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Spatial and temporal variation of Dona Francisca reservoir (Jacuí river, Rio Grande do Sul State), a subtropical reservoir

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ABSTRACT. The present study examined the behavior of a reservoir located on subtropical latitude (Dona Francisca reservoir). The limnological variables measured were dissolved oxygen, temperature, pH and electric conductivity. Measurements were taken quarterly at different sampling sites along the reservoir. The results indicated the formation of longitudinal zones regarding circulation patterns and stratification, beyond the influence from the water masses of the main tributary. The vertical profiles were obtained. The behavior of the reservoir is similar to others previously studied in the country, but with shorter time-lag stratification and a narrower range, possibly due to the shorter residence time of the water, and to the latitude, where summer is shorter.

Keywords: subtropical reservoir, thermal stratification, compartmentalization, thermocline.

Variação temporal e espacial do reservatório Dona Francisca (rio Jacuí, Estado do Rio Grande do Sul), um reservatório subtropical

RESUMO. O estudo buscou analisar o comportamento das variáveis limnológicas, dentre elas oxigênio dissolvido, temperatura, pH e condutividade elétrica, em um reservatório de latitude subtropical (reservatório Dona Francisca). Medidas trimestrais foram feitas em diferentes locais do reservatório, onde foram obtidos os perfis de profundidade. Os resultados indicaram a formação de zonas longitudinais a partir dos padrões de circulação e estratificação, além da influência exercida pelas massas de água do afluente principal. Conclui-se que o comportamento do reservatório se assemelha a outros no país, mas com intervalo de tempo de estratificação menos prolongado e amplitudes menos acentuadas, em parte, possivelmente, pelo pequeno tempo de residência da água e sua posição latitudinal, quando o verão é mais curto.

Palavras-chave: reservatório subtropical, estratificação de reservatório, compartimentalização, termoclima.

Introduction

Limnological ecosystems, such as reservoirs, are characterized by intense dynamic and gradient variability that describe the environmental conditions. Besides the climate, hydrologic regime, substances and materials from adjacent areas, the environmental conditions in aquatic systems are related to the system hydrology (SCHÄFER, 1984).

Concerning the hydrodynamic, reservoirs are open systems with continual flow and prominent pulse regime, with horizontal environment changes, similar to rivers. On the other hand, these environments are almost closed, alternating periods of stagnation and circulation; with little variations in the water level, and with mainly vertical spatial variations of environmental conditions, similar to deep lakes. Moreover, reservoirs are intermediate systems, between rivers and lakes, with gradient that changes longitudinally (MARGALEF, 1983).

Longitudinal gradients in reservoirs result in a compartmentalization in both horizontal and vertical directions, due to different residence times of water masses within each region of the reservoir (HENRY, 1999). Based on this gradient, a reservoir may be divided into three zones (THORNTON et al., 1990; TUNDISI, 1999): (i) *fluvial* or *lotic*, under strong influence of the main river; (ii) *intermediate* or *transition*, still with influence of the fluvial inflow, but with lacustrine environment traits; and (iii) *lacustrine* or *lentic*, with absence or little fluvial influence, where vertical stratification of the water column may still occur. Furthermore, other compartmentalization patterns may be mentioned, such as the vertical stratification of the lacustrine zone. According to Tundisi (1983), this is related to hydraulic characteristics, as well as the reservoir type and depth of water withdrawal. The importance and distribution of great lakes on Earth and the relation with latitude was studied (LEWIS JR., 1996).

The dynamics established for many factors due to spatial structure is important to reservoir characterization, especially at the lacustrine zone. However, reservoir characterization in Brazil as a result of the wide diversity of geographical variables (climate, geology, relief, etc), is scarcely examined. Regarding reservoir studies in Brazil, it is important to mention the pioneering work of Kleerekoper (1939) at the Santo Amaro Dam (currently Guarapiranga, São Paulo State). Since then, most studies on reservoirs in Brazil have focused mainly on biological populations and communities (e. g., FALCO; CALIJURI, 2002; TUNDISI, 1983,1999; SANTOS-WISNIEWSKI; ROCHA, 2007). Other subjects have also been approached, as primary production (ESTEVES, 1981; POMPÊO et al., 2001; HENRY et al., 2006), sediment (TOLEDO; LORANDI, 1991a and b; FÁVARO et al., 2007), limnology (LOPES; BICUDO, 2001; RAMIREZ; BICUDO, 2003), trophic relationships (WALKER, 2004) among others.

In Rio Grande do Sul State, the limnology in reservoir is still at early stages. The location at the south end of the country ascribes great importance to comparative studies about the ecosystems variability as a result of geographical location.

