Short term variation of physical characteristics of a shallow subtropical oligotrophic reservoir, southeast Brazil

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ABSTRACT: Short term variation of physical characteristics of a shallow subtropical oligotrophic reservoir, southeast Brazil. Locally called Astronomic and Geophysics Institute pond, it is a small, oligotrophic, shallow reservoir located in the Parque Estadual das Fontes do Ipiranga Biological Reserve, south of municipality of São Paulo, Brazil. Study was carried out in two phases to cover the two climatic periods (dry and rainy) that characterize the area, in an attempt to understand the thermal structure of the reservoir and its relationship with other physical variables of the reservoir at short time intervals (diurnal and daily). Physical variables were measured daily, during seven consecutive days (dry = 20-26/August/1996; rainy = 22-28/January/1997), three times a day (07:00 hr, 13:00 hr, and 19:00 hr), following the water column vertical profile at reservoir's deepest site (Z_{max} = 4.7 m). Relative thermal resistance, wind generated forces, light vertical attenuation coefficient (*k*) and euphotic and aphotic zones extension were calculated. Reservoir behaved differently during the two climatic periods, with daily circulation during the dry period and stability during the rainy one. Marked influence of seasonal events on the reservoir thermal behavior was demonstrated during the two periods, with high influence of air and water temperature on the stratification pattern and little influence of wind on the circulation pattern during the rainy season. Depth of mixing zone was lower during the rainy period indicating greater stability of stratification during that period. Despite of occurrence of stratification during both periods studied and of its longer or shorter persistence, a typical hypolimnion was never detected. Analysis of temperature and relative thermal resistance in the water column showed that thermal stratification was not as stable in the dry period as it was during the rainy one.
Key words: diurnal and daily variation, physical properties, circulation, stratification, subtropical urban reservoir, Brazil.

RESUMO: Variação em curto prazo de características físicas em um reservatório subtropical oligotrófico raso, Brasil sudeste. O 'lago' estudado é um pequeno reservatório raso situado na área do Instituto Astronômico e Geofísico, Reserva Biológica do Parque Estadual das Fontes do Ipiranga, região sul do município de São Paulo, Brasil. O estudo foi realizado em duas etapas, de modo a contemplar os dois períodos climáticos que caracterizam a área (seco e chuvoso) e a compreender a estrutura térmica do reservatório em curtos intervalos de tempo (diurna e diária) e sua relação com outras variáveis físicas do sistema. As variáveis físicas da água foram medidas diariamente durante sete dias consecutivos (seca = 20-26/agosto/1996 e chuva = 22-28/janeiro/1997), três vezes ao dia (07:00 h, 13:00 h e 19:00 h), obedecendo ao perfil vertical da coluna d'água na região pelágica do reservatório ($Z_{máx}$ = 4,7 m). O reservatório apresentou comportamento distinto nos dois períodos, com circulações diárias no período seco e maior estabilidade térmica no chuvoso. Comprovou-se clara influência dos eventos sazonais nas propriedades físicas do reservatório em ambos os períodos, isto é, alta influência das temperaturas da água e do ar no padrão de estratificação, assim como pouca influência dos ventos no padrão de circulação no período chuvoso. Análise da temperatura e da resistência térmica relativa na coluna d'água mostrou que a profundidade da zona de mistura foi menor no período chuvoso, indicando maior estabilidade da coluna

d'água nesse período. A transparência foi maior no período seco do que no chuvoso. No entanto, em ambos os períodos os coeficientes de atenuação vertical foram baixos, revelando poucos compostos em suspensão na água e alta penetração de luz no reservatório. A extensão da zona eufótica foi mais acentuada no período seco, quando se verificou total ausência de zona afótica. Apesar da ocorrência de estratificações em ambos os períodos e destas serem temporárias ou duradouras, não se observou hipolímnio característico em qualquer dos períodos. Análise dos dados sobre temperatura e resistência térmica relativa na coluna d'água demonstrou que a estratificação térmica não foi tão estável no período seco quanto no chuvoso.

Palavras-chave: variaçao diurna e diária, propriedades físicas, circulação, estratificação, reservatório subtropical urbano, Brasil.

Introduction

Stratification due to temperature and density is the regulator of almost all physical and chemical cycles in a pond and, as a consequence, of its metabolism and productivity. Thus, it is important to know the amount of heat needed to promote stratification as well as to evaluate the amount of heat that a lake, for instance, has to loose to overcome density differences (Wetzel, 1993).

