Longitudinal patterns and variations in water quality in a reservoir in the semiarid region of NE Brazil: responses to hydrological and climatic changes

Padrões longitudinais e variações na qualidade da água em um reservatório da região semi-árida do nordeste do Brasil: respostas a mudanças hidrológicas e climáticas

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Abstract: Aim: The main goal of this research was to investigate the changes in water quality and longitudinal patterns of the Pacajus Reservoir in response to alterations in hydrological and climatic conditions during the dry and rainy seasons; **Methods:** Four sites, located along the main longitudinal axis of the reservoir, were sampled bimonthly. Samples for chemical analysis were collected in depths corresponding to the surface, middle and bottom of the water column, while physical variables and dissolved oxygen were measured in regular intervals from subsurface to near the bottom sediments with a multiparametric probe. Samples for chlorophyll-*a* analysis were collected only in the surface of the water column; **Results:** The reservoir was particularly susceptible to wind action, especially during the second semester, when resuspension of the bottom sediments, internal phosphorus load and reduction in water transparency were observed. The rainy period was essentially characterized by the enrichment of the reservoir by the inflows from the Choró River and the greater longitudinal gradients between the fluvial and lacustrine zones. The decomposition of the flooded phytomass and deposition of the allochtonous material at the transitional zone of the Pacajus Reservoir gave rise to oxyclines in April and June/99. The longitudinal pattern of the reservoir revealed a superior zone, with high algal biomass during the dry period and probably light-limited during the rainy period; an intermediary site, characterized as a sedimentation and decomposition zone; and a lacustrine zone, optically deep and with low algal biomass variability throughout the research; **Conclusions:** With relation to nutrient dynamics, the Pacajus Reservoir was dependent on the loads from the Choró River inflows during the rainy period, and on the internal regeneration during the dry period, a process favored by high water temperatures and by the instability of the water column.

Keywords: Pacajus Reservoir, semiarid Brazilian region, water quality, internal phosphorus load, spatial-temporal heterogeneity.

Resumo: Objetivo: Esta pesquisa teve como principal objetivo investigar as mudanças na qualidade da água e no padrão de zonação longitudinal do Açude Pacajus em resposta às alterações no regime hidrológico e nas condições climáticas durante os períodos seco e chuvoso; **Métodos:** Quatro locais, distribuídos ao longo do eixo longitudinal principal do reservatório, foram amostrados com periodicidade bimestral. Amostras para análises químicas foram coletadas em profundidades correspondentes à superfície, meio e fundo da coluna de água, enquanto variáveis físicas e oxigênio dissolvido foram medidos em intervalos regulares, da sub-superfície às proximidades dos sedimentos de fundo, com o auxílio de sonda multiparamétrica. Amostras para análise de clorofila *a* foram coletadas somente na superfície; **Resultados:** O reservatório mostrou-se particularmente susceptível à ação desestabilizadora do vento, forçante climática atuante principalmente durante o segundo semestre, quando foram observados resuspensão dos sedimentos de fundo, carga interna de fósforo e redução da transparência da coluna de água. No período chuvoso, enriquecimento das águas do reservatório ocorreu pelas águas afluentes do Rio Choró e maiores gradientes longitudinais foram observados entre as zonas fluvial e lacustre. A decomposição da fitomassa submersa e a sedimentação de material alóctone na região intermediária do Açude Pacajus determinaram a formação de oxiclinas nos meses de Abril e Junho/99. A zonação longitudinal do reservatório destacou um compartimento superior, com elevada biomassa algal no período seco e provavelmente limitado pela luz durante o período chuvoso; um compartimento intermediário, caracterizado como uma zona de sedimentação e decomposição; e uma região lacustre, opticamente profunda e com pequena variabilidade na biomassa fitoplanctônica; **Conclusões:** Em relação à dinâmica de nutrientes, o Açude Pacajus apresentou-se dependente das cargas provenientes do Rio Choró durante os pulsos de chuva e da regeneração interna durante o período seco, processo favorecido pelas altas temperaturas da água e pela instabilidade da coluna de água.

Palavras-chaves: Açude Pacajus, semi-árido brasileiro, qualidade de água, carga interna de fósforo, heterogeneidade espaço-temporal.

1. Introduction

According to the classification proposed by Straskraba (1990), the great majority of reservoirs in Ceará (NE Brazil) are shallow (z_{max} < 30 m), a morphometric characteristic that makes them susceptible to the action from external agents, as the wind. In addition, the climatic characteristics of the region, typically semiarid, exerts substantial effects on the hydric availability, since the climatic conditions, characterized mainly by high evaporation rates and a short and irregular precipitation cycle, cause significant water losses, resulting in a negative hydric balance. The effect of the evaporative losses is more significant in dry years, when the water availability may become a critical factor to the region's economic development. Considering the hydric losses, the primary effect on the quality of the water stored in reservoirs is the increment in concentrations of dissolved salts, as normally occurs. However, with a growing population and low covering of sanitation services, the water bodies of Ceará have undergone extensive pollution-loads, especially from domestic sewage, discharged directly into the main tributaries. This scenario has contributed to increasing nutrient levels in the water column, resulting in the increment of algal density and frequency of cyanobacteria blooms, putting on alert the water resources management system of Ceará. However, in spite of the strategic importance of the region's social-economic development, the State of Ceará lacks limnological knowledgement on its reservoirs as a powerful tool in water quality management, until recently based in quantitative aspects, always prioritized by state politics. Although some assays have investigated the water quality stored in Ceará's Reservoirs, they have partially conducted short-term projects, without further continuity. In addition, the monitoring programs of water resources, notwithstanding collecting a great quantity of physical, chemical and biological data, lack the methodological procedures to transform them into useful information in order to manage the reservoirs' water quality. Considering this reality, the following question could be asked: Is it possible to manage what it is not known? In response to this situation a study was carried out at the Pacajus Reservoir with the main purpose of gathering knowledge concerning the system's responses to seasonal changes in hydrological and climatic conditions, especially in terms of alterations in water quality and longitudinal patterns.

2. Catchment Area

The Pacajus Reservoir was constructed by damming the Choró River as an alternative to the Water Supply System of the city of Fortaleza and its metropolitan area. The system comprises four reservoirs linked by tunnels and canals and provides water both for human and industrial use. As is typical in most of the State of Ceará, the Choró River basin is dominated by a crystalline stratum, a geological feature that favors surface runoff and makes the subsurface flow less important – a mechanism responsible for the maintenance of continuous rivers in other regions of the country (Ceará, 1999). The Pacajus Reservoir has a 240 hm^3 capacity and a 2.1 $m^3.s^{-1}$ outflow. During the research period, its mean residence time was superior to 1 year. According to the classification proposed by Straskraba (1990), the reservoir could be considered as a shallow system, with a mean depth of 3.4 m during the research (z_{max} < 10.0 m) (Freire, 2007).

The local pluviometric conditions are characterized by temporal and spatial heterogeneity, with 65 to 70% of the annual precipitation concentrated in the February/April or March/May trimesters, while the evaporation rates are more significant in the second semester (Figure 1a). During the rainy season, the relative air humidity is frequently over 80%, with the highest values occurring in the humid trimester of March/April/May (Ceará, 1999). However, especially between September and November, corresponding to the dry season, there is a significant reduction in these values. The insolation regime can be characterized as slightly variable (2,650 to 3,000 $hours.year^{-1}$; Ceará, 1999), with the greatest values observed in the dry months (Figure 1b).