This study asses sed the particularity of changes in vertical profiles of limnological variables in the water column and the compartmentalization pattern from a Brazilian reservoir located at higher latitude, and determined whether this condition results in a different pattern from those found in other Brazilian reservoirs.

Material and methods

Dona Francisca reservoir is located downstream from a sequence of four reservoirs (Passo Real, Jacuí and Itaúba) built on the river Jacuí course (Figure 1A and B). The drainage basin has an area of 13,200 km^2, and the reservoir area is of 19.00 km^2. The total reservoir volume at 94.5 m above sea level is 335 x 10^6 m^3. The water outlet is composed by two conduits with equal outflow of 182 m^3 s^{-1} for each turbine. The door-sill of the water taking is situated in a depth of 16.5 m. The reservoir depth along with the dam is 43.5 m. The surface spillway has a maximum outflow of 12,600 m^3 s^{-1}.

Four samplings were carried out seasonally during one year: December 2000 (summer), March 2001 (autumn), July 2001 (winter) and September 2001 (spring), corresponding to the period immediately after the closure of the dam. This period is important for reservoir metabolism, because much of the vegetation from the flooded area was not removed, resulting in a considerable initial supply of organic matter.

Samples were taken at day time, with a Van Dorn bottle. At each site, samples from the water column were obtained at every 5 m of depth, and temperature, dissolved oxygen (oximeter Yellow Springs YSI), electric conductivity (conductivimeter Yellow Springs WTW) and pH (pHmeter Alfakit WTW) were measured.

Six sampling stations (Figure 1C) were distributed along the main channel of the reservoir, and its main tributary, located by GPS, and described as UTM coordinates, as listed: (1) 6,759,135 N and 282,700 E (river Jacuí upstream from Itaúba); (2) 6,755,700 N and 283,390 E; (3) 6,748,490 N and 284,625 E; (4) 6,744,800 N and 283,580 E; (5) 6,739,650 N and 279,270 E (reservoir main channel); and (6) 6,750,900 N and 284,680 E (mouth of the river Jacuizinho).

Results

The patterns of vertical profile varied at each sampling station. In December 2000, except for sampling stations 1 and 2, a thermal and chemical stratification was observed along the reservoir (Figure 2A). Vertical profiles of temperature and dissolved oxygen (O_2) presented a decrease over the top-bottom gradient, while electric conductivity, an increase.

Anoxic conditions in the hypolimnion were recorded at stations 4 and 5, both from 15 m until the bottom, and station 6 only close to the bottom (20 m depth). The most accentuated decrease in temperature in this period occurred in station 5. In station 3, a stratification trend was observed, with the lowest concentration of 1.90 mg L^{-1} close to the bottom. The thermocline formation, in this case, occurred between 5 and 15 m depth at stations 4 and 5, and between 10 and 15 m at stations 3 and 6.

Concerning the differences between surface and bottom values of temperature, O_2 and electric conductivity along the reservoir main channel (Figure 3), the results of December 2000 presented an increase towards the dam. The temperature values in the surface also increased closer to the dam, whereas bottom values decreased. O_2 presented surface values closer to each other, whereas bottom values decreased towards the dam, reaching anoxic conditions at stations 4 and 5. Electric conductivity presented an inverse trend compared to O_2.

There was no stratification of the water column in any other period. Meantime, in March 2001 (Figure 2B) the vertical profiles were variable, and irregular, not corresponding to the stratification pattern observed in December 2000. In this case, the profiles, as well as the results of surface and bottom (Figure 3), despite the differences, reflected the vertical displacement of water masses.

In July and September 2001 (respectively Figure 4A and B), the temperature, O_2 and electric conductivity presented vertical profiles, as well as longitudinal gradients (Figure 3) relatively homogeneous, except for differences in temperature at stations 4 and 5 in July, the low temperature in the bottom of the station 2 and the variation of O_2 at stations 4 and 5 in September.

