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Application of Hydrological and Limnological studies on Building Model for Water circulation of Meromictic Black Water Lakes at the Central Amazonia, Brazil

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Abstract

In the last decade, hydrological and limnological studies were conducted in a black-water lake aiming to develop a model of water circulation to meromictic lakes from Negro River basin at the Brazilian Central Amazonian. Parameters as temperature, euphotic zone (Z_{eu}), attenuation coefficient (K), density, oxygen and morphometry were measured daily. Z_{eu} and K proved somewhat constant throughout the hydrological year. In the low waters periods were observed a theoretical mean residence time of water of about 150 days. The meromixis condition was observed with continuous physical and chemical stratification in all hydrological cycle, showing a hypolimnion very defined. The thermal stability was explained by the distinction densities between upper and lower strata, with bottom water flux from forest-rivers. The morphometry of the lake and presence of a flooded forest surrounding, were important factors in reducing wind action on the water column, reducing the effect of stimulating the circulation and stratification process.

Keywords: Meromictic lake, thermal stratification, attenuation coefficient, black-waters, Negro River

Introduction

Brazilian Amazon is covered with rain forest, great rivers, many lakes and a large floodplain area, which are wetlands periodically inundated by the lateral overflow of the rivers. In the floodplain areas of the Amazon, the '*igapós*' and lakes showing high space-time variation in water quality due to an extraordinary range of water types, nutrient levels and suspended matter. Negro River basin has a drainage area of 690,000km^2, covering around 14% of the total area of the Amazon Forest and 10-12% of the entire Amazon basin[1,2]. The basin has a huge amount flooded forest and lakes, which are distinguished by their acidic water (pH≈ 4.0) staining wine, a low sediment load and high content in dissolved organic matter derived from broken down plant material and of humic and fulvic substances production.

Information on hydrological and limnological processes in lakes can offer valuable contribution to ecological researches in the lentic systems. The annual inundation of the Negro River causes profound changes in the aquatic environment and provides a variety of habitats to aquatic fauna. The circulation type of the water column play an essential function in the behaviour of the local lentic ecosystems, and physical, chemical and biological processes are depending of that trend. The total or partly mixing phenomena of the water column are closely related with the thermocline, which in stratification conditions restricts the heat and matter transport to the upper water layers[3,4]. Stratification has a clear and consistent effect on nutrient-saturated increase rate and on algal[5] and macrophytes community growth. In a typical lake of the Negro River basin the aims of this research were: i. to study the daily physical and chemical properties of the lake based on annual hydrological cycle, ii. to define its morphological and hydrological characteristics, iii. to identify the type of stratification, and iv. to establish circulation model water to lakes meromíticos Amazon.

Material and Methods

Description of lake: Tupé Lake basin (3º00'50.4"-3º03'07.2"S and 60º14'16.8"-60º15'43.2"W) is a shallow black-waters '*Ria*' lake with a "*T*" shape, which occupies a shallow depression between rows of Pleistocene soils containing reserved tertiary and clay sediments. Tupé Lake is located in the left margin of the Negro River (Central Amazonian), and it is situated 25km upstream of Manaus City and of the confluence of the Negro and Solimões rivers, known as "The meeting of the waters" (figure-1). Descriptions of geomorphological characteristics of the Tupé Lake can be founded in details in diverse manuscripts[6,7]. Main morphometric and hydrological characteristics of Tupé Lake are showed in table-1.

Mean annual fluctuation of the lake water level is about 10m in the sampling site more depth (P10, see figure-1). The lake water level has its flood-peak (14.5m) between June and July and maxima dry (4.5m) between November and December. An annual average of precipitation ranged between 2000 and 2200mm.year^{-1} can be observed in the Tupé Lake and surrounding areas[8]. According to Köppen classification, the local climate is “*Am*” equatorial hot and wet.

Analytical proceeds: Water temperature (TºC) and oxygen saturation (O_2%) levels were measure at three hours intervals daily, at 0.5m intervals in all water column and in eleven sampling sites (figure-1) with a WTW OXI-197 thermistor electrode. Total density of the water was determined for each 1m depth at each sampling period. To water total density we considered the sum of the density due to temperature more significant that the density due to salts presence. Density (D_z) of water due to temperature (T) was obtained of table modified from Birge[9], and contrasted with density calculated[10].

$$D_z = \left[1 - \frac{T + 288.9414}{508929.2\,(T + 68.12963)}(T - 3.9863)^2\right] \quad (1)$$

Were: D_z is density of water in a depth ($g.cm^{-3}$).