High air temperatures and strong winds, especially during the second semester (Figure 2a, b), contribute to significant evaporation rates and water losses in the Ceará reservoirs (Ceará, 1999). Annual evaporation means measured in Class A Pans vary from 2,300 to 2,800 mm. The daily average evaporation rate is 3.5 to 4.5 $mm.day^{-1}$, reaching 12 $mm.day^{-1}$ during the dry months (Ceará, 1999). Although meteorological and geological factors can severely restrict the amount of stored water, the reservoirs that comprise the Water Supply System are the main hydric reserves for human and industrial demands for the city of Fortaleza and its metropolitan region.

3. Material and Methods

The Pacajus Reservoir was sampled bimonthly between December/98 and November/99, with two samplings in the rainy season (February and April/99) and four in the dry period: December/98 (first sampling), June, August and November/99. The sampling stations (PJ01, PJ02, PJ03 and PJ04) were located along the longitudinal Choró River-dam axis (Figure 3). Vertical profiles of pH, dissolved oxygen (DO), electrical conductivity (E.C.), turbidity and water temperature were determined in situ using a portable multiprobe meter (Horiba, model U-10; Kyoto, Japan). Measurements were taken at regular intervals from the subsurface to near the bottom sediments. Turbidity, E.C., pH and DO electrodes were calibrated with the respective standard solutions in accordance to the manufacturer's manual.

Samples for dissolved inorganic phosphorus (DIP), total phosphorus (TP), ammoniacal nitrogen (NH_3 + NH_4^+ – N), nitrate (NO_3^- – N), nitrite (NO_2^- – N), calcium

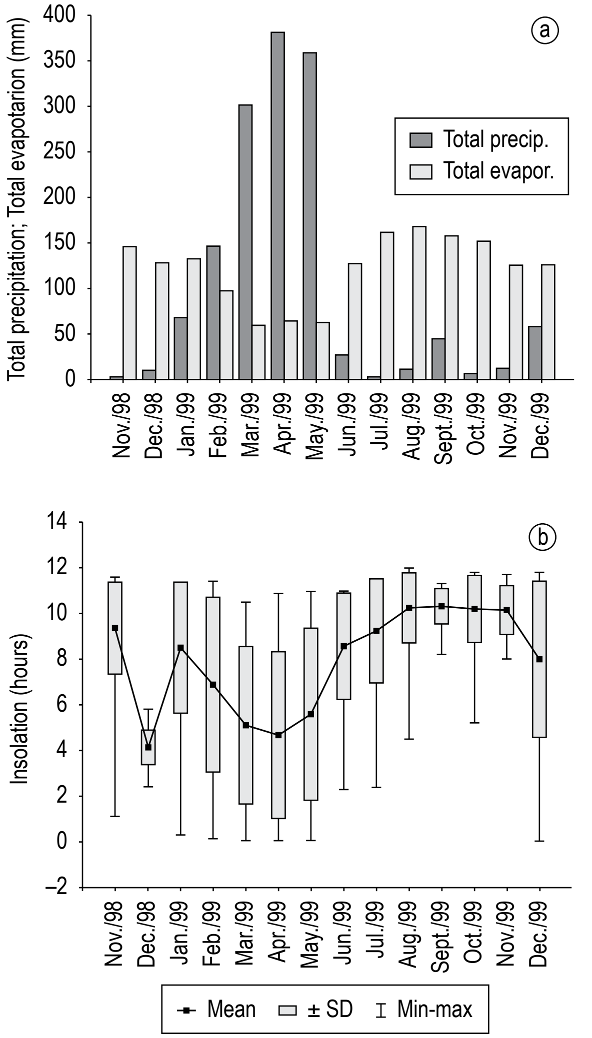

Figure 1. a) Totals of precipitation and evaporation and b) monthly means of insolation on the hydrographic basin of the Pacajus Reservoir.

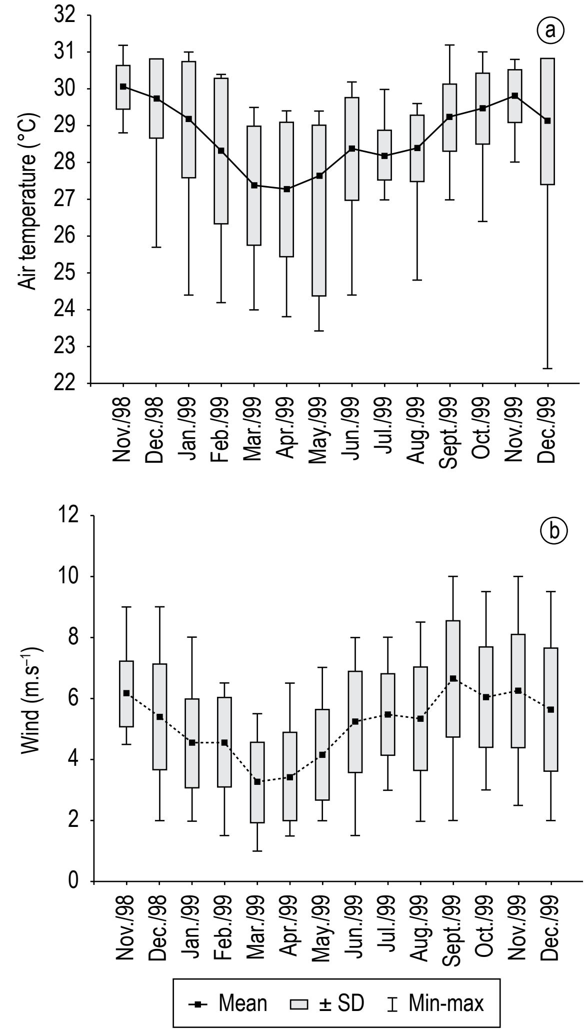

Figure 2. a) Monthly means of air temperature and b) wind velocity on the hydrographic basin of the Pacajus Reservoir.

(Ca^{2+}), magnesium (Mg^{2+}) and total alkalinity analysis were collected with a horizontal Van Dorn sampler at depths corresponding to the surface, middle and bottom of the water column. Samples for dissolved nutrients analyses were filtered using pre-combusted glass fiber filters (Whatman GF/F, Whatman; Maidstone, UK) and were kept frozen until analytical procedures. All the samples were analyzed according to the analytical methods described in APHA (1992). Samples for chlorophyll-*a* analysis were collected from the subsurface, preserved by adding 1.0 mL of a 1.0% solution in $MgCO_3$, filtered onto glass fiber membranes (Whatman GF/F), and, subsequently, extracted with 90% acetone solution. Chlorophyll concentrations were calculated after corrections for pheophytin, as recommended by APHA (1992). The carbon dioxide, CO_2 (free and total), bicarbonate, HCO_3^-, and carbonate, CO_3^{2-} ion concentrations were estimated from the corresponding data of water temperature, total alkalinity and pH (APHA, 1992). The water transparency (z_{sd}) was determined with a 30 cm diameter Secchi disk, while the vertical attenuation coefficient was calculated according to Kirk (1986). Dissolved oxygen saturation was calculated according to Straskraba and Tundisi (1999). Water sampling and probing were performed between 9:00 and 12:00 hours, beginning in the fluvial zone and ending near the dam.