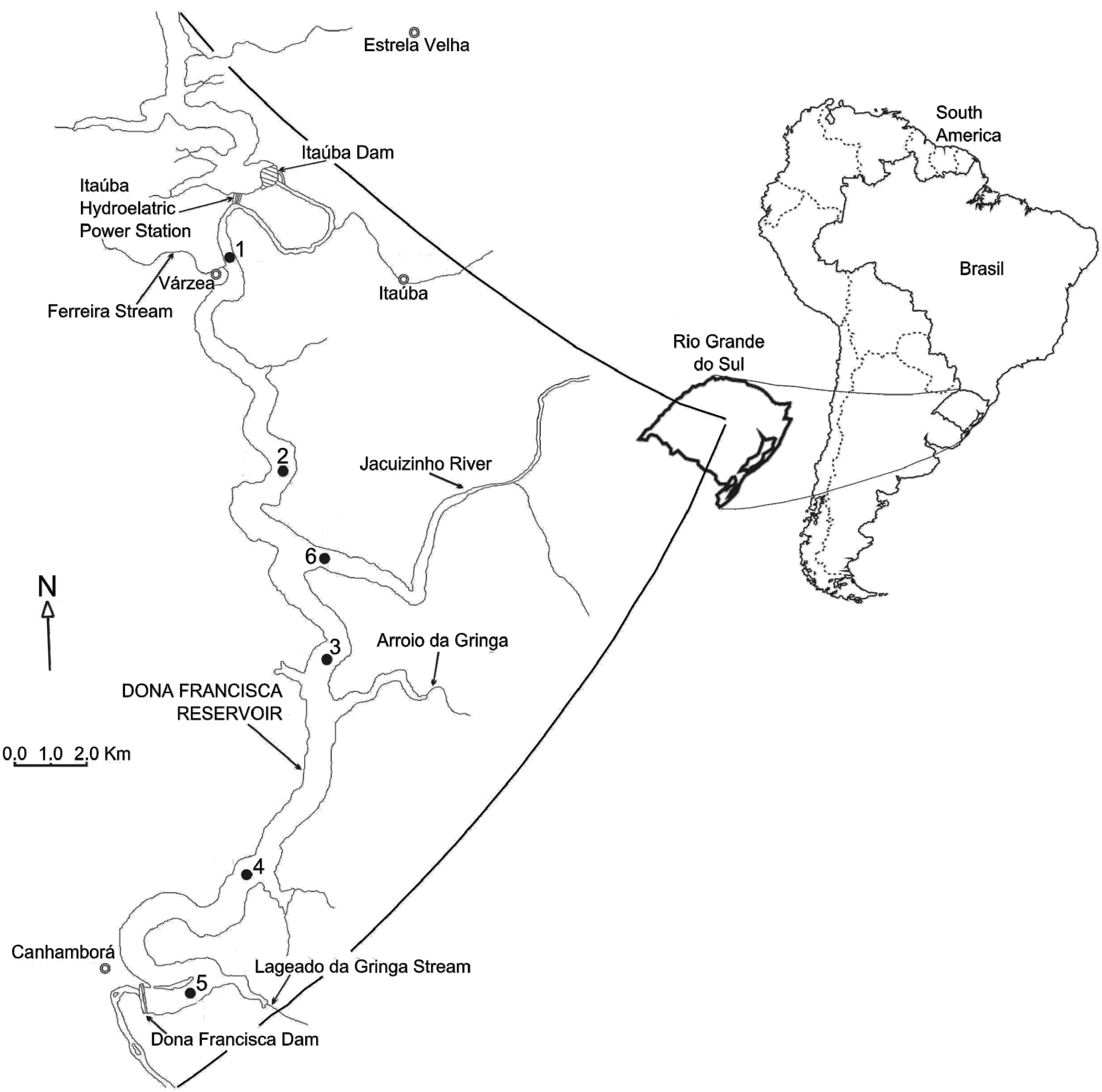

Figure 1. Dona Francisca reservoir: (A) South America; (B) Rio Grande do Sul State; and (C) Dona Francisca reservoir (UHDF) and sampling stations. ● Sampling stations.