Most studies ever carried out on the water physical properties in Brazil dealt with lacustrine systems in the southeastern region, both in large reservoirs and in some lakes deeper than 10 m. Examples are the papers by Froehlich *et al.* (1978), Barbosa (1981), Tundisi *et al.* (1981), Matsumura-Tundisi *et al.* (1981), Arcifa *et al.* (1981), Esteves *et al.* (1985), Arcifa & Froehlich (1986), Giani *et al.* (1988), Henry & Barbosa (1989), Henry (1990), Huszar *et al.* (1994), Calijuri & Santos (1996), Henry *et al.* (1998), and Ferreira (1998). There also are papers that were carried out on shallow systems (3-5 m deep), like those by Henry (1981), Arcifa *et al.* (1990), Nogueira & Matsumura-Tundisi (1994), Marinho (1994), Silva (1995), Henry (1995), Ramírez (1996), Moura (1996), and Nogueira (1996).

For the Amazonian region, papers by Tundisi *et al.* (1984), McIntyre & Melack (1984, 1988), Camargo & Myiai (1988), and Huszar & Reynolds (1997) dealing with 1-8 m deep lakes should be mentioned. However, despite these lakes being shallow and thus somewhat comparable to the presently studied pond, it should be taken into consideration that their hydraulic regimens are totally different as well as characteristic, since their depth is subjected to the region's typical climatic variation.

Present paper aimed at investigating the short term (diurnal and daily) variation of the water physical properties in a subtropical, shallow, oligotrophic reservoir in two distinct climatic periods, dry and rainy.

Material and methods

Locally called 'pond' the studied system is, in fact, a small, shallow, oligotrophic reservoir located in the portion of the Parque Estadual das Fontes do Ipiranga Biological Reserve, south of municipality of São Paulo (23° 38' 08"S-23° 40' 18"S e 46° 36' 48"W-46° 38' 00"W), under jurisdiction of the Astronomic and Geophysics Intitute of the University of São Paulo. According to Bicudo *et al.* (2002), reservoir's maximum depth is 4.7 m, maximum length 311.5 m, maximum width 45.5 m, and volume 76,652.64 m^3.

Samplings were performed during seven consecutive days at a single station (maximum depth 4.7 m) both during the dry (20 to 26/August/1996) and rainy (22 to 28/January/1997) periods. Physical variables were studied in the whole water column at three different hours (07:00 hr, 13:00 hr, and 19:00 hr). At 19:00 hr of day 22 there was no sampling due to very severe weather conditions. Water temperature was measured directly with a portable FAC model 40 thermistor, and relative thermal resistance (RTR) calculated according to Wetzel (1993) and Dadon (1995). It was considered mixing zone, *i.e.* the water layer subjected to turbulent mixing, the layer comprised between the reservoir surface and that in which density gradient was greater than 2×10^{-2} $kg.m^{-3}.m^{-1}$ (= 2×10^{-5} $g.cm^{-3}.m^{-1}$) (Reynolds, 1984).

Forces generated by wind action on the water column were calculated according to formulas in Reynolds (1992, 1994, 1997). Water transparency was measured with a Secchi disk and its values used for calculation of the extension of the euphotic zone (Cole, 1983) and of the vertical light attenuation coeficient (Poole & Atkins, 1929).

Results and discussion

Despite the shallowness of the reservoir (Z_{max} = 4.7 m), it was possible to identify a marked tendency towards thermal stratification along the two study periods, except for days 20 to 22/August/1996 and for the 07:00 hr of day 28/January/1996. Stratifications were established from thermal gradients equal to or higher than 0.5°C.m^{-1} (Payne, 1986), in spite of temperature differences of 0.1-0.2°C may, in warm lakes (~25°C), generate considerable density gradients in the water column (Lewis, 1983a).

