermal stability at lakes Carioca (maximum 92.77 g-cm cm^{-2} in December 2002) and Dom Helvécio (maximum 514.20 g-cm cm^{-2} in December 2006) (Table 1). Temperature depth and time diagram indicated a warm monomictic profile (Figure 2).

Seasonal differences in the heat content were small for both the Carioca (maximum 16,037.51 cal cm^{-2} in February 2006 and minimum 11,451.04 cal cm^{-2} in July 2004) and the Dom Helvécio lakes (maximum 32,246.10 cal cm^{-2} in December 2006 and minimum 19,976.01 cal cm^{-2} in August 2004) (Table 1). Seasonally, heat loss did not reach 2.5% (maximum observed during the rainy season) in Lake Dom Helvecio, thus suggesting a conservative thermal behavior. The maximum thickness of the epilimnion layer (Z_{mix}) is about 6.5 m at Lake Carioca and 12 m at Dom Helvécio. Maximum metalimnion depth at Lake Carioca was 8.5 m and that of hypolimnion just 2-3 m. At Lake Dom Helvécio, the beginning of metalimnion was between 13 and 16 m, its maximum extension reaching 26 m.

Consequently, according to underwater light regime Lake Dom Helvécio showed high water transparency values (variation range 2-4 m) and

Table 1. Morphometric and climatic factors information on lakes Carioca and Dom Helvécio, Rio Doce State Park, Minas Gerais State, southeast Brazil. (Source of morphometric factors: Bezerra-Neto and Pinto-Coelho, 2008; Bezerra-Neto et al., 2010).

Climatic data	Period			
	Stratification		Mixing	
Pluviometric precipitation (mm)	101.5 (±75.5)		4.0 (±6.8)	
Air temperature (°C)	25.3 (±0.9)		21.4 (±1.2)	
Wind speed ($m.s^{-1}$)	13.4 (±7.3)		18.2 (±8.4)	
Variables	**Lake Carioca**		**Lake Dom Helvécio**	
	Stratification	**Mixing**	**Stratification**	**Mixing**
Thermal stability (g-cm cm^{-2})	41.7 (±21.7)	33.3 (±25.3)	455,4 (±114.3)	127.2 (±106.7)
Caloric content (cal cm^{-2})	14054 (±2615)	12846.5 (±1005)	32453.9 (±926)	29406.4 (±925)
Morphometric data	**Lake Carioca**		**Lake Dom Helvécio**	
Surface area (A)	0.141 km^2		5.27 km^2	
Volume (V)	$671.2 \times 10^3\ m^3$		$59.4 \times 10^6\ m^3$	
Effective maximum length (Le)	572.8 m		37.7 km	
Effective maximum width (We)	350.7 m		32 km	
Maximum depth (Z_{max})	11.8 m		39.2 m	
Mean depth (Z)	4.76 m		11.3 m	
Shoreline development (D)	1.28 m		4.61 m	

low light attenuation ones (0.48-0.70 m) and Lake Carioca lesser water transparency (0.5-2.5 m) and higher light attenuation values (0.85-3.4 m) (Figure 3).

3.1. Indication of chemical stratification

Principal Component Analysis of the abiotic factors of both lakes at the vertical scale explained 48.6% of total variance of the two first axes (Figure 4). The four following variables contributed most to axis 1 ordination: temperature (r = 0.65), TN (r = –0.38), DO (r = 0.31) and electrical conductivity (r = –0.51). For axis 2 ordination pH (r = –0.31), NO_3 (r = –0.33) and free CO_2 (r = –0.29) were the best correlated variables. All sampling units related to subsurface and 10% incident light were grouped at the positive side of axis 1 associated to the highest temperature and DO values. On the other side, however, sampling units related to 1% incident light and Z_{apho} were placed at the positive side of axis 1 associated to the greatest TN, NO_3, and total CO_2 concentration and the greatest electrical conductivity values.

Principal Component Analysis performed with integrated data resumed *c.* 66% of data total variability in the two first axes (Figure 5). The four following variables contributed effectively to ordinance of first axis: Z_{mix} (r = 0.6), thermal stability (r = 0.6), Secchi disk (r = 0.4) and light attenuation coefficient (r = –0. 4). For ordinance of axis 2, however, thermal stability (r = 0.55), PO_4^{-3} (r = 0.12), Z_{mix} (r = –0.8) and light attenuation coefficient (r = –0.15) had the greatest correlation. Lake Dom Helvécio showed a clear separation between thermal stratification and mixing periods, its sampling units being associated to the positive side of axis 1 and water transparency to the negative side of the same axis. Sampling units of Lake Carioca showed a less pronounced separation between stratification and mixing periods, with light attenuation coefficient, NH_4^+ and PO_4^{-3} associated at the negative side of axis 1.