In order to evaluate the longitudinal patterns in the reservoir during the dry and rainy seasons, a Cluster analysis was performed using UPGMA agglomeration method (unweighted pair-group method) and the Euclidian distances as similarity index. Prior to performing statistical analysis, the data were separated in two sets corresponding to the dry and rainy periods. Then, the data were standardized according to procedures described in the "User Manual" of the Statistica 6.0 (Statsoft. Inc., 2001) - package used to perform all the statistics presented in this manuscript. Surfer 7.0 software (Golden Software, 1999) was used for the construction of the isopleth graphics. The climatological data were provided by Fundação Cearense de

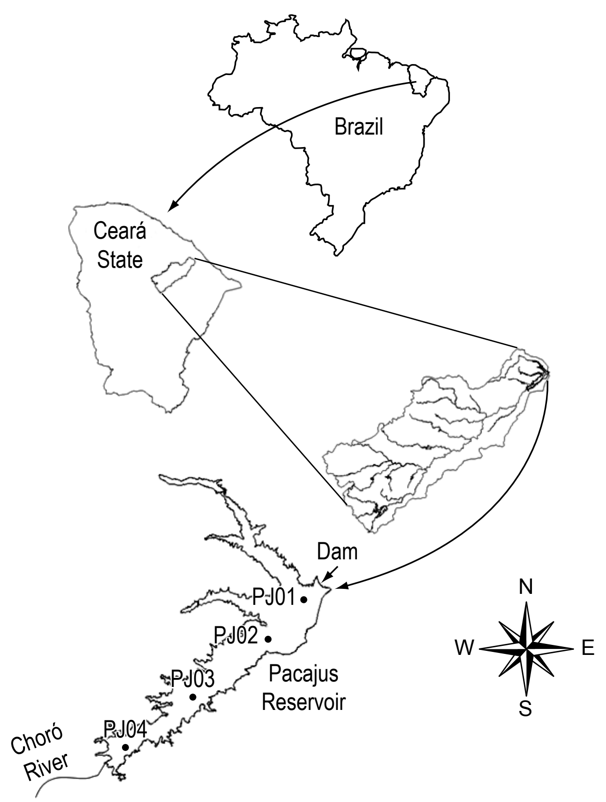

Figure 3. Sampled sites and localization of the Pacajus Reservoir.

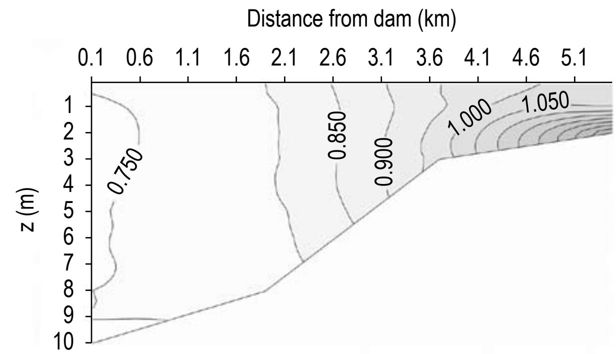

Figure 4. Isopleths of E.C. ($mS.cm^{-1}$) along the Choró River-dam axis. August/99.

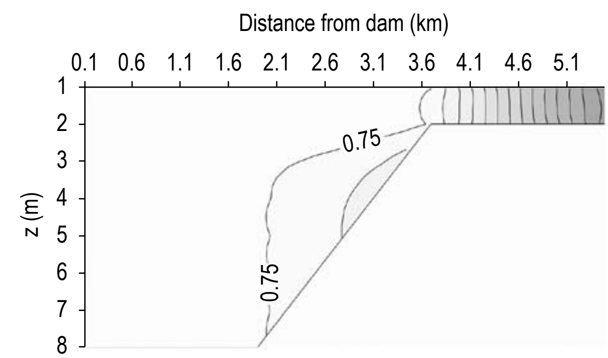

Figure 5. Isopleths of E.C. ($mS.cm^{-1}$) along the axis Choró River-dam axis. June/99.

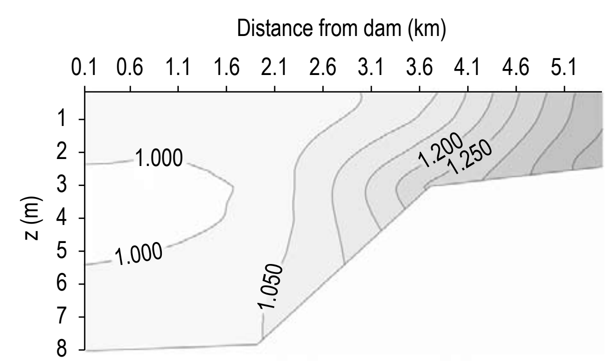

Figure 6. Isopleths of E.C. ($mS.cm^{-1}$) along the Choró River-dam axis. April/99.

Meteorologia (FUNCEME) and by the Instituto Nacional de Meteorologia (INMET). The stored volumes at the Pacajus Reservoir during the research were provided by the Companhia de Gestão dos Recursos Hídricos do Estado do Ceará – COGERH.

4. Results

Isopleths of electric conductivity (E.C.) along the main longitudinal axis of the Pacajus Reservoir were predominantly vertical in every month sampled, especially in the lacustrine zone. In August/99, a prominent vertical gradient of 0.398 $mS.cm^{-1}.m^{-1}$ was observed in the riverine region (Figure 4), a significant value considering its shallow depth (z_{max}: 1.5 m). This behavior contrasted the general pattern found in June (Figure 5) and even in August/99, when an isothermy tendency and insignificant vertical saline gradients were observed. The greatest saline longitudinal gradients were registered during the rainy season, especially in the fluvial zone. This reservoir site showed the highest E.C. values throughout the research. However, isopleth arrangements showed smoothness of the longitudinal gradients of E.C. towards the dam (Figure 6). When observing the temporal dimension, the E.C. means showed an increment in the course of the year, with the higher ones registered during the second semester, which correspond to the dry period. The lowest monthly E.C. mean (0.777 $mS.cm^{-1}$) was observed in June/99, while in December/98 (end of the dry season), the greatest mean (1,220 $mS.cm^{-1}$).

The small water temperature variation between the rainy and dry seasons (Table 1) followed the typical seasonal behavior of air temperature in the Brazilian semiarid region, where only slight differences prevail between the months. During the dry season, mainly in the lacustrine zone, the vertical position of the isotherms confirmed the instability of the water column, resulting in the absence or only small vertical gradients. In fact, in this period, the discreet vertical gradients, even in the reservoir's deepest region (PJ01 site; z_{max}: 10.0 m) were not enough to cause a vertical compartmentalization (Figure 7).

The efficient mixing of the water column in the lacustrine zone, which occurred mainly in June and August/99, when strong winds were registered, was confirmed by the smallest differences between surface and bottom temperatures near the dam (PJ01: 0.2 °C; August/99) (Figure 8). Even at the PJ02 site (z_{max}: 8.5 m), located in a reservoir site where the environmental conditions, such as tree trunks, could limit wind action, a ΔT of 0.4 °C between surface and bottom layers was recorded (August/99). The maximum vertical gradient in June/99 was 0.2 °C.m^{-1} (PJ02), characterizing an isothermal situation in all the reservoir.

In the rainy season, the predominance of horizontal isotherm arrangements revealed a greater vertical stability of the system (Figure 9). This physical behavior resulted in the highest temperature differences between the surface and the bottom at the PJ02 site: 0.8 °C (February/99) and 0.9 °C (April/99). However, especially at the PJ01 site, located in the lacustrine zone, the slight temperature decrease along the vertical profile was not favorable to the formation of thermoclines. In April/99, the warmer and denser inflows from the Choró River by lower layers of the water column as an underflow, originated a negative thermal gradient of –0.3 °C.m^{-1}.