Dry period (20-26/August/1996)

During the dry period a tendency towards mixing of the water column was observed at 07:00 h, which could be indicated by the low relative thermal resistance (RTR) values at that time, thus evidencing the occurrence of water column mixture during night hours (Fig. 1). Wind speed values registered during the whole period did not surpass the average of 1.7 m.s^{-1}, thus restricting circulation to the upper portion of the water column and, consequently, defining a mixing zone (Fig. 2). Extension of the mixing zone (Z_{mix}) could be indicated by the low RTR values. Maximum mixing zone depth value was registered during days 20 to 23 at 07:00 hr, and miminum ones every day at 13:00 hr. Values variation was greater among hours than among sampling days, and progressively diminished towards the 13:00 and 19:00 hr (Fig. 3).

At 13:00 and 19:00 hr, DT' values oscillated between 0.1 and 1.4°C.m^{-1}, thus making possible detection of a greater tendency towards thermal stratification and a strong resistance to water mixing. Such observations could be proven by the very high RTR values calculated for those same hours (Fig. 1). A marked relationship between thermal discontinuity position (thermocline) and high RTR values was then established, a fact that also was observed by Henry & Barbosa (1989) for two lakes in the Rio Doce Valley National Park, Minas Gerais State, Brazil, and by Lewis (1983a) for Lake Valencia, Venezuela.

Despite the notorious developement of thermal and density gradients that encompassed over two thirds of the water column, the dry period did not present neither well-marked thermoclines nor hypolimnion. However, even considering the high RTR values that most probably did not allow mixture of the water column by wind action, it was possible to detect daily stratifications despite they were just temporary at 13:00 and 19:00 hr. Considering the whole water column, thermal and density gradients were observed in Amazonian lakes by Tundisi *et al.* (1984) with stratifications that went down to the system bottom.

Reverse thermal gradients (reverse stratification) eventually occurred at the superficial layer of the IAG reservoir water column. According to Henry (1981), reverse stratification at the superficial layer due to a drop of water temperature may, occasionally, be detected in shallow environments.

Temperature differences between reservoir's surface and bottom were greater than 1°C (except for days 20 to 22 at 07:00 hr), and ranged up to 4.4°C. According to Esteves *et al.* (1985), such thermal differences between the water body's surface and bottom are, in spite of being small, more than enough to generate great density differences among water masses and, consequently, relatively stable stratifications in the water column.

Transparency was high throughout the period and its variation did not follow a definite pattern (Fig. 4). Despite the low variation coefficients (3.7-5% during the dry period) would reinforce the small variability of measurements, transparency was statistically significant among days (p = 0.006) and depths (p = 0.000), but not among sampling hours (p = 0.495).

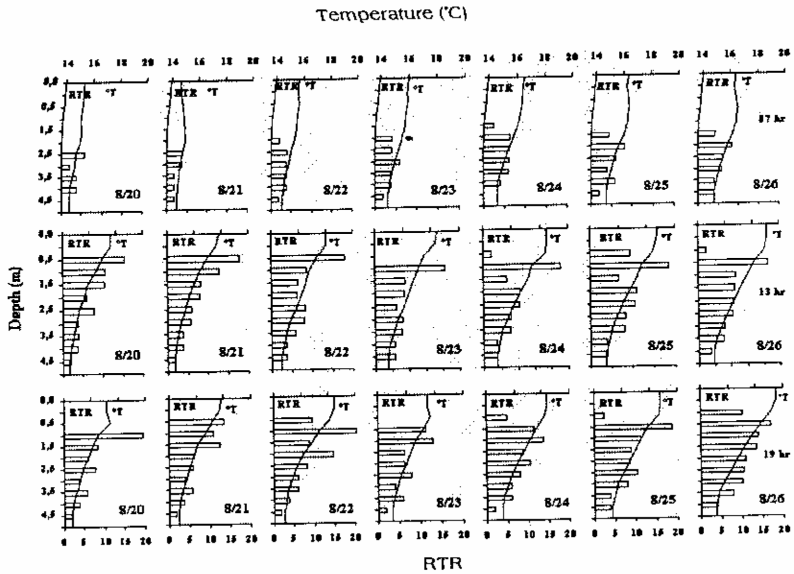

Figure 1: Water temperature (°C) and relative thermal resistance (RTR) vertical profiles during the period from 20 to 26/August/1996.