The stratification period registered dissolved oxygen super-saturation (>100%) at the epilimnion and sub-saturation (<50%) below the metalimnion, resulting in a clinograde profile (Figure 6), although the dissolved oxygen profile did not show total anoxia during the stratification periods, except for from September 2003 to July 2005, when its concentration was zero. Chemical stratification with

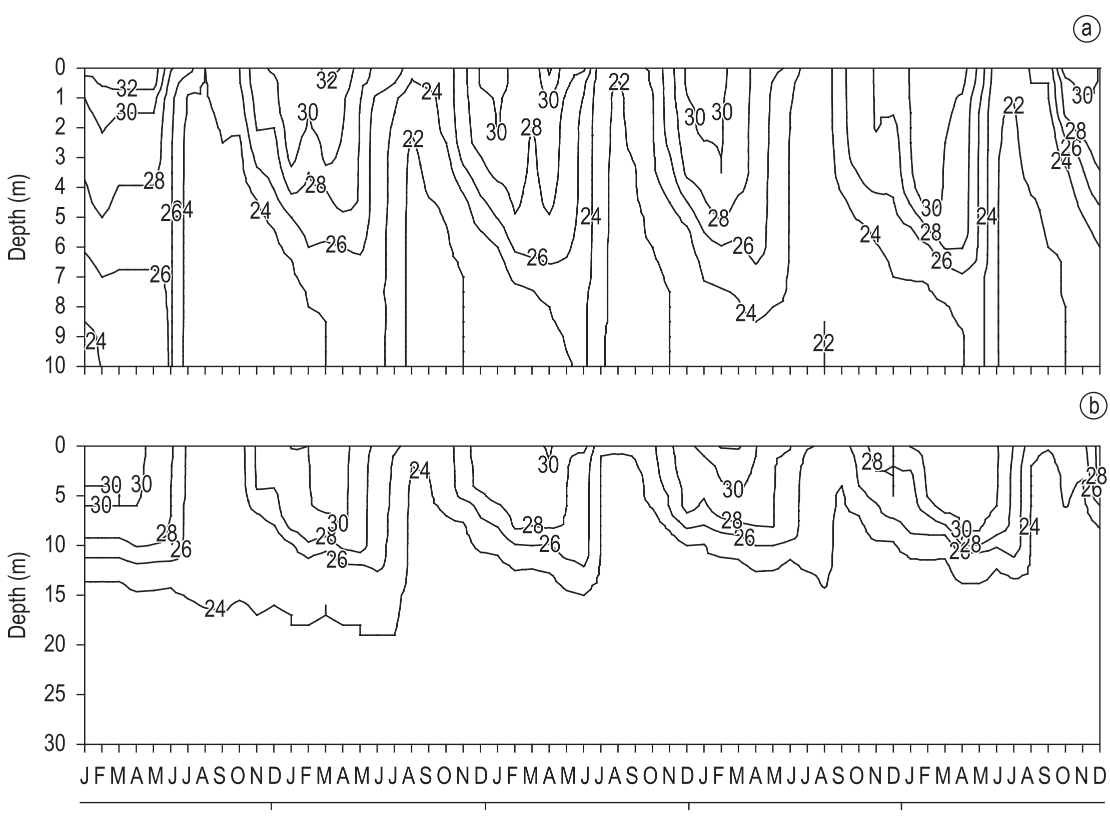

Figure 2. Depth-time diagram of water temperature (°C) over 5 years (2002-2006) in lakes Carioca (a) and Dom Helvécio (b), Rio Doce State Park, southeast Brazil.

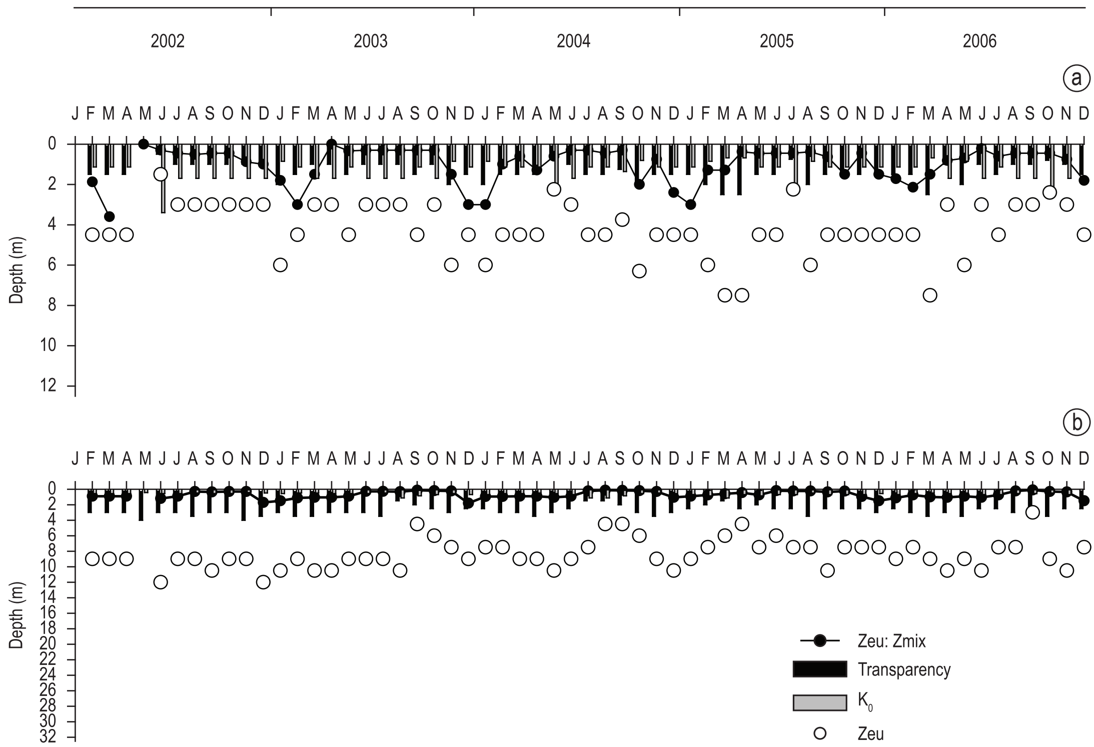

Figure 3. Z_{eu}:Z_{mix} ratio, water transparency (m), light attenuation coefficient (K_o) and Z_{eu} (m) of lakes Carioca (a) and Dom Helvécio (b) during the study period (2000-2006), southeast Brazil.