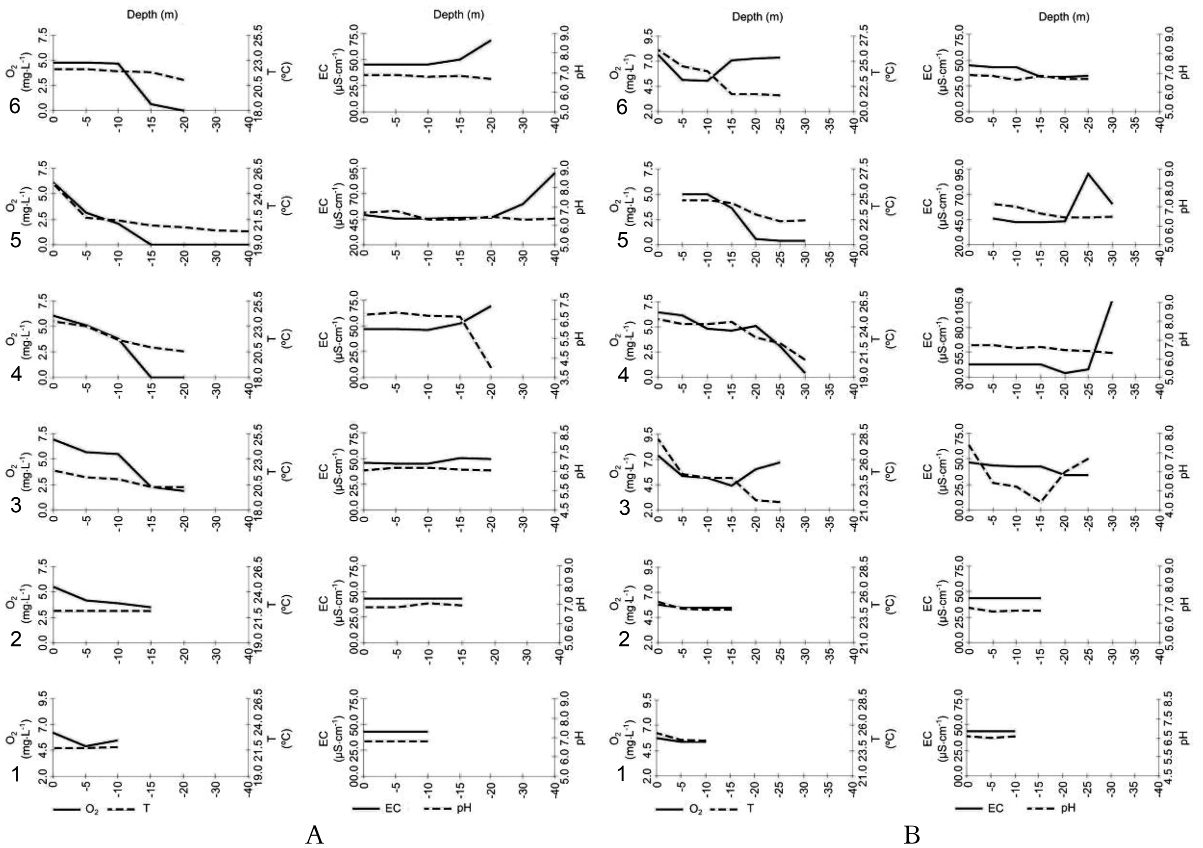

Figure 2. Vertical profiles of temperature (T) dissolved oxygen (O_2), electric conductivity (EC) and pH at each sampling station, in December 2000 (A) and March 2001 (B).