The OD concentrations were typical of sub-saturation during the rainy season; in February and April/99, it was registered the lowest means during the survey (4.00 and 4.08 mgO_2.L^{-1}, respectively). In this period, the chlorophyll-*a* mean concentrations (February/99: 29.18 µg.L^{-1}; April/99: 27.45 µg.L^{-1}) were lower than in December/98 (94.10 µg.L^{-1}), month formerly sampled.

In April and June/99, DO profiles at site PJ02, located in the transition zone, evidenced considerable vertical gradients, creating sharp oxyclines (Figure 10; 2.60 and 5.95 mgO_2L^{-1}.m^{-1}). This zone of the reservoir had not been cleared prior to filling and contains a considerable quantity of flooded phytomass (tree trunks that emerge

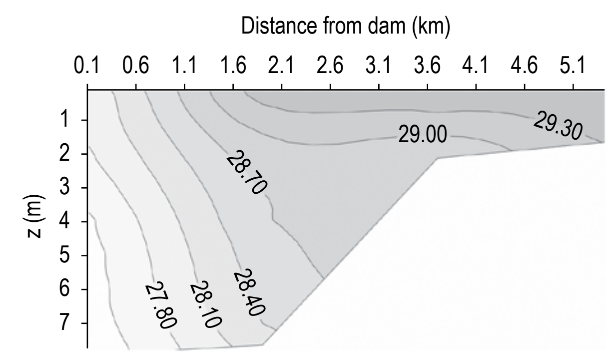

Figure 7. Isopleths of water temperature (°C) along the Choró River-dam axis. November/99.

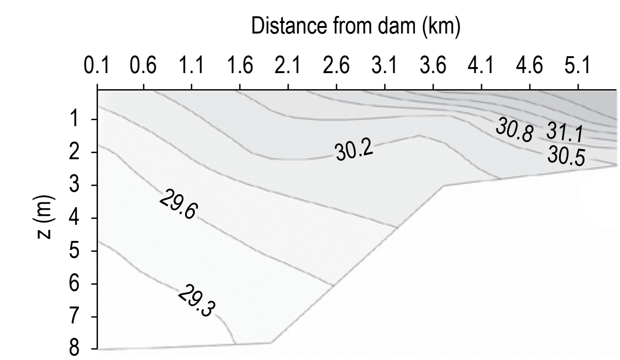

Figure 9. Isopleths of water temperature (°C) along the Choró River-dam: a) February/99 e b) April/99.

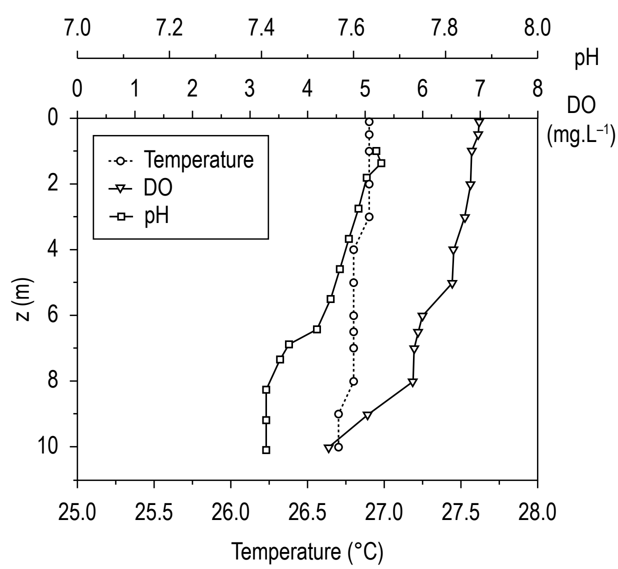

Figure 8. Vertical profiles of water temperature, DO and pH corresponding to site PJ01 site. August/99.

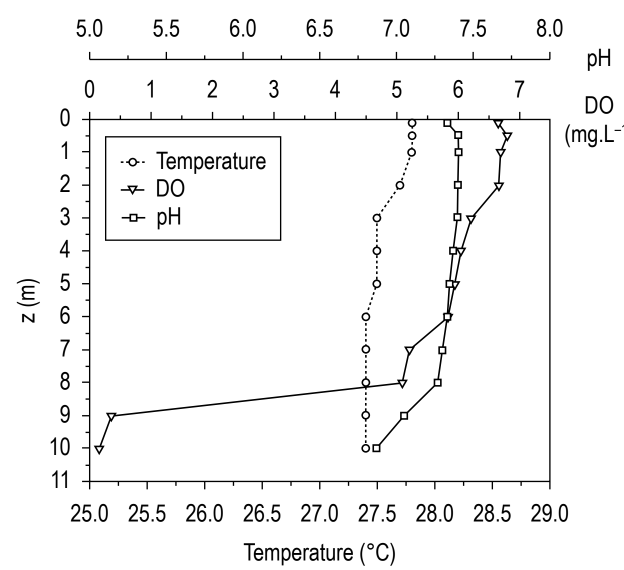

Figure 10. Vertical profiles of water temperature, DO e pH corresponding to site PJ02 site. April/99.

more or less completely). DO concentrations, typical of supersaturation conditions, were found in June/99 in all the reservoir, even below the euphotic zone (z_{eu}) at most sampling sites. In contrast, reduced DO concentrations were found in August/99 when compared to June/99, with values typical of sub-saturation. Also in August/99, the isopleth arrangements clearly showed an "intrusion" of less oxygenated waters from the bottom up to the surface in the intermediary zone of the reservoir (Figure 11a). With the exception of the site PJ02, the DO vertical gradients were low, without the formation of oxyclines. Spatially, the lacustrine and riverine zones indicated the highest concentrations, mainly during the dry period. The PJ04 site showed the highest supersaturation value in December/98: 12.53 $mgO_2.L^{-1}$ at the surface (≅ l60 %).

The pH values were in the neutral-alkaline range, from 6.87 to 9.28. The pH isopleths arrangements showed a close resemblance to the DO ones, as can be seen for August/99 (Figure 11b). The maximum pH value (9.28) was registered in December/98 at site PJ04. Also in this site, the highest chlorophyll-*a* concentration (256.32 $\mu g.L^{-1}$) was observed. The highest vertical pH gradient (0.32 m^{-1}) was registered at site PJ02. However, in general, the vertical and longitudinal gradients of pH were mild.

The high total alkalinity values in the Pacajus Reservoir confirmed the buffering nature of its waters. The highest monthly means were observed in the rainy season (February/99: 1.87 $meqCaCO_3.L^{-1}$;

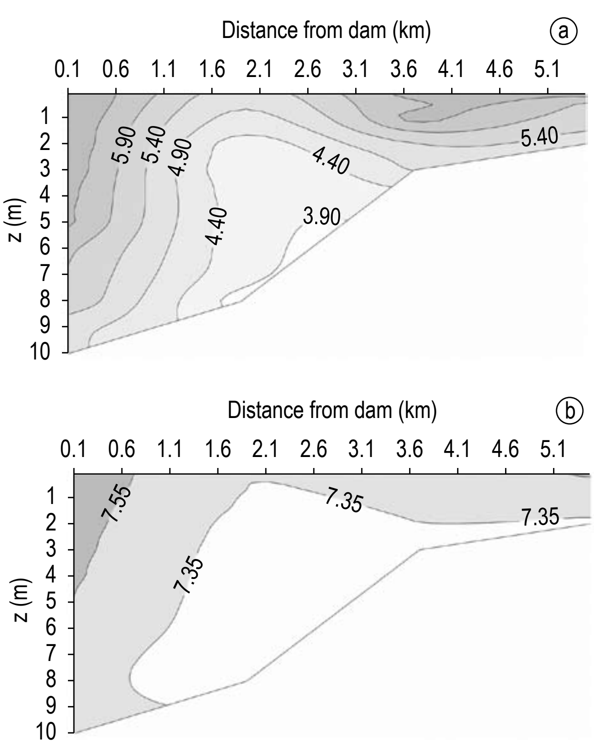

Figure 11. Isopleths of a) DO ($mg.L^{-1}$) and b) pH along the Choró River-dam. August/99.