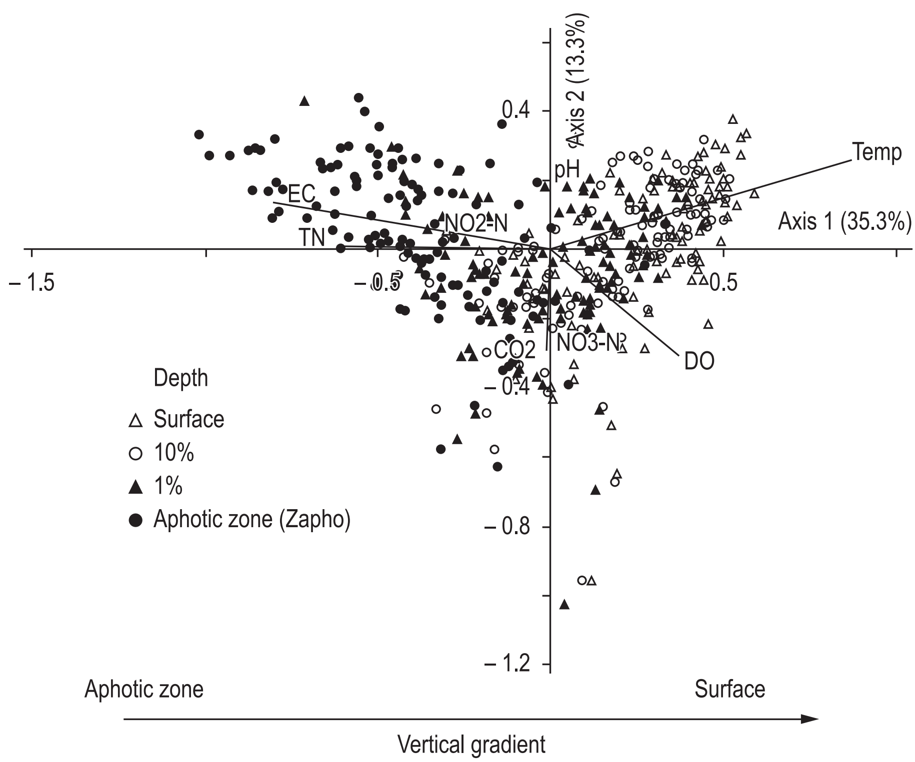

Figure 4. PCA biplot of limnological variables considering vertical and time profiles over the study period (2000-2006) at lakes Carioca (a) and Dom Helvécio (b), southeast Brazil.

high electrical conductivity and total dissolved solids (Figure 7), besides total and dissolved nutrients occurred at the hypolimnion (Figure 8) in the Carioca and Dom Helvecio lakes. In contrast, Lake Carioca epilimnion (65.4% of lake's total volume) and that of Dom Helvécio's (81.22%) presented PO_4^{-3}-limiting, as demonstrated by the NID:SRP ratio (Table 2).

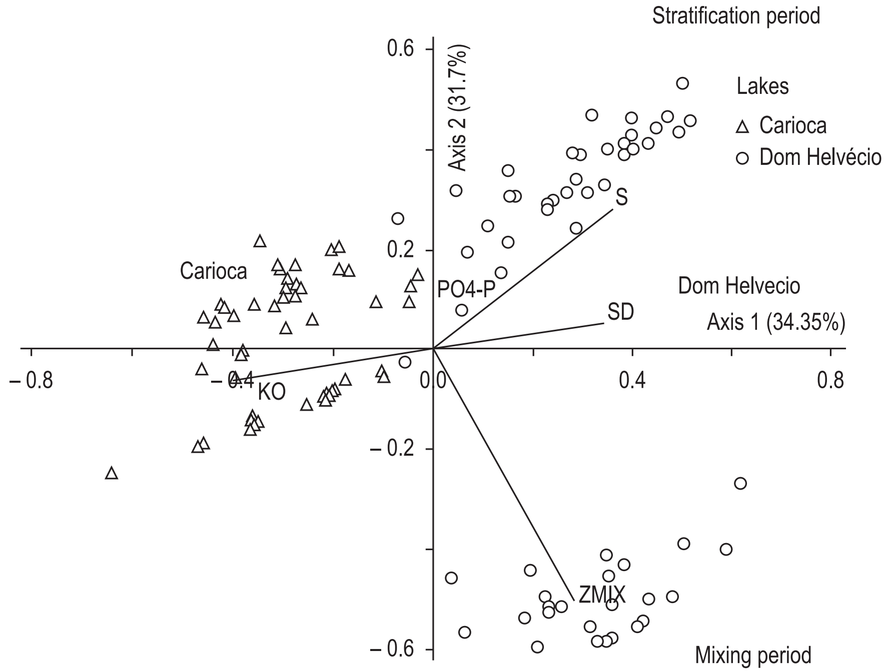

Figure 5. PCA biplot of limnological variables over the study period (2000-2006) at lakes Carioca and Dom Helvécio, southeast Brazil.