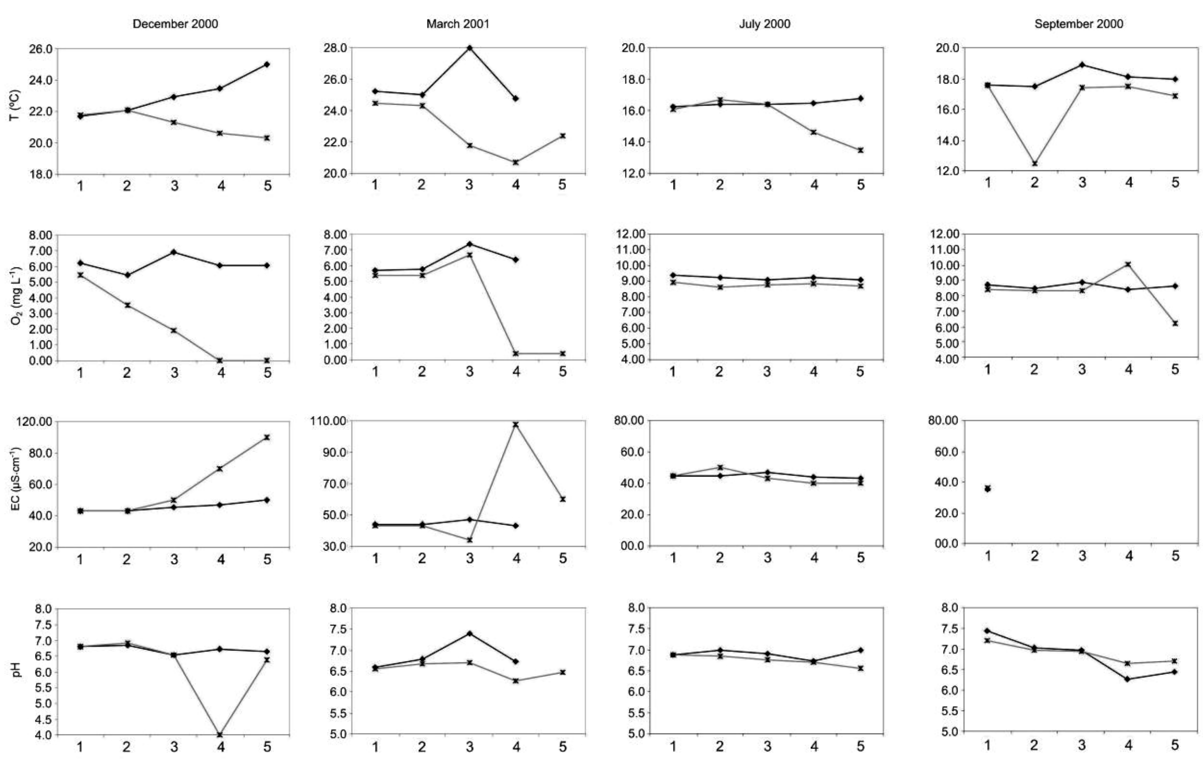

Figure 3. Surface and bottom values of temperature (T) dissolved oxygen (O_2), electric conductivity (EC) and pH along the main channel, in December 2000, March, July and September 2001.

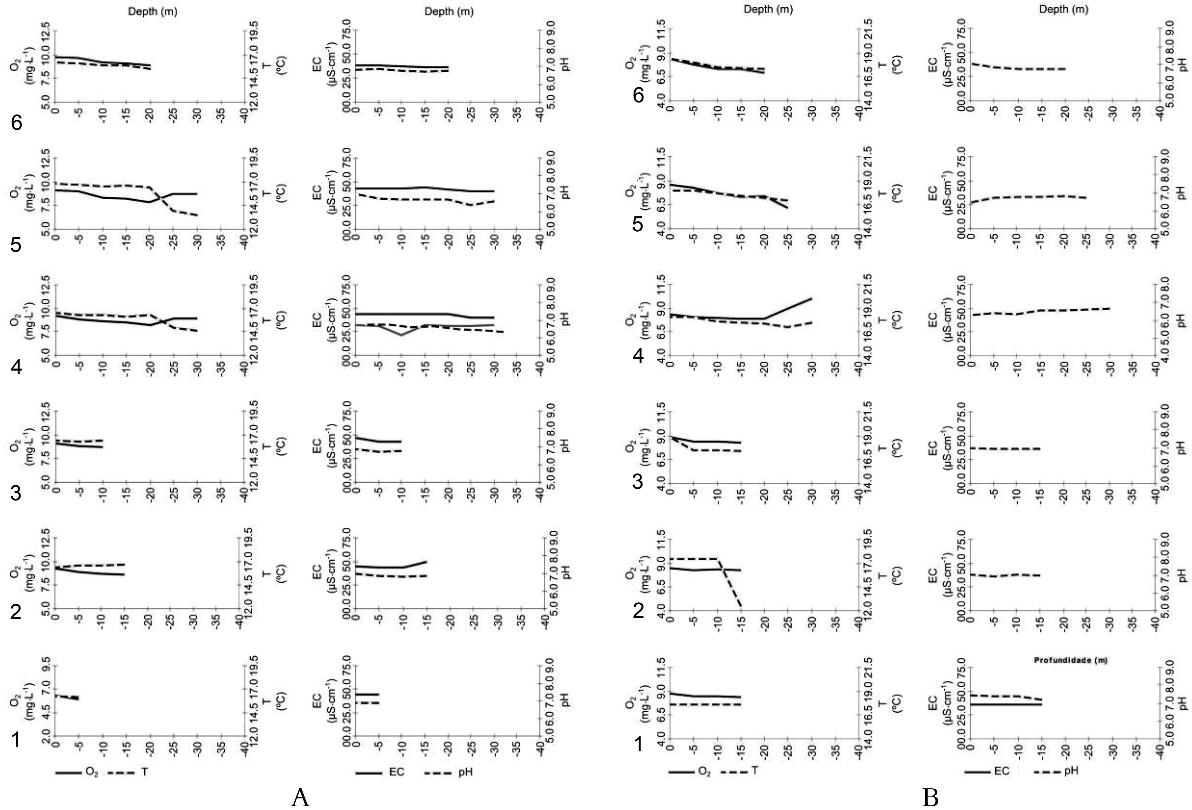

Figure 4. Vertical profiles of temperature (T) dissolved oxygen (O_2), electric conductivity (EC) and pH at each sampling station, in July 2001 (A) and September 2001 (B).