April/99: 1.74 $meqCaCO_3.L^{-1}$) and in November/99: 1.87 $meqCaCO_3.L^{-1}$). The mean values tended to increase from June to November/99: 1.56 $meqCaCO_3.L^{-1}$ (June/99); 1.64 $meqCaCO_3.L^{-1}$ (August/99) and 1.87 $meqCaCO_3.L^{-1}$ (November/99) (Table 2). In the pH range observed, there was a predominance of bicarbonate ions (HCO_3^-), although there were considerable concentrations of carbonate ions (CO_3^{2-}) in the riverine and lacustrine zones. The lowest total alkalinity values registered at site PJ03 (June/99) corresponded to high chlorophyll-*a* concentrations in the transitional zone, giving rise to a negative correlation coefficient between these two variables (r^2: –0.9364, p: 0.0060). The minimum total alkalinity value measured during the whole research period was 0.65 $meqCaCO_3.L^{-1}$ (PJ04; December/98), which corresponded to the highest chlorophyll-*a* concentration in the reservoir waters: 256.32 $\mu g.L^{-1}$.

In December/98, dissolved inorganic phosphorus concentrations (PID) were undetectable at sites PJ01 and PJ04, where the highest chlorophyll-*a* concentrations were found (56.91 and 256.32 $\mu g.L^{-1}$, respectively; Table 3). Although the reservoir waters had been enriched during the rainy season (February and April/99), as confirmed by the increase of the PID concentrations in the riverine zone, there was no algal biomass increment when compared to December/98. The water enrichment of the Pacajus Reservoir during the rainy season was responsible for the highest monthly PT mean (43.00 $\mu mol.L^{-1}$), observed in February/99. In June/99, a month characterized by DO supersaturation in the entire reservoir, the PID concentrations decreased, resulting in a monthly mean (0.36 $\mu molPO_4^{3-} – P.L^{-1}$) lower than for the rainy months. On the other hand, greater concentrations of PID (mean: 0.79 $\mu molPO_4^{3-} – P.^{-1}L$) were recorded in August/99. Similarly, there was an increase in TP concentrations, resulting in a mean of 15.53 $\mu mol.L^{-1}$. Compared to June/99, a reduction in DO mean concentration (5.58 $mg.L^{-1}$) was detected in August/99. Among the dry months, the highest PT mean concentration (17.59 $\mu mol.L^{-1}$) was found in December/98 which coincided with the highest chlorophyll-*a* values observed.

Water transparency was at its lowest in the riverine zone, with minimum values of euphotic zone, z_{eu}, in December/98 and February/99 (0.20 and 0.30 m, respectively). This reservoir site was characterized by high turbidity and phytoplankton biomass for most of the year. In December/98, the maximum turbidity value in the Pacajus Reservoir (380 NTU) was coincident with the highest chlorophyll-*a* concentration in the reservoir waters (256.32 $\mu g.L^{-1}$). In February/99, despite the significant reduction in chlorophyll-*a* in this zone (40 $\mu g.L^{-1}$), the turbidity remained high (276 NTU). The highest z_{eu} (4.65 m) was observed in February/99 at site PJ02 (z_{max}: 7.0 m). The lacustrine zone presented the lowest variability in water transparency among the sampled sites during the study. In

Table 1. Minimum, maximum and mean (±SD) values of Water Temperature (°C), Electrical Conductivity - E.C. ($mS.cm^{-1}$), Turbidity (Turb., NTU), pH, Dissolved Oxygen - DO ($mg.L^{-1}$) and Euphotic Zone - Z_{eu} (m).

	Temp.			E.C.			Turb.			pH			OD			Z_{eu}		
	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.
December/98	27.7	30.5 ± 0.9	29.0	1.130	1.25 ± 0.13	1.990	21	70 ± 117	380	7.19	7.75 ± 0.64	9.28	3.72	6.44 ± 2.52	12.00	0.2	1.7 ± 1.0	2.6
February/99	28.4	29.8 ± 0.4	29.0	1.040	1.25 ± 0.13	1.850	4	54 ± 89	276	7.50	7.88 ± 0.34	8.52	0.67	4.00 ± 0.40	6.42	0.3	2.3 ± 1.9	4.7
April/99	28.7	29.4 ± 0.4	30.0	0.909	1.04 ± 0.15	1.410	6	39 ± 36	116	7.28	7.94 ± 0.36	8.51	0.02	4.08 ± 0.43	6.90	1.1	2.0 ± 0.9	2.9
June/99	28.0	28.4 ± 0.4	29.4	0.738	0.79 ± 0.20	1.430	9	17 ± 3	43	7.68	8.14 ± 0.30	8.75	1.21	7.53 ± 0.36	12.53	1.7	2.5 ± 0.6	3.2
August/99	26.7	27.5 ± 0.5	28.2	0.743	0.82 ± 0.15	1.420	8	35 ± 32	112	7.21	7.42 ± 0.13	7.66	3.65	5.51 ± 0.51	6.98	0.8	2.2 ± 1.4	3.8
November/99	27.4	28.3 ± 0.7	30.2	0.751	0.88 ± 0.15	1.320	7	25 ± 26	117	6.87	7.31 ± 0.33	8.43	0.16	5.38 ± 0.73	8.23	1.1	2.3 ± 1.1	3.5

Table 2. Minimum, maximum and mean (±SD) values of Total Alkalinity (meq $CaCO_3.L^{-1}$), Calcium - Ca^{2+} ($meq.L^{-1}$), Magnesium - Mg^{2+} ($meq.L^{-1}$), Bicarbonate ions - HCO_3^- ($mg.L^{-1}$), Carbonate ions - CO_3^{2-}($mg.L^{-1}$) and Dioxide of Carbon free - CO_2 ($mg.L^{-1}$).