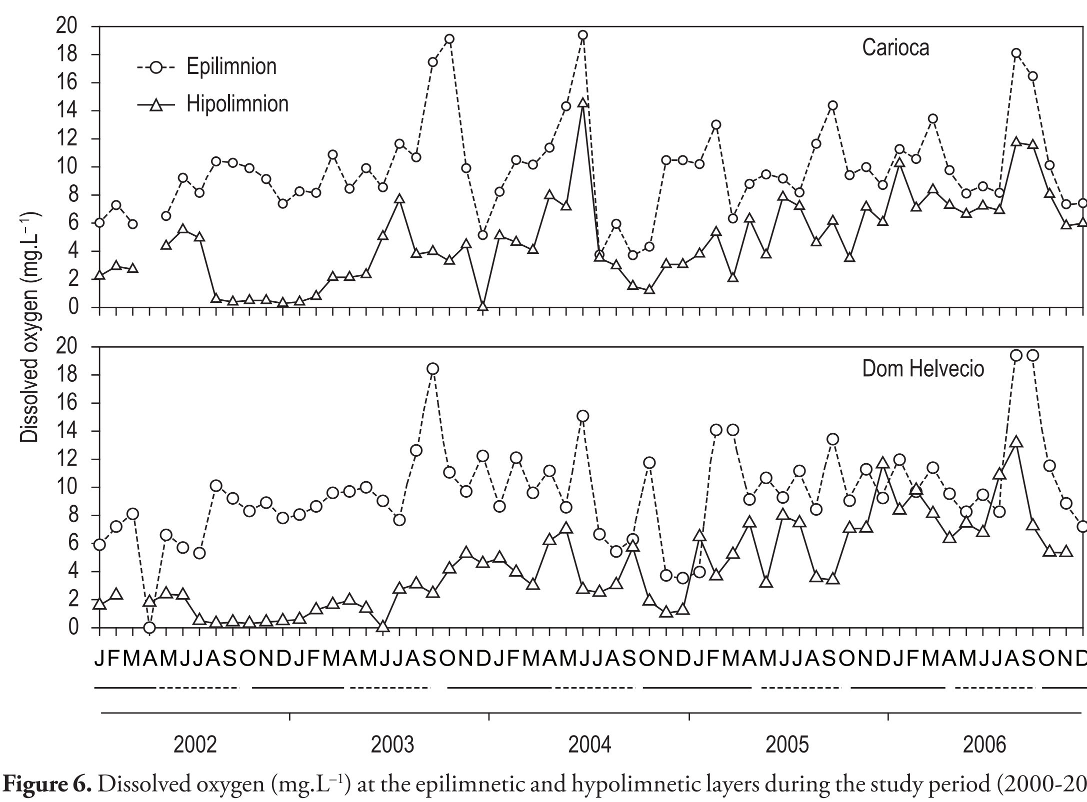

Figure 6. Dissolved oxygen ($mg.L^{-1}$) at the epilimnetic and hypolimnetic layers during the study period (2000-2006) at lakes Carioca and Dom Helvécio, southeast Brazil.

pH values showed high variation between layers in both lakes, the epilimnion being slightly more alkaline than the hypolimnion due to decomposition processes that take part in the last layer. Between lakes, pH values were a little more acid for Lake Carioca both at the subsurface (4.98-8.6) and at the aphotic zone (4.52-10.09). At Lake Dom Helvécio, pH values were always above 6 (Table 2).