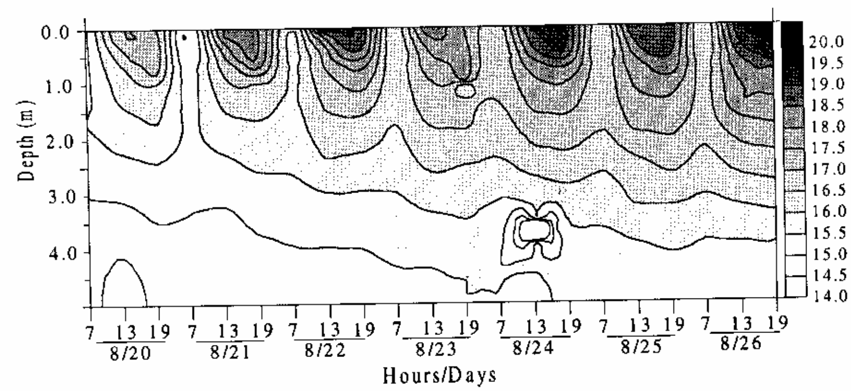

Figure 2: Depth and time temperature (°C) isolines during the period from 20 to 26/August/1996.

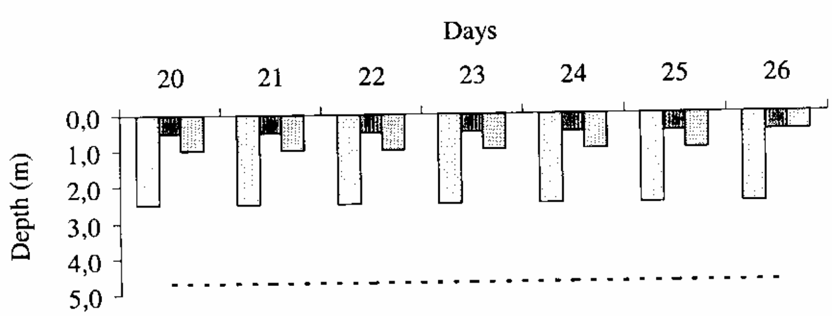

Figure 3: Mixing zone (m) daily depth variation during the period from 20 to 26/August/1996.

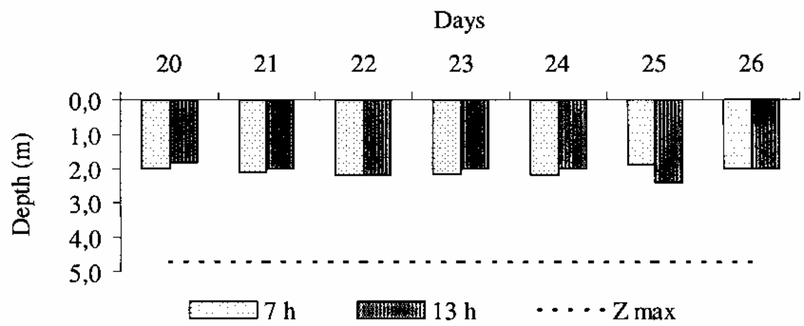

Figure 4: Water transparency daily variation during the period from 20 to 26/August/1996.

According to Esteves (1998), high transparency together with low turbidity values suggest the presence of little suspended material in the water column. Presence of little suspended material in the IAG reservoir was related to the absence of rain during the period and the consequent absence of allochthonous material input into the reservoir. If compared to those from the surface, highest values observed at the deepest part of the reservoir would probably derive from liberation of compounds resulting from decomposition of organic matter at the bottom of the system (Fig. 5). Seasonal transparency difference with decrease during the rainy season and increase during the dry one was observed also by Henry (1990) in the Jurumirim reservoir, state of São Paulo.

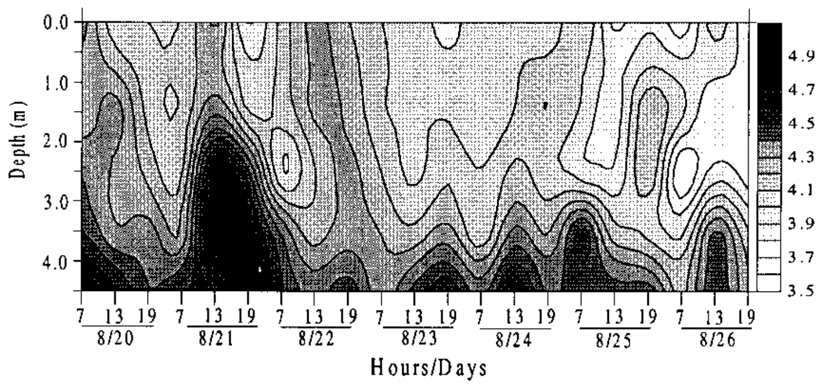

Figure 5: Depth and time turbidity (NTU) isolines during the period from 20 to 26/August/1996.