Discussion

Stations 1 and 2 show vertical profiles little variable or even homogeneous, during all periods, as result of the discharge influence from the Itaúba hydroelectric power plant. These sites are strongly affected by the river inflow from the Itaúba power plant, resembling lotic systems, due to their location in the fluvial zone of the reservoir. The stratification recorded in December 2000 – both thermal and chemical – may be related to increased air temperature in the summer, residence time in the lacustrine zone, lower influence of the river inflow, and depth of water outlet (16.5 m). The remarkable reduction of the values at station 5 was expected due to the location at the deepest region of the reservoir.

Thermal stratification and circulation patterns, according to Thomaz et al. (1997), influence the vertical distribution of other limnological variables. The authors also stated that the stagnation of the water column causes the sedimentation of particulate inorganic matter; in which the organic carbon, calcium, iron, manganese, carbonate, and phosphorus are adsorbed. That explains the vertical profiles of electric conductivity in December 2000, which indicates the increase towards the bottom.

The profiles of dissolved oxygen and electrical conductivity might be related to two mechanisms: (1) mineral precipitation and sedimentation due to water stagnation (stratification in summer); increasing concentration towards the bottom, reflecting on electrical conductivity; and (2) decaying of submerged vegetation after flooding, which would increase oxygen consumption in the deeper water layers, and could result on increased loads of ionic substances as decomposition products, besides the microbial enzymes that may remain in the environment for a certain time (PUSCH et al., 1998).

Electrical conductivity in summer varied from 30.5 to 56.0 μS cm^{-1} at surface. These values are similar to the results obtained by Esteves et al. (1985), at Três Marias reservoir, which varied between 30 and 55 μS cm^{-1} and were considered low. For example, the São José do Rio Preto municipal Dam (São Paulo State) is affected by artificial eutrophication, with conductivity ranging from 77 to 140 μS cm^{-1} (BOZELLI et al., 1992). The Rio das Pedras reservoir (São Paulo State) ranges from 88.0 to 166.0 μS cm^{-1} (PADIAL et al., 2009). The low values of Dona Francisca reservoir are probably because the samplings were accomplished during the first year after the impoundment. Thus, there was not enough time for the accumulation of materials. On the other hand, the low values may be due to retention by upstream reservoirs.

In March 2001, despite the low values at the deepest sampling stations, a discontinuity in the vertical profiles was observed, indicating the beginning of the vertical circulation, but without total mixing of the water masses. Moreover, anoxia was not recorded in the hypolimnion. Station 6 (river Jacuizinho) presented increases in O_2 concentration in the deepest layers in the same period, similar to observed at station 3 – downstream from the confluence of the rivers Jacuizinho and Jacuí. This situation may be due to the water input from Jacuizinho river. The lotic origin of the water possibly result in greater oxygen concentration and lower temperature. Additionally, the electric conductivity results from the stations 3 and 6 follow the values of temperature and dissolved oxygen during the same period, with a decrease in the deepest layers. The other sampling stations probably reflect the displacement of water masses within the reservoir. Possibly, a non-steady stratification with short duration might be occurring, during this period, as registered by Ramirez (1995) in a study on the vertical variation of limnological variables during a diel cycle at the Punchiná reservoir, Colombia. The author did not verify diurnal variation; however, the vertical profile indicated displacement of water masses without mixing, due to the absence of uniformity (homogeneity) and regularity (stratification) in the vertical profiles.

In July and September 2001, the higher uniformity of vertical profiles, comparing to previous periods, corresponds to the circulation period with intense mixing of water masses, including the sampling stations closer to the dam (4 and 5). The duration of stratification and mixing phases may be related to the rate of irradiance. In a study considering data from thirty-nine natural lakes in Cameroon (West Africa), a strong, positive relationship between water transparency and thermocline depth was verified in both tropical and temperate lakes, suggesting that the reduction in buoyant resistance to vertical mixing, caused by deeper penetration of solar radiation, is important in the establishment of mixing depths in several lakes (KLING, 1988). Dona Francisca reservoir appears to reflect the irradiance, since the period of mixing occurs in winter, unlike the period of stratification, in summer.

Tropical lakes with moderate to great depth are predominantly warm monomictic, and show great regularity in both seasonal mixing (in winter) and stratification, which is less stable than at higher latitudes; the amount of heat exchange required to cause important changes in stability is also smaller than at higher latitudes (LEWIS JR., 1996). The trend of regularity over the years in the behavior of tropical reservoirs may be evidenced in the study of Lewis Jr. (1984) on Lake Valencia (Venezuela). The Lake Valencia is located near latitude of 10º north and shows, according to Lewis Jr. (1984), a stratification persisting for eight to nine years. The Dona Francisca reservoir seems to hold a shorter period of stratification, which may be related to the greater latitude.