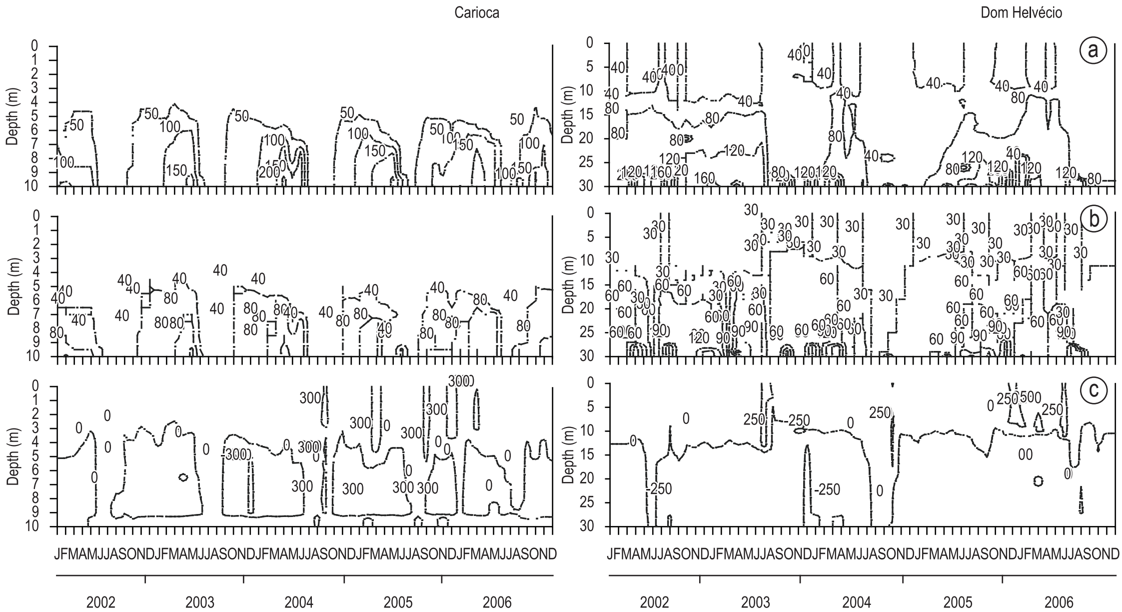

Figure 7. Depth-time diagram of electrical conductivity (µS.cm^{-1}) (a), total dissolved solids (mg.L^{-1}) (b) and redox potential (c) during the study period (2000-2006) at lakes Carioca and Dom Helvécio, southeast Brazil.

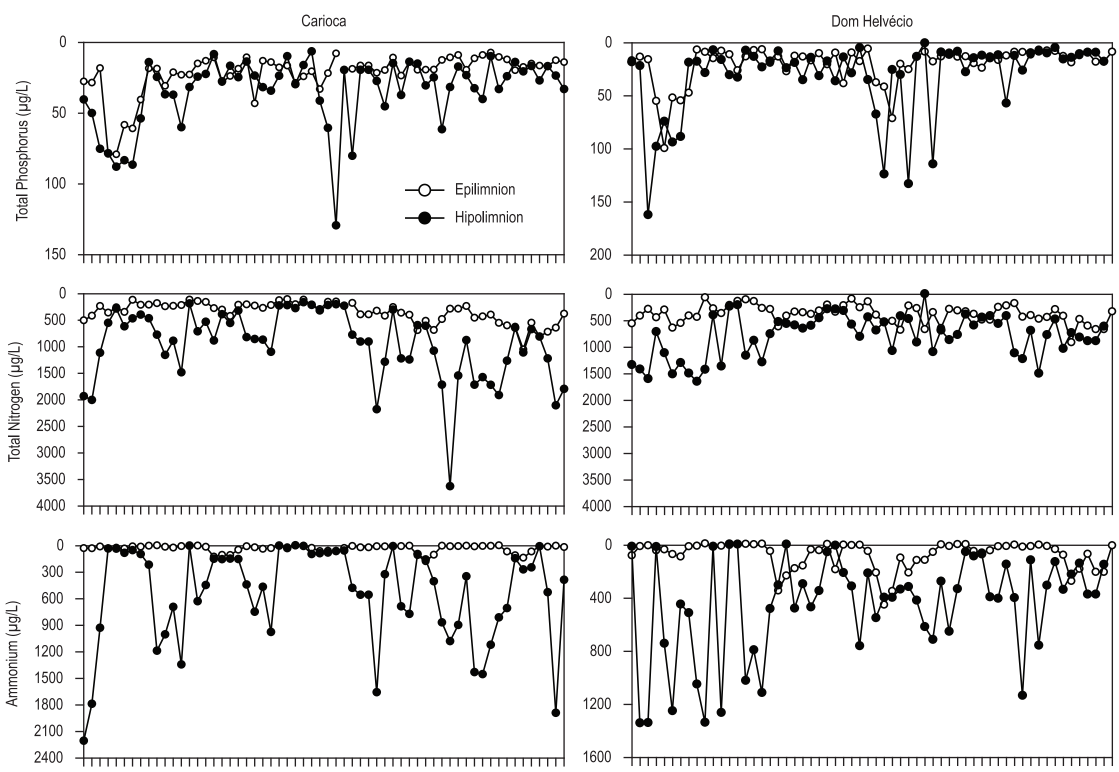

Figure 8. Total phosphorus (µg.L^{-1}), total nitrogen (µg.L^{-1}) and ammonium (µg.L^{-1}) at the epilimnetic and hypolimnetic layers during the study period (2000-2006) at lakes Carioca and Dom Helvécio, southeast Brazil.

Electrical conductivity at Lake Carioca presented its minimum value (32 µS.cm^{-1}) at the epilimnion and the maximum (181 µS.cm^{-1}) at the hypolimnion during stratification. At the Dom Helvécio, a similar trend was detected, i.e. the lowest values (39-58 µS.cm^{-1}, n = 140) being detected at the epilimnion and the highest ones at the hypolimnion (73-210 µS.cm^{-1}, n = 140). This pattern was also detected during circulation (maximum 229 µS.cm^{-1} at the deeper layers). Electrical conductivity's vertical distribution during stratification presented significant differences for both Lake Carioca (Anova one way, p = 0.000) and Lake Dom Helvécio (Anova one way, p = 0.000), but for the Dom Helvécio significant differences were also detected during stratification (Anova one way, p = 0.000).

Maximum values of total dissolved solids (TDS) were detected at the hypolimnion of both lakes during stratification (90 and 130 mg.L^{-1} for lakes Carioca and Dom Helvécio, respectively). The same was measured for the electrical conductivity, the high TDS values also measured at the Z_{aph} during circulation (maximum 90 mg.L^{-1}). Redox potential measurements indicated, as expected, dominance of oxidation processes above the thermocline and of reduction below the thermocline in both lakes, but at the Dom Helvécio reduction processes also dominate below 9-12 m during circulation.