	Total alkalinity			Ca^{2+}			Mg^{2+}			HCO_3^-			CO_3^{2-}			Free CO_2		
	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.
December/98	0.65	1.40 ± 0.40	1.96	1.20	1.48 ± 0.42	2.28	2.60	3.15 ± 0.73	4.77	14.09	33.42 ± 11.85	47.99	0.04	0.43 ± 0.80	2.52	0.01	1.91 ± 1.29	4.47
February/99	1.55	1.92 ± 0.18	2.11	1.09	1.36 ± 0.28	1.88	2.86	3.19 ± 0.36	3.83	37.43	46.94 ± 4.65	51.88	0.14	0.44 ± 0.43	1.51	0.29	1.59 ± 1.00	3.13
April/99	1.21	1.68 ± 0.28	2.11	0.14	0.53 ± 0.29	0.87	3.07	3.84 ± 0.90	5.71	28.54	40.83 ± 7.27	51.88	0.08	0.53 ± 0.36	1.07	0.20	1.20 ± 1.37	4.40
June/99	1.40	1.55 ± 0.29	2.31	0.33	0.86 ± 0.23	1.12	2.03	2.43 ± 0.73	4.78	33.54	37.49 ± 7.47	56.88	0.17	0.74 ± 0.54	1.98	0.13	0.55 ± 0.37	1.30
August/99	1.49	1.64 ± 0.11	1.79	1.01	1.08 ± 0.09	1.23	1.86	2.20 ± 0.29	2.71	35.76	39.58 ± 2.71	43.54	0.06	0.10 ± 0.03	0.15	1.99	3.24 ± 1.02	4.96
November/99	1.72	1.85 ± 0.09	1.98	0.72	1.04 ± 0.15	1.19	1.78	2.28 ± 0.65	3.93	41.88	45.03 ± 2.40	48.54	0.03	0.20 ± 0.39	1.23	0.36	5.70 ± 3.42	12.80

Table 3. Minimum, maximum and mean (±SD) values of Chlorophyll-*a* ($\mu g.L^{-1}$), Total Phosphorus - TP (PO_4^{3-} – P $\mu mol.L^{-1}$), Dissolved Inorganic Phosphorus - DIP (PO_4^{3-} – P$\mu mol.L^{-1}$), Ammoniacal Nitrogen - NH_4^++NH_3 – N ($\mu mol.L^{-1}$), Nitrate - NO_3^- – N ($\mu mol.L^{-1}$) e Nitrite - NO_2^- – N ($\mu mol.L^{-1}$).

	Chlorophyll-*a*			DIP			TP			NH_4^+ + NH_3 – N			NO_3^- – N			NO_2^- – N		
	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.	Mean ± SD	Max.
December/98	25.10	94.10 ± 108.94	256.32	0.19	0.94 ± 0.81	2.25	2.97	0.94 ± 0.81	39.74	2.81	12.65 ± 13.09	36.04	0.05	1.37 ± 1.15	3.08	0.21	0.24 ± 0.04	0.26
February/99	18.69	29.18 ± 8.92	40.05	0.18	0.73 ± 0.87	3.01	1.82	0.73 ± 0.87	88.96	*	*	*	2.75	4.28 ± 1.23	6.56	0.16	0.31 ± 0.12	0.44
April/99	18.85	27.45 ± 10.12	41.01	0.36	0.82 ± 0.39	1.53	1.19	0.82 ± 0.39	24.94	9.51	12.80 ± 3.17	16.94	2.07	2.32 ± 0.23	2.69	0.03	0.03 ± 0.03	0.03
June/99	8.83	18.36 ± 9.09	29.54	0.25	0.41 ± 0.09	0.52	2.79	0.41 ± 0.09	27.06	10.33	22.05 ± 7.09	34.84	0.03	0.20 ± 0.14	0.43	0.07	0.21 ± 0.16	0.71
August/99	11.15	17.91 ± 4.68	21.12	0.41	0.82 ± 0.31	1.32	2.73	0.82 ± 0.31	71.88	3.64	11.40 ± 6.98	22.95	0.03	0.19 ± 0.15	0.43	0.02	0.09 ± 0.09	0.22
November/99	8.83	22.51 ± 16.93	46.82	0.04	0.36 ± 0.20	0.73	1.45	0.36 ± 0.20	10.05	20.75	34.87 ± 20.34	87.09	0.85	4.66 ± 2.45	7.00	0.16	0.27 ± 0.08	0.37

* Missing data - suspiction of samples contamination with nitric vapours.

general, there was a transparency reduction from dam to riverine zones, with marked longitudinal gradients, particularly in December/98 and February/99. A transparency reduction was registered in August/99 when compared to June/99, especially at sites PJ01, PJ03 and PJ04.

The Cluster analysis revealed three longitudinal compartments in the reservoir during the dry season (Figure 12a): i) a riverine zone, represented by site PJ04, ii) a transitional zone, characterized by sites PJ03-PJ02, and iii) a lacustrine zone, represented by PJ01. During the rainy season, a different longitudinal configuration was found and two zones were evidenced (Figure 12b): i) a fluvial or superior compartment, represented by the sampling sites PJ04-PJ03, and ii) a lacustrine region (PJ02-PJ01). In this period there was an expanded riverine zone.

5. Discussion

The inverse thermal gradient observed in April/99 in the riverine zone was induced by warmer and denser waters entering by an inferior stratum of the water column, as evidenced by the turbidity isopleth arrangements (Figure 13).

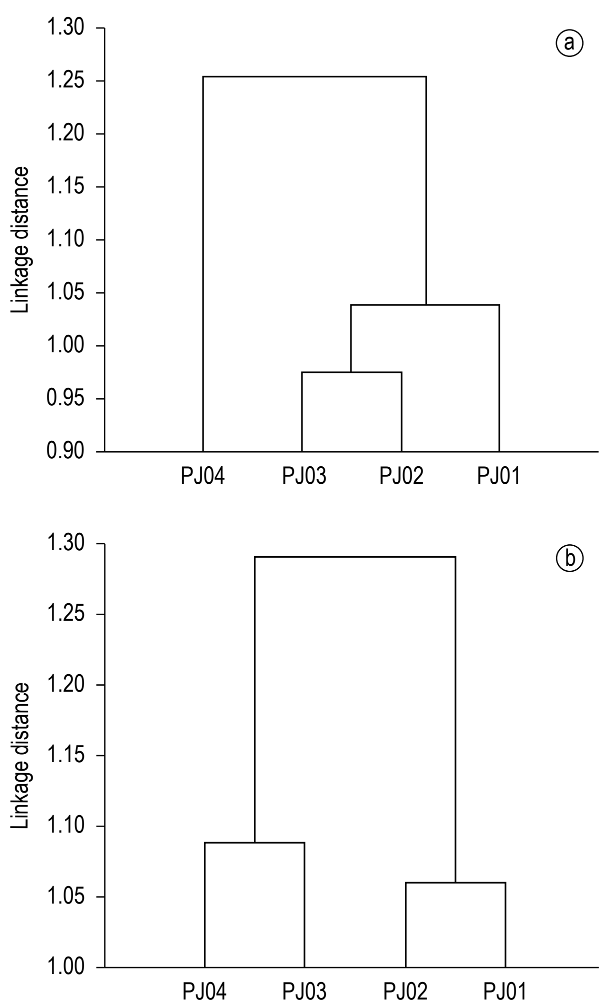

Figure 12. Cluster analysis corresponding to the dry a) and rain seasons b).

This phenomenon was described by Torrez-Orozco et al. (1996) in Escondida Lake (Mexico) during high-rainfall events, when inflowing waters, hotter and richer in suspended material, entered the bottom of the water column. Inverse thermal stratification was also observed in studies carried out by Campos et al. (1982) and Margalef (1983). The inverse thermal gradient observed in the Pacajus Reservoir confirmed the influence of the lotic inflows on the vertical structure of the reservoir's riverine region during the rainy period. The small vertical thermal gradients observed in Pacajus Reservoir, particularly during the second semester, could be accounted to the smoothness of its surrounding relief and to its small mean depth, characteristics that favored the wind action on the system. The presence of flooded phytomass in the intermediary zone of the reservoir, although being a physical barrier to turbulent mixing, was not enough to induce the formation of stable thermoclines. Although there were not enough data to infer about the circulation pattern of the reservoir, since it would demand a more complete data set, including a higher frequency of sampling and nictemeral measures, is reasonable admit that the system could be classified as polimictic.