Presently detected comparatively low values (0.71-0.94) of the vertical attenuation coeficient (*k*) suggest low radiation attenuation, presence of few chemical compounds in the water, and deep light penetration in the reservoir. Such observations are reinforced if the extension of the euphotic zone and the high luminosity in the water column are analyzed (Fig. 6).

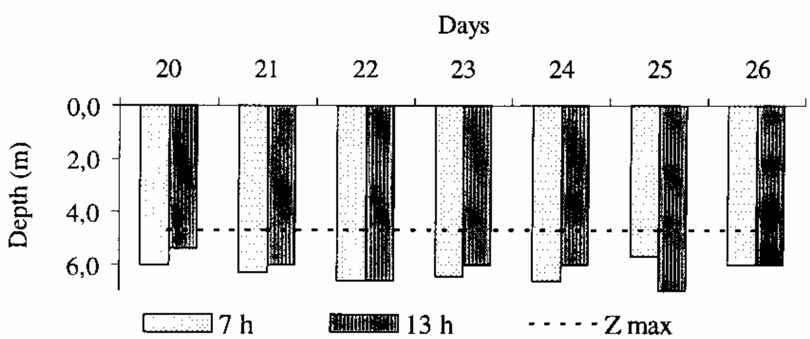

Figure 6: Euphotic zone (m) daily variation during the period from 20 to 26/August/1996.

Rainy period (22-28/January/1997)

During the rainy period, compared to the dry one, increases of air and water temperature values were also followed by greater stability of the water column at all days and hours studied. Thermal and density gradients demonstrated that the reservoir presented a strong tendency towards daily stratifications from 07:00 hr on. Definite thermoclines were identified at 13:00 and 19:00 hr. Opposite to the dry period, RTR values were higher mainly between 1 and 2 m depth, including at 07:00 hr but not on day 28, probably indicating the non-existence of mixing of the water column during night hours. Thermoclines were positioned between 1 and 2 m depth, as a consequence of the greatest values of the RTR. It was possible to detect a tendency towards mixture of the water column on day 28, at 07:00 hr, and stratification at 13:00 and 19:00 hr of all other sampling days and hours (Fig. 7-8).

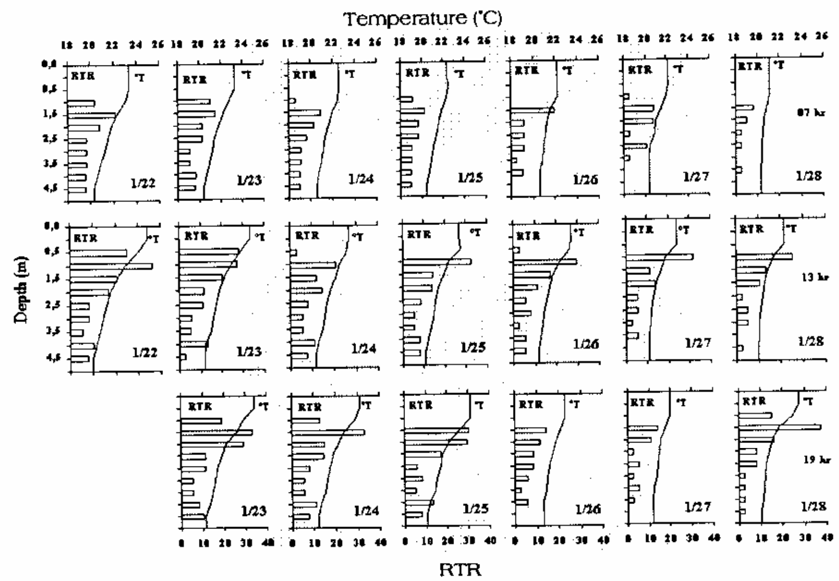

Figure 7: Water temperature (°C) and relative thermal resistence (RTR) vertical profiles during the period from 22 to 28/January/1997.