Nutrients varied seasonally, their lowest concentrations being detected at the epilimnion and the highest at the hypolimnion during stratification. Regarding dissolved inorganic nitrogen (DIN), NH_4^+ was its main component fraction with maximum concentration at the hypolimnion of the two systems during stratification, coinciding with the highest electrical conductivity and the lowest DO values. The highest NH_4^+ concentration was obtained for Lake Carioca. PO_4^{-3} concentrations were relatively low at the two lakes. During the turnover period, dissolved oxygen concentration exhibited an orthograde curve associated with N (N-NH_4) and P (total and dissolved) concentrations, whose distribution along the water column was uniform during this period. Hypolimnetic anoxia was typical of the stratification period of both Carioca and Dom Helvécio lakes, but more frequent at the latter during stratification of years 2002 and 2004.

Significant inter-annual differences for TP, TN and NO_2 were identified for lakes Carioca (Anova one way, p = 0.000) and Dom Helvécio (Anova one way, p = 0.000). These nutrient forms at Lake Carioca also presented differences among depths, with subsurface and bottom always unlike each other (Anova one way, p = 0,000) as a consequence of nutrient accumulation at the bottom of both systems. Lake Dom Helvécio's vertical profile shows a different distribution for TN (Anova one way, p = 0.000), PO_4^{-3} (Anova one way, p = 0.003) and NO_2 (Anova one way, p = 0.02).

At Lake Carioca, molar ratio DIN:SRP average values (6.1-15; n = 140) indicated P and N availability at the Z_{eu} during both stratification and circulation periods, where concentration of dissolved nitrogen forms was high (mainly NH_4^+, whose concentration varied from 0.7 to 39.8 µg.L^{-1} at the subsurface and from 235.7 to 2210 µg.L^{-1} at the Z_{aph}) and the PO_4^{-3} concentration was low (2.1-4 µg.L^{-1}) at subsurface and Z_{aph} (5-12 µg.L^{-1}). However, P-limitation was documented at the Z_{aph} with values always above 100, and N-limitation detected in March 2004 (DIN:SRP < 3).

During stratification, DIN:SRP molar ratio was below 50 (n = 140) at the epilimnion of Lake Carioca and in the entire water column of Lake Dom Helvécio indicating P-limitation. During circulation, values were always above 40, also indicating SRP-limitation. DIN-limitation was registered in March 2003 and 2004 (DIN:SRP < 3). Consequently, DIN:SRP ratio at Lake Dom Helvécio reflected lower concentration of NH_4^+ (maximum 1353 µg.L^{-1} at the hypolimnion), and indicated P and N co-limitation. PO_4^{-3} distribution showed concentration similar to those measured at Lake Carioca's subsurface (2.9-16 µg.L^{-1}) and Z_{aph} (5.8-12.3 µg.L^{-1}). During circulation, TP and TN concentrations, as well those of their dissolved forms, were uniformly distributed along the water column, the PO_4^{-3} concentration of 2.16-7.7 µg.L^{-1} at the subsurface and of 0.4-9.7 µg.L^{-1} at the Z_{aph}.

Concerning NO_3, an important N source for the phytoplankton, concentrations were extremely low in the two lakes, with a tendency of stratification during the thermal stratification period, with lowest concentrations being measured at the epilimnion. As far as the trophic state concerns, present results showed that Lake Carioca shows a tendency to mesotrophy, whereas Lake Dom Helvécio varied between oligotrophic during the stratification period and mesotrophic during the circulation period.

4. Discussion

Lake morphometry has high correlation with variables associated to energy quantity, so that heat losses do not occur in deep lakes (>50 m) throughout the entire water column, but there is some heat storage in the deepest layers (Ambrosetti and Barbanti, 2002). According to the same authors, shallow lakes are more efficiently heated than deep ones. However, shallow lakes are also more susceptible to heat losses (Barbosa et al., 2011). The heat storage is proportional, i.e. the deeper the lake, the greater its capacity to store heat (Ramírez Restrepo, 2000).

According to Timms (1975), active (climate and wind action protection) and passive (morphometry) components are involved in lakes' thermal regulation. Among the different lake types identified for the Rio Doce Lake District, Lake Dom Helvécio is considered dendritic, deep, with slow circulation, whereas Lake Carioca is somewhat round-shaped, small and shallow, with more effective circulation (Meis and Tundisi, 1997).

Thermal stability's numerical differences between lakes Carioca and Dom Helvécio were previously observed (Henry and Barbosa, 1989), Dom Helvécio presenting the highest values of the thermal stability and caloric content. At Lake Dom Helvécio, several factors act synergistically both on heat capture and its loss, among which the greatest surface area, greatest effective length and the dendritic shape will favor wind movement in different directions (Henry and Barbosa, 1989). Dom Helvécio is the Brazilian deepest natural lake and despite of being much shallower than most Italian and African ones (Ambrosetti and Barbanti, 2002), its depth does not favor the complete mixing of its water column, mainly that of the chemical compounds (Mitamura and Hino, 1985).