The smoothness of the saline gradients towards the lacustrine zone was caused by the gradual mixing of the inflows with the reservoir's waters, a process apparently favored by the long residence time of the reservoir. Greater distances among the vertical E.C. isopleths towards the transitional and lacustrine zones reinforced the smoothness of the saline gradients along the longitudinal axis. The E.C. absolute values in the Pacajus Reservoir were similar to those found by Bouvy et al. (1999) in the Ingazeira Reservoir (Pernambuco State), also inserted in the semiarid Brazilian region. The magnitude of E.C. values was mainly due to the high concentrations of the major ions in the reservoir waters. The ionic dominance in the Pacajus Reservoir follows the order: $Cl^- > HCO_3^- > CO_3^{2-} > SO_4^{2-}$ :: $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ (Freire, 2007). In the dry season, the evaporative concentration was the process responsible for the increasing mean values for E.C. from June/99 to November/99.

The alkaline nature of the Pacajus Reservoir waters was mainly associated to the high HCO_3^- concentrations from the allochthonous contributions, in addition to the shifting in the equilibrium of the $CO_3^{2-} - HCO_3^-$ system caused by phytoplankton photosynthesis. The HCO_3^-, ion derived from a weak acid, tends to undergo hydrolysis in aqueous solution producing hydroxyl ions (HO^-), responsible for increasing of the pH values (Wetzel, 1983). The CO_2 assimilation by phytoplankton and subsequent HCO_3^- hydrolysis seems to be the main mechanism in regulating the pH in the trophogenic layer of the Pacajus Reservoir. Therefore, the $HCO_3^- - CO_3^{2-}$ buffering system seemed to control most of pH variation in the Pacajus Reservoir, weakening the vertical and longitudinal gradients.

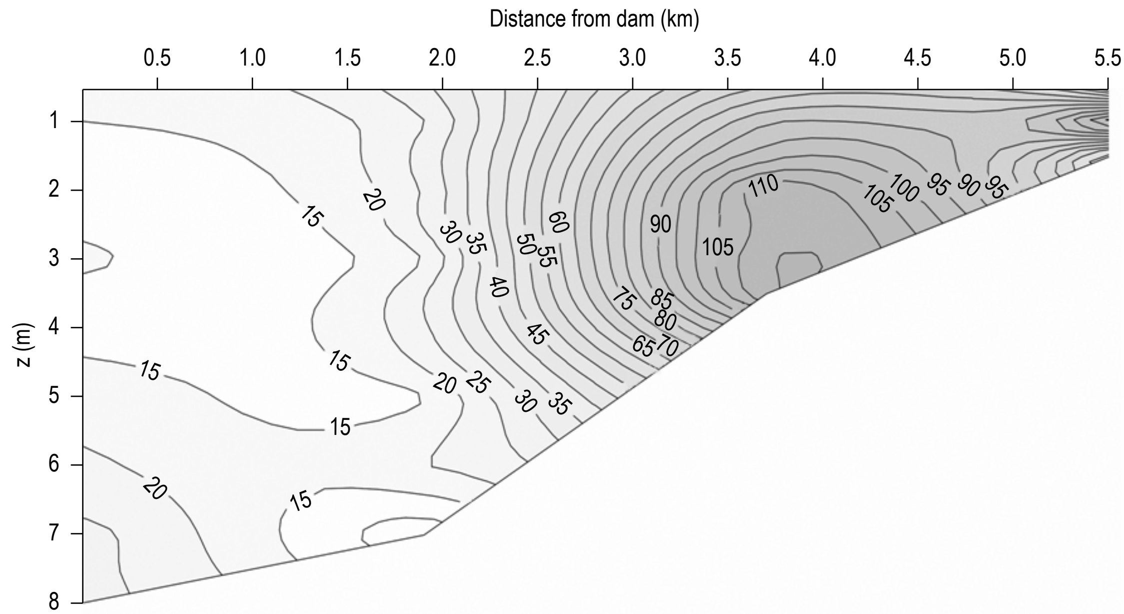

Figure 13. Isopleths of Turbidity (NTU) along the Choró River-dam. April/99.

The maximum pH value (9.28) observed in the fluvial zone of the Pacajus Reservoir in December/98 was probably due to an intense phytoplankton photosynthetic activity, since in this site the maximum value of the chlorophyll-*a* (256.32 µg.L^{-1}) was observed. Tafas et al. (1997) attributed the high pH values in the epilimnion of Trichonis Lake (Greece) during the summer due to the intense phytoplankton photosynthesis.

The highest pH and DO vertical gradients found at the PJ02 site, particularly in April and June/99, resulted from the flooded phytomass and allochthonous material decomposition processes. In these months, the anoxia observed in the low stratum of the water column characterized this reservoir region as a typical decomposition zone, where significant DO deficits could be found along the vertical profile. The greatest free CO_2 concentrations found at this site, with an increase towards the bottom, indicated the occurrence of mineralization processes. DO deficits have been reported in Amazon lakes with submerged vegetation (Melack and Fischer, 1983; Gunkel et al., 2003). Nogueira et al. (1999) identified, in Jurumirim Reservoir (São Paulo, Brazil), a zone of "active sedimentation" located in the transitional site, where a high oxygen consumption by allochthonous sediments and precipitated organic matter caused a sharp decrease in DO concentrations in the bottom water layers.

The significant algal biomass observed at site PJ01 resulted in high pH and DO values, especially in the epilimnion. This reservoir region was optically deep during the entire study period, since it was not directly influenced by the pulses of suspended material brought in by the Choró River during the rainy season. Such conditions favored phytoplankton growth, resulting in slight variations in the chlorophyll-*a* concentrations in the dam zone, a similar situation found by Fernandez-Rosado et al. (1994) in the La Concepcion Reservoir - Spain. Nogueira et al. (1999) attributed the small influence of the sediment inputs in the lacustrine zone of the Jurumirim Reservoir (São Paulo, Brazil) to its long hydraulic retention time and extended longitudinal axis. However, these researchers stated that in small and shallow reservoirs located in similar latitudes, a complete disruption of the system can be observed during pulse events. Henry and Maricato (1996) attributed the dissipation of the pulses towards the Jurumirim Reservoir to the high sedimentation of allochthonous material in the river mouth zone.

DO supersaturation observed in June/99 resulted mainly from the turbulent mixing induced by strong winds. DO supersaturation concentrations, registered beyond z_{eu} in most of the sampled profiles, showed the importance of the wind regime on the oxygenation of the Pacajus waters. Nevertheless, the contribution of phytoplankton photosynthesis to oxygenation of the trophogenic zone should be taken into account. At the Pacajus Reservoir, the DO dynamics seemed to be more associated with the wind regime, primary production and decomposition processes rather than vertical thermal structure. Townsend (1999) reported that the DO seasonal patterns in tropical reservoirs differ from the ones found in temperate regions because the warm tropical waters are more susceptible to oxygen depletion. On the other hand, the high phytoplanktonic productivity, usually observed in the tropics, tends to favor supersaturation in the trophogenic zone (Townsend, 1999). Torrez-Orozco et al. (1996) ascribed the hypolimnion oxygenation of the del Zacata Lake-Mexico to the turbulent mixing process induced by strong winds and favored by its shallow depth. The unfavorable morphometric characteristics of Murchison Lake - Tasmania, a sinuous aquatic system well protected from wind action, especially near the dam, were essentially responsible for the thermal and chemical stratification (Bowling and Tyler, 1990). Boland and Griffiths (1995) reported that hypolimetic oxygen deficits originated from the vertical stability of the system, which restricted mixing with the epilimnetic waters oxygenated by gaseous exchanges at the air-water interface and photosynthetic activity.