Thomaz et al. (1997) verified, for the Segredo reservoir (Paraná State), the permanence of stratification during winter (from June to September), but with lower differences in temperature between the surface and bottom layer, compared to summer. According to these authors, even though thermic uniformity has not been recorded, a complete circulation is suggested by the increase in dissolved oxygen at deepest layers, as well as by the more homogeneous vertical distribution of other limnological variables, such as electrical conductivity. In this way, the authors ascribed the thermic gradients, during the winter, to diurnal stratification, whereas circulation would take place at night/dawn or at irregular periods. Such analysis corresponds to similar conditions in the Dona Francisca reservoir, but with less intense circulation, and a longer stratification period in the latter. The same authors also considered this behavior as an exception because it occurs in only a few reservoirs, in Southeastern Brazil. Nevertheless, the results from the present study showed that this may be a common condition of reservoirs situated in Southern Brazil. Similarly, Tundisi (1983) studied reservoirs in São Paulo – a state located in the Southeast – and reported that in several reservoirs deeper than 20 m – similar of Dona Francisca reservoir (43.5 m) – the circulation is not enough to produce a complete enrichment and oxygenation of the water column. In Dona Francisca, the circulation is complete and stratification is apparently of shorter time.

In the Pontal reservoir (Minas Gerais State), the water column presented thermal stratification from February to October, whereas an isothermal condition was observed in June (DABÉS et al., 1990). In this case, water stagnation lasted for at least 10 months, a much longer period than in Dona Francisca (Rio Grande do Sul State) and Segredo (Paraná State). Such differences are probably associated to the higher latitudes of the last two reservoirs. On the other hand, Três Marias reservoir (Minas Gerais State) is characterized by a stratification period that lasts for at least four months in summer (ESTEVES et al., 1985), similarly to the results found at Dona Francisca.

Comparable to the Pontal reservoir, and differently from Dona Francisca, is the Valle de Bravo reservoir (Mexico City) that, according to Olvera et al. (1998), presented stratification from March to November (9 months). Bezerra-Neto and Pinto-Coelho (2001), recorded at Nabo Lake (Minas Gerais State), a stratification persistent from September to May, and mixing only in June and July. Although it is a small reservoir, it showed a pattern consistent with the discussion above.

Amongst the intrinsic characteristics of reservoirs, the hydrodynamics is clearly the most important (DABÉS et al., 1990); hydrological behavior is strongly influenced by morphology. Reservoirs from São Paulo State, such as Billings reservoir, are mostly flat and occupy extensive areas, whereas Segredo (Paraná State) and Três Marias reservoirs are deep and dendritic, similar to Dona Francisca. This can be verified through the ratio between surface area (km^2) and volume (hm^3) of reservoirs: Billings = 0.11; Segredo = 0.03; Três Marias = 0.05; e Dona Francisca = 0.06.

The circulation evidenced for July and September 2001 was expected, and reflects the relationship between climate, altitude and lacustrine morphology already considered in the classic scheme of thermal balance and lake classification by Hutchinson and Löffler (1956). According to these criteria, Dona Francisca reservoir is *warm monomytic*, with stratification periods of a few months, probably limited to summer (November to February).

On the other hand, according to Lewis Jr. (1996), considering the geostrophic factor that may magnify the variability of wind-generated mixing, tropical lakes show much more intra-seasonal variation in extent of the mixed layer than morphometrically similar temperate lakes. Also, small systems are more susceptible to climate changes (STRAILE et al., 2003). For example, Chapman et al. (1998), working on a small protected Ugandan crater lake (Lake Nkuruba), concluded that the system responds rapidly to short-term meteorological changes, and the annual heat exchange cycle was confined to upper waters. This feature is due to the small size of the lake, and the equatorial location of Uganda. Therefore, in order to confirm any trend observed in the present study, samples and measurements taken in shorter time intervals are necessary. Furthermore, Tundisi et al. (2004), analyzing the impacts of cold weather fronts on the vertical structure of the Carlos Botelho (Lobo-Broa) reservoir (São Paulo State) – a shallow reservoir – in winter (July/August), found that when cold weather fronts occurred frequently, the reservoir presented vertical mixing, and after the dissipation of the cold fronts, a period of stability followed by thermal, chemical, and biological (chlorophyll-*a*) stratification. Meanwhile, the mechanism of such influence has now been clarified for reservoirs from medium to great depth.

In order to formulate a typology for lakes and reservoirs, the interaction of climate, (variation in air temperature, and rainfall) and geographical location (latitude, and altitude) with lake characteristics (morphology, and size), must be carefully considered (STRAILE et al., 2003).