The long-lasting thermal stratification in the two lakes studied promoted physically and chemically different layers, with the discontinuity among layers and occurrence of an intermittent mixing in the epilimnion favored by atelomixis (Barbosa and Pádisak, 2002). In the present study similar recurrent patterns were identified with regard to thermal stratification and mixing, the thermal regime being a determinant for distribution of abiotic factors, limiting their distribution to the stratification periods and favoring homogenization during the mixing period. However, in Lake Dom Helvécio temperature, electrical conductivity, total dissolved solids, redox potential and nutrient profiles during the circulation period suggested some characteristics rather similar to those of meromictic lakes. In these lakes, total stability is subdivided into chemical (or meromictic) and thermal stability, and major inferences are made as to the depth of their winter mixing (Ambrosetti and Barbanti, 2002). The lower effective circulation, slight meromixis may occur at Lake Dom Helvécio.

Epilimnion temperatures during the rainy periods or that of the deeper layers during the circulation period were less affected by the daily climatic variation (e.g. air temperature oscillations). According to Ambrosetti and Barbanti (1999), deep lakes (>100 m) have a "climatic memory" to be assessed for long periods, thus indicating the past changes and projecting a prognostic character. This memory is favored for environments with high thermal and chemical stability, with the deeper layers preserved or stagnant, as Lake Dom Helvecio. Meromictic lakes circulate occasionally, but never completely due to the presence of a dense, stagnant stratum (Wetzel, 2001). The suggested "chemical memory" may persist during stratification periods in monomictic lakes, tending to meromictic.

Deep lakes, besides presenting lower nutrient concentrations (mainly TP), also present lower productivity due to their cells' smaller surface:volume ratio when compared to those of shallow lakes (Meding and Jackson, 2003). Furthermore, shallow lakes are more sensitive to changes in nutrient loadings and usually respond more rapidly to climatic changes due to their greater surface and smaller volume and depth (Schindler et al., 1996). Nutrients (P and N) present in the Lake Carioca's deepest layers are more efficiently transferred to Z_{eu} due to the system's complete circulation during the dry period, the nutrient recycling being more efficient during this part of the cycle. These factors would explain the more drastic nutrient limitation at Lake Dom Helvécio Z_{eu}.

In Dom Helvécio, the complex spatial distribution of depths indicates a high spatial variability in several ecological properties of the lake (Bezerra-Neto and Pinto-Coelho, 2008). Such a fact implies differences in nutrient distribution and, consequently, favors an effective homogenization at Lake Carioca and promotes an increase of primary production values (Barbosa and Tundisi, 1989).

Besides being more susceptible to abiogenic and biogenic turbidity, shallow lakes undergoing complete mixing (as is the case of Lake Carioca) are also sensitive to increases in nutrient concentration (mainly TP), such increases in loads possibly reflecting on the excessive increase of primary production, the algal blooms or on the increase of aquatic macrophyte occupation (Jeppesen et al., 1998). Furthermore, the high concentrations of

Table 2. Physical and chemical factors (means and ranges) of the Carioca and Dom Helvecio lakes over the period of 2002-2006.