Table-1
Tupé Lake basin morphometric and hydrological data to the low waters (source Aprile and Darwich[7]).

Aspect	Value	Aspect	Value
basin type	Ria	max width (W_{max} m)	250.10
surface area (A km^2)	0.67	min width (W_{min} m)	32.40
volume (V m^3)	$1.44x10^6$	mean width ($\overline{W}$ m)	97.40
max depth (Z_{max} m)	5.60	max length (L_{max} km)	2.50
min depth (Z_{min} m)	0.10	min length (L_{min} km)	1.15
mean depth ($\overline{Z}$ m)	2.10	max declivity (α_{max} $m.km^{-1}$)	4.10
relative depth (Z_R m)	2.20	total declivity (α_{total} $m.km^{-1}$)	1.90

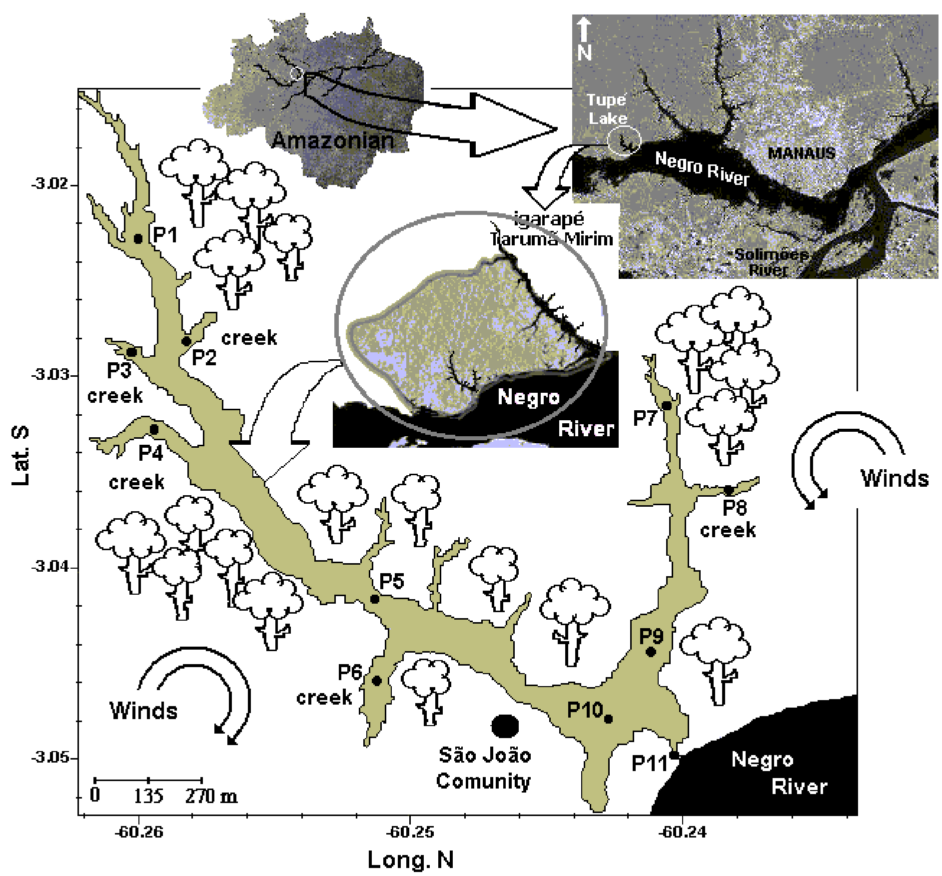

Figure-1
Location of sampling sites in the Tupé Lake basin, Central Amazonian – Brazil

PAR radiation measurements were made with a Quantum Radiometer LI-COR Li-250 and sensor sub-aquatic LI-COR Li-192SA and the results were utilized to calculate euphotic zone (Z_{eu} m) and attenuation coefficient (*K* m). The data were reported as means±SD. Wind speed (U_w $m.s^{-1}$) dates were obtained from a weather station of the University of Amazonas (UFAM) and from one of the meteorological databank at the Manaus harbor between 2003–2011. The vertical thermal and chemical variations (ΔT and ΔO_2) were studied for the hydrological cycle (low and high waters) with morphometric and hydrological dates association, and as results were showed a thermal trend to black-waters lakes of the Central Amazonian.