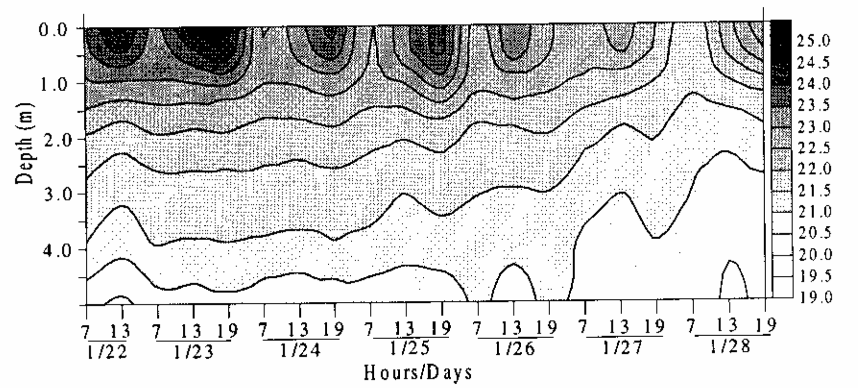

Figure 8: Depth and time temperature (°C) isolines during the period from 22 to 28/January/1997.

Comparison of the two periods studied regarding depth of the mixing zone showed that variation of the extension of Z_{mix} was much more pronounced during the rainy period and that there was a marked decrease of Z_{mix} during the latter period at 07:00 hr. It also indicated a much greater stability of the water column during that hour compared to the dry period (Fig. 9).

Temperature differences between reservoir's surface and bottom were higher than 1.5°C and ranged up to 4.6°C, except for day 28, at 07:00 hr, when there was a strong tendency towards mixture of the water column as detected by the low RTR values at that time compared to the other hours (Fig. 7).

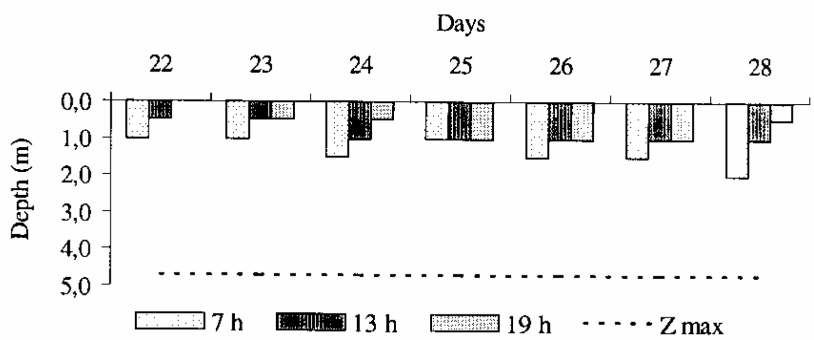

Figure 9: Depth of mixing zone (m) daily variation during the period from 22 to 28/January/1997.

In spite of being detected very well defined surface thermoclines, a typical hypolimnion was never observed. However, thermal stability of the water column was followed by stratification of the physical and chemical characteristics of reservoir (non published data), thus indicating that the water column was stratified during this period.

Similarly to the dry period, in the rainy one despite the wind speed being a little greater (1-3.2 $m.s^{-1}$) its strength was not enough to break the RTR barrier and mix the water column. Thermal discontinuity of metalimnion represented an effective barrier against mixture, and it is necessary a large amount of energy to break it down (Wetzel, 1993). According to Reynolds (1994), the most important factors for generation of turbulence are its own intensity and the space available for its dissipation. The least the depth the highest the dissipation rate. In the present study, energy dissipation rate values (1.39×10^{-8}-1.59×10^{-7} $m^2.s^{-3}$) were inversely proportional to the depth of the mixing zone. According to Ramírez (1996), dissipation of turbulence generating energy probably present in the mixing zone, whose depth varied from 0.5 to 1.5 m, was frenated by the high thermal resistance detected during the whole period.

Water transparency was lower in the rainy (Fig. 10) than in the dry period, but turbidity was greater. A heterogeneous turbidity distribution pattern in the water column was observed, the greatest values detected at the bottom of the reservoir (Fig. 11), a fact testified by the high variation coeficients. Such high values at the bottom are related to the water column stratification pattern.