Variables	Carioca lake							
	Stratification period				Mixing period			
	100%	10%	1%	Zaph	100%	10%	1%	Zaph
pH	6.7 (±1.0)	6.9 (±6.9)	6.6 (±1.1)	5.9 (±0.3)	6.2 (±1.1)	6.4 (±0.9)	6.4 (±1.0)	5.7 (±0.2)
Electrical condutivity (μS.cm^{-1})	29.0 (±1.5)	29.0 (±1.5)	39.8 (±19.1)	81.0 (±22.7)	30.8 (±1.1)	30.5 (±0.5)	30.8 (±1.1)	41.0 (±16.7)
Dissolved oxygen (mg.L^{-1})	7.6 (±1.6)	7.6 (±1.6)	5.2 (±3.9)	1.5 (±1.2)	8.9 (± 1.6)	8.4 (±2.2)	7.8 (±2.8)	3.2 (±2.5)
Temperature (°C)	31.6 (±1.5)	30.0 (±0.9)	26.9 (±1.4)	25.1(±2.5)	26.2 (±1.5)	24.9 (±1.4)	24.1 (±1.4)	23.5 (±1.5)
STD (mg.L^{-1})	20.0 (±0)	20,0 (±0)	26.7 (±12.1)	53.3 (±16.3)	20.0 (±0)	20.0 (±0)	20 (±0)	24.0 (±5.5)
Total phosphorus (μg.L^{-1})	32.5 (±21.3)	30.0 (±19.1)	39.6 (±17.6)	49.4 (±20.5)	54.7 (±25.6)	64.2 (±33.4)	58 (± 25.6)	68.4 (±36)
PO_4^{-3} (μg.L^{-1})	3.9 (± 2.8)	4.1 (±2.5)	4.6 (±1.7)	8.9 (±7.6)	3.6 (±2.2)	4 (±1.6)	5.5 (±5.2)	6.2 (±4.6)
Total nitrogen (μg.L^{-1})	304.6 (±118.6)	407.6 (±233.6)	516.8 (±195.7)	1199.0 (±561.1)	228 (±95)	243.9 (±93.6)	357.8 (±158.2)	454.3 (±136)
NH_4^--N (μg.L^{-1})	22.8 (±12.5)	11.1 (±7.7)	104.8 (±209.7)	1124.7 (±712.2)	21.2 (±14.5)	13.9 (±11.9)	25.6 (±31.4)	100.3 (±81.8)
NO_3-N (μg.L^{-1})	11.4 (±6.7)	9.4 (±4.9)	11.0 (±5.8)	11.7(± 7.0)	8.9 (± 3)	8.4 (±3.4)	8.4 (±3.9)	8.3 (±4.1)
NO_2-N (μg.L^{-1})	1.9 (±1.4)	1.8 (±0.7)	2.2 (±1.3)	5.9 (±3.3)	1.3 (±1)	0.8 (±0.7)	1.4 (±0.6)	2.3 (±1.2)
NID:SRP	39.4 (±42.1)	34.7 (±59.7)	119.9 (±264.1)	523.4 (±433.6)	18.8 (±10.4)	11.5 (±5)	20.5 (±23.2)	108.9 (±201)
CO_2 (mg.L^{-1})	1.5 (±1.9)	0.6 (±0.8)	2.2 (±3.4)	6.1 (±5.6)	3.9 (±3.7)	1.9 (±1.7)	1.5 (±1.5)	37.2 (±33.5)
HCO_3 (mg.L^{-1})	1.4 (± 1.0)	1.1 (±0.3)	1.2 (± 0.5)	2.4 (±0.8)	4.1 (±5.4)	3.8 (±5.3)	3.5 (±5.1)	9.4 (±7.8)
	Dom Helvécio lake							
	100%	10%	1%	Zaph	100%	10%	1%	Zaph
pH	5.74 (±2.6)	6.9 (±2.8)	5.5 (±2.5)	5.1(±2.2)	6.4 (±0.9)	6.5 (±0.7)	6.1 (± 0.3)	8.3 (±0.5)
Electrical condutivity (μS.cm^{-1})	32 (±14.2)	32.3 (±14.3)	32.0 (±14.2)	71 (± 31.5)	39.4 (±1.5)	39.4 (±1.5)	39.6 (±1.8)	9.9 (±9.3)
Dissolved oxygen (mg.L^{-1})	6.6 (± 3)	6.3 (±3)	2.7 (±1.9)	0.9 (± 0.9)	7.4 (± 2.2)	6.9 (± 2.5)	5.4 (±1.7)	69.0 (±1.0)
Temperature (°C)	29.5 (±0.9)	29.3 (±0.8)	26.5 (±1.4)	23.6 (±0.3)	25.8 (±1.5)	25.7 (±1.4)	25.3 (±1.5)	1.0 (±0.2)
STD (mg.L^{-1})	17.1 (±7.5)	17.1 (±7.5)	17.2 (±7.5)	44.2 (±19.8)	24.0 (±5.5)	24.0 (±5.6)	24.0 (±5.5)	38.4 (±20.7)
Total phosphorus (μg.L^{-1})	18.6 (±16.3)	19.5 (±13.3)	31.3 (±28.7)	38.8 (±54.6)	51.7 (±32.9)	55.9 (±36.4)	59.8 (±31.1)	43.8 (±32.5)
PO_4^{-3} (μg.L^{-1})	2.9 (±1.3)	3.7 (±3.4)	4.3 (±3.7)	4.4 (±3.7)	1.8 (±1.6)	2.9 (±2.1)	4.3 (±2.4)	57.7 (±5.6)
Total nitrogen (μg.L^{-1})	346.4 (±155.6)	455.2 (±85.3)	533.7 (±157.6)	1310 (±419)	469.3 (±131.7)	496.4 (±140.9)	518.9 (±144.7)	26.9 (±330.0)
NH_4^--N (μg.L^{-1})	31.8 (±29.9)	33.8 (±38.2)	146.6 (±220.9)	739 (±679)	53 (±36)	42.5 (±38.9)	62.3 (±45.8)	74.9 (±452.4)
NO_3-N (μg.L^{-1})	9.6 (±6.4)	9.5 (±6.6)	12.5 (±7.9)	15.2 (±7.5)	8.7 (±3.2)	9.7 (±3.2)	11.3 (±4.7)	47.5 (±4.9)
NO_2-N (μg.L^{-1})	1.4 (±0.6)	1.8 (±0.9)	2.7 (±2.8)	1.79 (±0.7)	1.4 (±1.4)	1.8 (±2.0)	1.7 (±1.2)	99.5 (±3.3)
NID:SRP	122.4 (±262.3)	61.9 (±76.2)	123.5 (±158.8)	527.9 (±702.8)	155.0 (±122.3)	47.7 (±23.7)	57.2 (±59.6)	66.5 (±89.9)
CO_2 (mg.L^{-1})	1.9 (±3.9)	0.4 (±0.42)	1.6 (±1.5)	8.2 (±5.1)	4.5 (±6.2)	2.2 (±2.8)	2.6 (±1.8)	100.8 (±6.0)
HCO_3 (mg.L^{-1})	1.6 (±0.5)	3.0 (±4.0)	3.6 (±5.5)	5.1 (±5.3)	1.8 (±0.5)	1.9 (±0.3)	1.8 (±0.4)	60.0 (±2.0)

dissolved organic carbon and colored organic matter (Bezerra-Neto et al., 2006) favored heat absorption and the consequent increase of thermal contents and stability in the two lakes, mainly at Lake Carioca, where these variables' concentration was much greater (Bezerra-Neto et al., 2006). However, the transparency associated with the high concentration of pigmented organic matter was low.

Chemical stratification patterns may contribute in the typological classification of shallow environments, Lake Carioca being a typical representative of a shallow, turbid and nutrient-rich lakes and Lake Dom Helvécio of a deep, clear and nutrient-poor one.

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