Results and Discussion

Thermal and chemical structure: Analyses of the physical and chemical structure of water column were performed daily at 3 hours intervals at all stations, and the results are showed in the figure-2. All sampling sites of the Tupé Lake were permanently stratified during the hydrological cycle. Depth varied from 4.5m in the low water to 14.5m in the high water periods at the central site (P10, see sampling site in figure-1), but the pattern was the same on every date. The lake showed a perceptible thermal to strong chemical stratification in the low waters with mean variations ΔT of 4.7ºC and ΔO_2 of 104.9% between surface and bottom. Temperature in the high waters (between May and July) ranged from 27.9ºC at 6am to 29.3ºC at 6pm (average 28.8±0.30ºC) at the surface layers, and ranged from 26.9ºC at midday to 27.1ºC at afternoon (average 27.0±0.07ºC), keeping on 27.0ºC for all the night in the bottom (figure-2A). During the low waters (between October and December), the water temperature ranged from 30.0ºC at 6am to 33.1ºC at 3pm, with average 31.1±0.31ºC at the surface layers, and stayed for all the time in 27.2ºC at the bottom layers (figure-2B). The chemical stratification, resulting from differences in oxygen concentration between the epilimnion and hypolimnion, was quite clear in both high water and low waters. During the period of high waters, the oxygen saturation ranged from 44.2% for 12pm to 55.1% for 6am (average 49.7±4.5%) on the surface, and from 0.3% for 12pm to 5.4% at 9am (average 1.6±1.7%) at the bottom (figure-2C). During low water, the O_2% ranged from 87.8% for 6am to 148.6% for 3pm, with average 106.2±22.8%. In the same hydrologic period the variation in the percentage of oxygen saturation in the bottom of the lake was 0.0% most of the night and in the morning reaching 8.0% at 3pm, with average 1.3±2.8% (figure-2D).

The layer above the compensation level is referred to as the euphotic zone (Z_{eu}), which in the Tupé Lake ranged from 3.3-4.5m, with attenuation coefficient ranged between 1.0 and 1.4m to the high waters and between 1.2m and 1.3m to the low waters (table-2). Others values in Amazon region to black-waters are Cristalino Lake with *K*= 0.53 and Negro River with *K*= 1.54[11]. The attenuation coefficient describes the rate at which light penetration decreases with depth. Thus, a high *K* represents a rapid decrease in the light over depth, such as when there is a high concentration of suspended material or elevates coloration due to humic substances from decomposition processes. In Amazonian black-waters, the humic substances are the main reason to reducing the *K*.

Stratification trend: The morphology of the Tupé Lake has influence on its limnological characteristics, e.g. dissolved oxygen level and biologic productivity, as well as on the sedimentation processes, residence time of water and, stratification process of the water column. In the low waters periods were observed a theoretical mean residence time of water of about 150 days. Studies on heat budgets and thermal structure in Brazilian reservoirs[12] demonstrated only in systems with residence time higher than 40 days can be observed thermal stratification processes. In the Tupé Lake, its transverse section looks like a '*V*' shape (figure-3) and, probably, that has contributed to high residence time of water and so, to physical and chemical stratification in the lake.

The surface water density of the lake, based on mean temperature and salinity, was computed to be D_0 = 0.99547g.cm^{-3}, while the water from forest-rivers had a density of D_0 = 0.99668g.cm^{-3}. Apparently, this small difference between the water density of the lake and of the forest-rivers is enough to obstruct the mixture of the layers. The density variation of water (ΔD) is more significant in tropical that temperate lakes. According to equation-1 showed by Martin and McCutcheon[10], the ΔD from 29ºC to 30ºC is about 7.7 times higher than 6ºC to 7ºC. Therefore, the major reason reducing the daily mixing of the lake appeared to be density differences between upper and lower layers. In the water column the higher difference was observed in the low waters periods, with D_0 = 0.99505g.cm^{-3} to 32ºC and D_5 = 0.99646g.cm^{-3} to 27.3ºC. High-density water entering the lake tended to flow along the bottom and to settle down in the deepest area of the lake. This layer of water of higher density increased sufficiently the stability, avoiding the mixing of the lower 4 m, how is showed in the figure-4. Therefore, the thermal stratification was continuous in all hydrological cycle and the meromixis condition was observed. The lakes stability based on density differences due to temperature has been computed from the start of the twenty century[9,13,14]. Hutchinson[14], such as, considered lake stability in terms of density differences caused by temperature and salinity changes. With base in the results the water column of the Tupé Lake was divided in epilimnion (surface – 1.5 m depth), metalimnion (1.5–4 m) and hypolimnion ($Z \geq 4$m). The mean temperatures of the layers for each seasonal period are showed in the table-2. One kind of peculiar physic-chemical stratification involving the black waters from forest-rivers was observed, and the black waters occurred through most or all the hypolimnion, where the temperature and density these waters from forest-rivers are dissimilar of the same parameters in the lake.