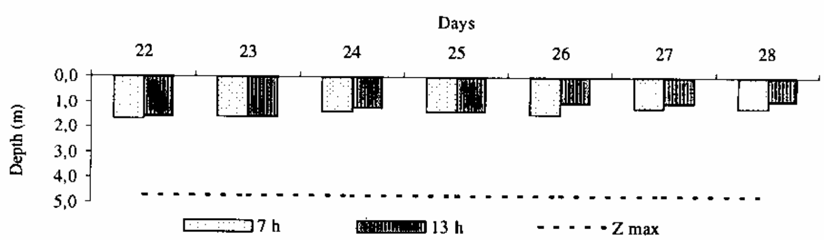

Figure 10: Water transparency daily variation during the period from 22 to 28/January/1997.

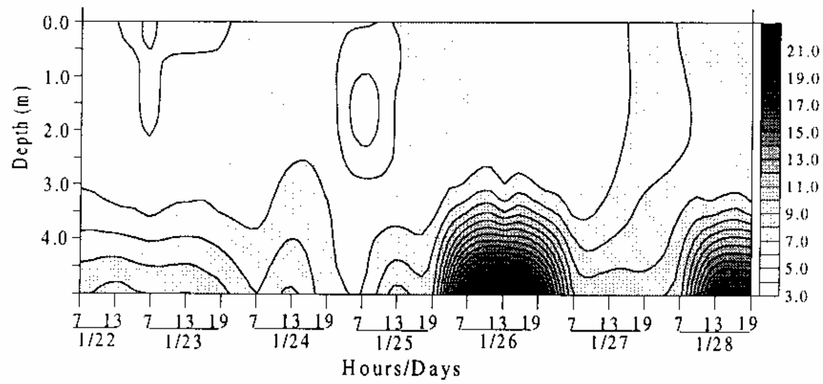

Figure 11: Depth and turbidity (NTU) isolines during the period from 22 to 28/January/1997.

During the rainy period, turbidity showed considerable relationship with precipitation thus coinciding with Henry & Curi's (1981) observations of the same kind of dependence in the River Pardo reservoir. At the IAG reservoir daily precipitation bringing allochthonous material into the reservoir and consequently increasing turbidity, contributed to the decrease of water transparency. Precipitation always occurred towards the end of the afternoon or early night hours, thus most probably explaining the greater water turbidity in the next day (Fig. 12). Beyruth (1996) and Moura (1996) demonstrated the same influence of precipitation on turbidity in two reservoirs located in the municipality of São Paulo, respectively Gurapiranga and Garças. In both cases, turbidity increased with precipitation.

Despite vertical attenuation coeficient (*k*) values being greater in the rainy than in the dry period, they also were relatively smaller indicating low light radiation attenuation, presence of few chemical compounds in the water, and high light penetration in the reservoir. Smallest values occurred during the hours in which the greatest depths for the Secchi disk were observed. Similar observations were made in other Brazilian freshwater systems as documented in Esteves (1998).

Values of the euphotic zone depth were smaller during the rainy period than in the dry one. Such values indicated existence of high luminosity in the whole water column (Fig. 13). Ratio Z_{euf} : Z_{af} calculated for the days in which an aphotic zone was present was greater than 1.0 and meant consequent existence of a greater illuminated zone.

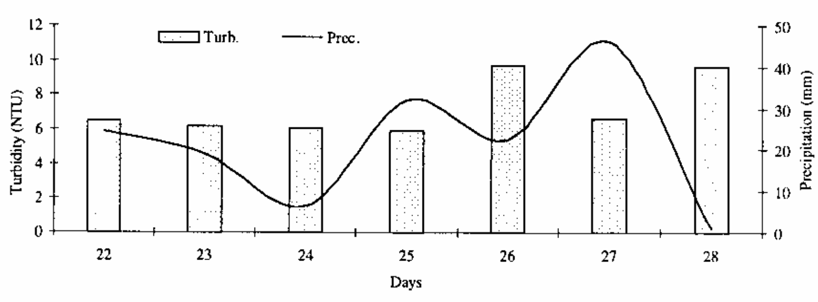

Figure 12: Turbidity and precipitation daily variation during the period from 22 to 28/January/1997.