The strong winds registered in August/99 were fundamental to the alteration in physical and chemical conditions in the Pacajus Reservoir and contributed decisively to the resuspension of the bottom sediments. The internal sediment load in shallow lakes susceptible to wind action is largely responsible for affecting water optical quality and determining internal nutrient regeneration rates (Cristofor et al., 1994; Knuuttila et al., 1994; Ramm and Scheps, 1997). Ignatieva (1996) emphasized the importance of this component on the phosphorus regeneration in lakes, acting as source and sink through continuous processes of chemical species mobility at the water-sediment interface. Molecular diffusion, convective and advective transport mechanisms, bioturbation, adsorption and oxy-reduction reactions are the most important mechanisms responsible for phosphorus liberation from lakes and reservoir sediments (Redshaw et al., 1990; Ignatieva, 1996; Martinova, 1993; Ulrich, 1997). The highest PID mean concentration in August/99 resulted from internal phosphorus load mechanisms, since external contributions could be considered insignificant during this period. The bottom sediments resuspension hypothesis was reinforced by the increased turbidity values towards the bottom at PJ01 – the deepest site – as well as at the other sites (Figure 14). According to Knuuttila et al. (1994), the internal phosphorus load occurring in Finnish lakes resulted from the following processes: i) sediment resuspension induced by turbulent mixing; ii) phosphorus liberation due to anaerobic conditions at the water-sediment interface; iii) liberation under high pH values, and iv) bioturbation of the benthos.

The internal phosphorus load observed in August/99 might have been influenced by high pH and water temperature values, besides reduced DO concentrations in relation to June/99. Redshaw et al. (1999) concluded that the association of these conditions was responsible for the phosphorus liberation from Ardleigh reservoir (United Kingdom). Internal phosphorus regeneration can severely limit eutrophic reservoir recovery after allochthonous load reductions, especially in shallow tropical systems. Because phosphorus content in the superficial sediments is higher than the adjacent water column, even a small release can cause a significant increase in total phosphorus concentration in the reservoir water column (Pettersson, 1998).

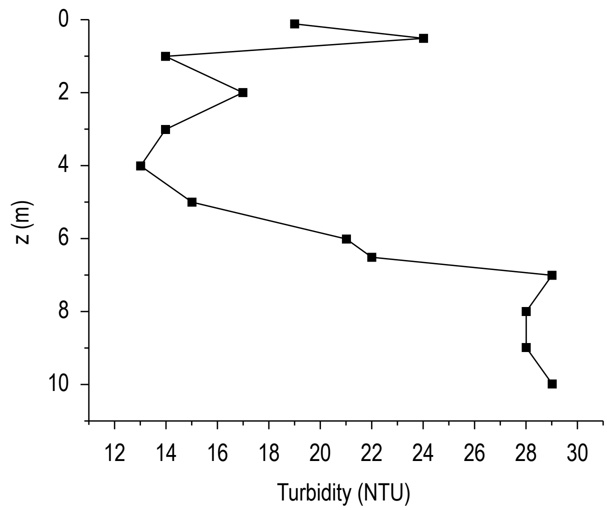

Figure 14. Turbidity vertical profile at site PJ01. August/99.

The low levels of PID in December/98 were due to its assimilation by phytoplankton. Ansa-Asare and Asante (1998) attributed epilimnetic PID depletion in two reservoirs (Weija and Kpong) in southeastern Gana-Africa to the occurrence of algal blooms during the dry season.

Although the Pacajus Reservoir waters were enriched during the rainy season, there was no increased phytoplanktonic biomass in response to greater nutrient availability. The reduction in algal biomass in the riverine zone during the rainy period was largely due to light limitation caused by highly turbidity inflows from the Choró River. The greater nebulosity, typical of the rainy season, can also be considered as a controlling factor on algal biomass because of its interference with the availability of the photosynthetically active radiation.

In August/99, there was also z_{eu} reduction in relation to June/99 as a consequence of the resuspension of the internal sediment load induced by turbulent mixing. The probable interference of turbidity on the algal biomass increase in this month resulted in the lowest chlorophyll-*a* mean concentration (13.45 $\mu g.L^{-1}$) during the sampling period. Grobbelaar (1992) reported the effects of suspended material on the underwater radiation regime and, consequently, on phytoplankton primary production in two South-African reservoirs (Krugersdrift and Mockers). Increased turbidity in these reservoirs after flooding pulses drastically reduced the water transparency and the algal primary productivity when compared with the previous period, despite greater nutrient availability. In the Pacajus Reservoir, particularly in the riverine zone, the z_{sd} values were closely associated with rainfall pulses. Calijuri (1988) observed that high concentrations of suspended material from precipitation pulses in the Barra Bonita Reservoir (Brazil) altered the underwater radiation regime, considerably reducing the z_{sd} values. In a few hours, the z_{sd} dropped from 2.0 to 0.3 m in the reservoir. Besides the z_{eu} reduction, Calijuri (1988) found there was an influence of inorganic suspended solids on the physiological state and photosynthetic activity of the phytoplankton. During the dry season, the algal biomass was the main attenuating factor affecting water transparency in the Pacajus Reservoir, especially in December/98 in the shallowest part of the reservoir (PJ04), when a chlorophyll-*a* concentration of 256.32 $\mu g.L^{-1}$ corresponded to a vertical attenuation in the radiation coefficient of 128.6 m^{-1}.

The reservoir's compartmentalization in three zones, as reported by Kimmel et al. (1990), was especially evident in the dry season. Inputs of suspended material, dissolved salts and macronutrient during the rainy season caused the expansion of the riverine zone, resulting in a new longitudinal configuration in response to the Choró River inflows. It is important to recognize that these zones are usually quite dynamic and expand and contract in response to watershed runoff events, density flow characteristics and reservoir operational procedures (Kimmel et al., 1990).

6. Conclusion

Wind action on the system's vertical structure was evident, especially during June and August/99, when the smallest thermal vertical gradients were observed, and dissolved oxygen supersaturation occurred in almost all the reservoir below the euphotic zone (June/99). The greatest Choró River inflows occurring during the rainy season were responsible for the chemical and physical changes observed in the riverine region, besides contributing to the enrichment of the reservoir waters. The rainfall pulses also determined the extended longitudinal gradients between the riverine and lacustrine regions. However, the gradual mixing of waters and sedimentation of the allochthonous material along the Choró River-dam axis, favored by the long hydraulic retention time, were decisive in controlling the optical quality and thus phytoplankton growth in the lacustrine zone. Flooded phytomass and allochthonous sediment decomposition in the transition zone induced oxyclines formation in April and June/99. The bottom sediment resuspension in August/99 conditioned the internal phosphorus load, emphasizing the importance of this component in the internal regeneration of nutrients during the dry season, when the external sources of nutrients are negligible. Therefore, nutrients released from bottom sediments can become a controlling factor determining the trophic state of the Pacajus Reservoir, even after the adoption of management strategies to reduce loads. The longitudinal zoning in the reservoir showed a superior compartment, with high algal biomass during the dry season and light-limited during the rainy season, despite greater nutrient availability; an intermediary compartment, characterized as a sedimentation and decomposition zone; and a region located close to the dam, characterized by high algal biomass and good optical quality. In relation to nutrient dynamics the system was dependent mainly on the inputs from the Choró River during the rainy period and internal regeneration during the dry season, a process strongly influenced by the wind-driven mixing.

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