Regardless, the thermic balance of lakes, according to Schäfer (1984), depends on the climatic region, and employed as a criterion for lake classification. Studies carried out in Segredo reservoir, showed that this system presented stratification with thermocline formation, as well as anoxic hipolimnion, both in summer and autumn, especially next to the dam (JULIO JUNIOR et al., 1997). Such patterns are very similar to those found at Dona Francisca. Segredo reservoir is located in the Iguaçu river basin (Paraná State), and therefore in a geographic and climatic region very similar to the Jacuí river basin.

According to Thomaz et al. (1997), the thermal structure of sites next to the dam along with circulation patterns, and transport of materials, is consequence not only from meteorological phenomena (temperature, wind, and precipitation), but also from the interaction with the inflow by the main river, the spill/turbine ratio, the water withdrawal as well as the operation of the dam. For example, the Dona Francisca reservoir presented a thermocline between 5 and 15 m, coinciding with the height of the water withdrawal, whose door-sill is located at 16.5 depth. This relationship was verified by Casamitjana et al. (2003) to Boadella Reservoir (Catalonia, Spain) in a specific study.

Thomaz et al. (1997) pointed out that another aspect is that the differences between surface and bottom layers gradually increase downstream, on a longitudinal gradient. This phenomenon was recorded in December 2000. Such results demonstrate, clearly, the lotic behavior of the fluvial zone (sampling stations 1 and 2), and lentic behavior of the lacustrine zone closer to the dam (sampling stations 4 and 5). Zanata and Espíndola (2002), studying the Salto Grande reservoir (São Paulo State), concluded that the observed differences demonstrated a characteristic pattern for reservoirs, with the formation of a longitudinal gradient, leading to physical and chemical changes of the water, as well as a more significant correlation during the dry than in the rainy period.

A study on spatial variation of zooplankton community registered higher values of species richness and development of non-planktonic species in lotic environments, while highest abundances were recorded in lentic environments (TAKAHASHI et al., 2009). A similar pattern was observed for cladoceran assemblage from Corumbá reservoir (Goiás State) (TAKAHASHI et al., 2005).

Longitudinal variations in composition, density, and distribution of communities are also affected by seasonal changes in environmental factors, mainly due to the hydrological regime (CASANOVA; HENRY, 2004). This relationship was found between community and environmental factors in the Barragem da Pedra reservoir (Bahia State) (SIMÕES; SONODA, 2009). In a survey on distribution of copepods in Corumbá reservoir (Goiás State), the authors concluded that the hydrology is the primary process that controls the abundance of copepods, limnological features and food resources, which are commonly used to explain variations in zooplankton abundance (VELHO et al., 2001). These results reveal the importance of spatial and temporal variations recorded at Dona Francisca reservoir, which showed clear seasonal and spatial variations.

Establishment of longitudinal gradients was also observed by Falco and Calijuri (2002), studying the phytoplankton community in the Americana dam (São Paulo State), and Corbi and Trivinho-Strixino (2002), who examined the benthic community from Ribeirão das Anhumas reservoir (São Paulo State). Both studies detected the formation of two compartments (one lotic and one lentic) based on community structure.

Regarding the pH, in general, the values were neutral (6.3 - 7.4) in Dona Francisca reservoir, except for sampling station 3, in March 2001, and 4, in December 2000, the latter only at the bottom, which values lower than 6. The Brazilian reservoirs show in general neutral values of pH (ESTEVES et al., 1985; RAMÍREZ; BICUDO, 2003; FILISBERTO; RODRIGUES, 2005).

The climate can influence the metabolism, reflecting on the pH. However, pH is a complex variable, and there are no studies that provide an assessment of the relationship with latitude.

Conclusion

The longitudinal gradient, detected mainly in December 2000, probably led to the reservoir zonation, as follows: (i) fluvial zone, at sampling stations 1 and 2; (ii) intermediate zone, at sampling stations 3 and 6; and (iii) lacustrine zone, at stations 4 and 5. Despite the evidence already obtained, further studies about reservoirs behavior should be done, in order to confirm this hypothesis. The temporal variation corresponded to three periods: (i) stratification with anoxic hipolimnion at the lacustrine zone, in summer; (ii) circulation, without total mixing of water masses, in the beginning of autumn; and (iii) circulation, with total mixing of water masses, in winter and spring. Dona Francisca reservoir may, therefore, be characterized as *warm monomytic*, with a stratification period lasting for few months, probably limited to summer (November to February). Meantime, more studies are needed in order to test the conclusions obtained in the present study.

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