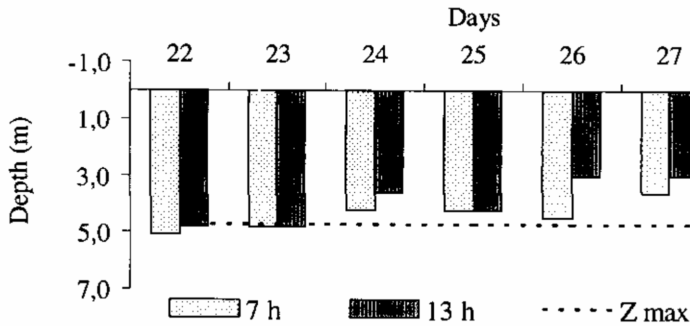

Figure 13: Euphotic zone depth daily variation during the period from 22 to 28/January/1997.

Euphotic zone depth and water transparency reduction with consequent decrease of the Z_{eut} : Z_{at} ratio as well as increases of turbidity and *k* values observed daily from 07:00 to 13:00 hr showed that light penetration in the water column was attenuated. It seems that such an attenuation was much more due to the presence of allochthonous material. According to Ramírez (1996), light attenuation and turbidity at Garças reservoir during mainly the spring was due to the increase of phytoplankton density. At the IAG reservoir, however, chlorophyll *a* values (non published data) indicated how small was the participation of the chlorophyllated organisms as a factor for light attenuation. Such observations corroborate Henry's (1990) conclusions for Jurumirim reservoir, in the state of São Paulo.

In spite of the thermal profiles in this study included just a brief period and did not include measurements at the dark part of day, observations carried out daily at 07:00 hr of both rainy and dry periods led to conclude that the reservoir presented night mixtures during the whole dry period and long lasting stratifications (with just one night mixing) during the rainy period. Such observations, however, are far from being final. They simply demonstrate a short term tendency.

Arcifa *et al.* (1990) and Huszar & Reynolds (1997) classified as warm discontinuous- and continuous polymictic, respectively, Lake Monte Alegre in the state of São Paulo and Lake Batata in the state of Pará. Arcifa *et al.* (1990) reported that, according to Lewis (1983b) Lake Monte Alegre should be classified as warm discontinuous polymictic because of its geographical location and of its small depth. On the basis, however, of the different mixing patterns displayed in its deepest and shallowest regions Lake Monte Alegre definitely presented both continuous and discontinuous warm polymictic characteristics. The latter authors also emphasized that there are several exceptions among shallow equatorial lakes, indicating that dynamic and static regional climatic factors are very and as important as the water body hydrologic characteristics (Arcifa *et al.*, 1990). Huszar & Reynolds (1997) considered Lake Batata continuous polymictic during the mixing period and discontinuous polymictic during the stratification one.

Conclusions

IAG reservoir thermal behaviour was influenced by seasonal events and was distinct during the two periods studied. Reservoir is a warm discontinuous polymictic system, whose mixing and stability patterns were primarily dependent on the air temperature influence on the water column, and secondarily on the wind action which was restrict to the reservoir surface. Highest RTR values were observed during the rainy period and circulation was, in both periods, restrict to the reservoir surface. Mixing zone depth extension was smaller during the rainy period thus indicating the greater stability of the water column during that period when compared to the dry one. Stratifications were temporary during the dry period, with possible circulation at night, and long lasting during the rainy period, when possible circulation indication was never detected, except for the day 28/January/1997 at 07:00 hr. In other words, thermal stratifications were not as stable during the dry period as they were in the rainy one. But, there always was strafication, temporary during the dry and long lasting during the rainy period. A typical hypolimnion, however, was never observed in both periods studied.

Changes in the optical properties of the IAG reservoir water were directly related to the input of allochthonous material brought by rain. There is a clear seasonal difference of water transparency which is higher in the dry than in the rainy period, thus demonstrating a close relationship of the first with the last one. During the dry period, water column was illuminated from surface to bottom; during the rainy period it also started entirely illuminated, but illumination was reduced to 50% towards the last sampling days. Ratio $Z_{eut} : Z_{mix}$ was always greater than 1, thus meaning that the mixing zone was always illuminated.

Despite turbidity values were considered low during the two periods studied, a vertical distribution pattern for that characteristic was evident during the rainy one with increase at the reservoir's deepest layer due to the greater input of allochthonous material by rain. Radiation attenuation was low, a fact proven by the low vertical attenuation coeficient values detected during both periods. These facts indicated presence of few chemical compounds in the water and high light penetration in the reservoir. There was no evidence of light penetration attenuation in the reservoir due to the phytoplankton community density.

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