The streamlines describe the paths of the water movement. Density and other related phenomena such as water flow and influence of the winds are of fundamental importance in heat and matter distribution, and as result in the regulating aquatic life. Water can move in turbulent or laminar flow, as showed in figure-4. The entire water mass may move in one direction (the stream direction), but the individual water particles have irregular paths. In laminar flow, tiny particles in water move in parallel tracks that can be visualized by parallel streamlines. The inflows and outflows between Tupé Lake and Negro River occurs very slowing, therefore the mixing energy in the flood and ebb periods were not enough to crack the hypolimnion stratification.

Table-2
Euphotic zone, attenuation coefficient and mean temperature ± SD for the hydrological cycle (Oct/01 - Dec/04) of the Tupé Lake basin, Central Amazonian

Water	Z_{eu} (m)	*K* (m^{-1})	U_w ($m.s^{-1}$)	epilimnion		metalimnion		hypolimnion	
				χ (ºC)	SD	χ (ºC)	SD	χ (ºC)	SD
High	3.3-4.5	1.0-1.4	31±3	28.8	0.30	28.0	0.28	27.0	0.07
Low	3.5-3.8	1.2-1.3	6±1.2	31.1	0.31	29.1	0.53	27.2	0.09

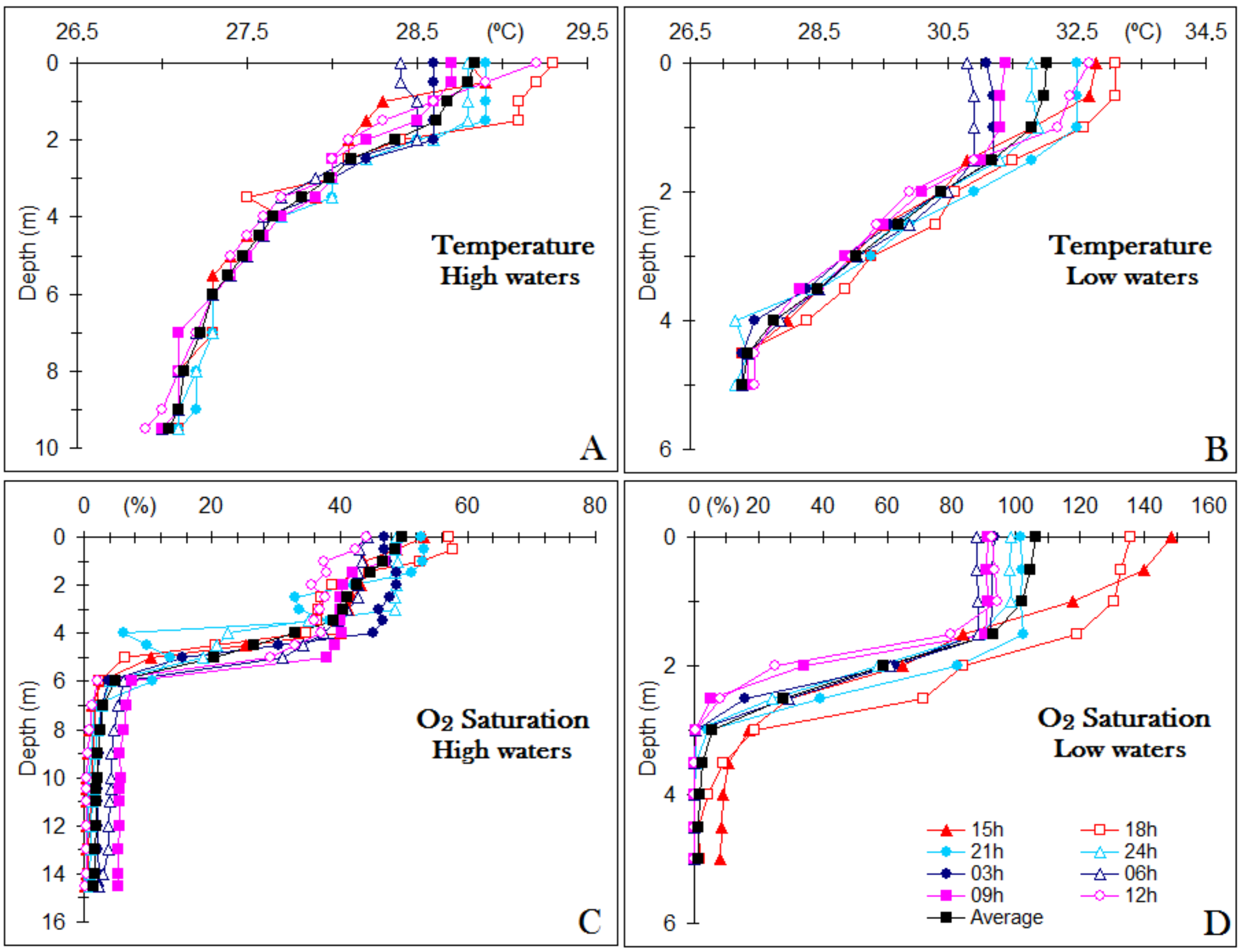

Figure-2
Nictemeral variation of the temperature and oxygen saturation, with evidence of the stratification processes, in the high and low waters at the Tupé Lake - Central Amazonian. Fit exponential decay of first order to the average values:
$y_{Depth} = 14.9067 \times e^{-(x-27.0)/0.6843}$ **equation-2 thermal variation to high waters;** $y_{Depth} = 4.9562 \times e^{-(x-27.3)/2.8746}$ **equation-3 thermal variation to low waters;** $y_{Depth} = 11.6821 \times e^{-x/23.5193}$ **equation-4 O_2 variation to high waters;**
$y_{Depth} = 4.1892 \times e^{-x/61.0014}$ **equation-5 O_2 variation to low waters**

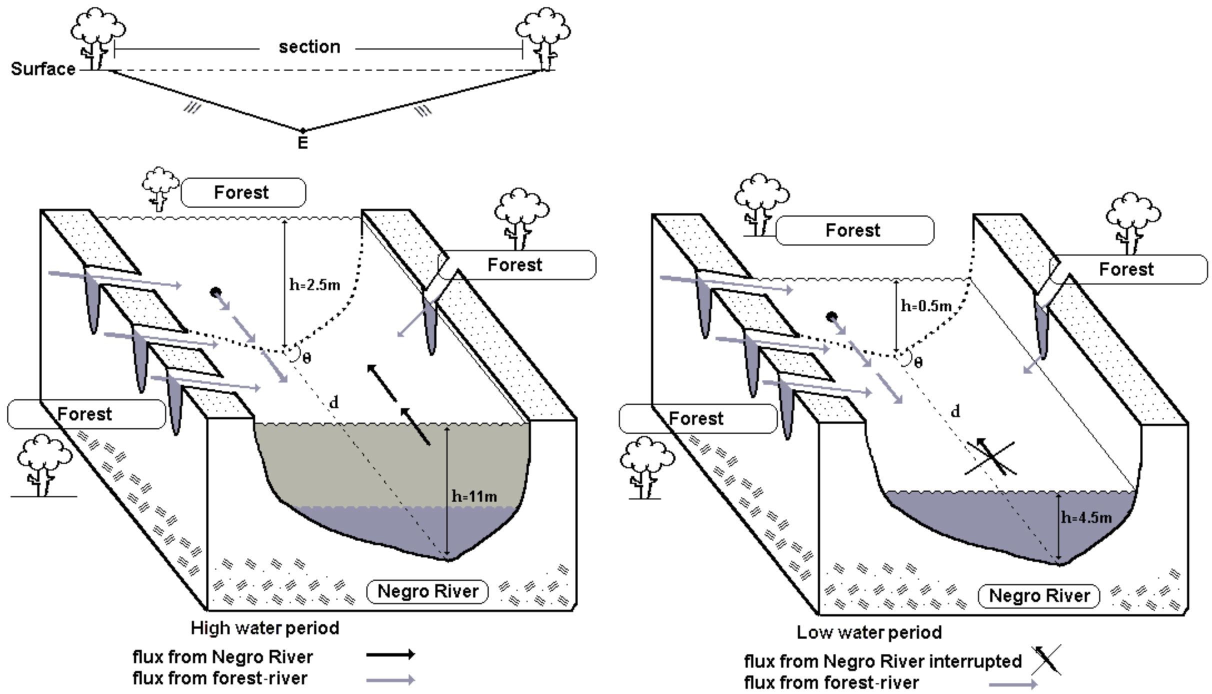

Figure-3
Transverse '*V*' section of the Tupé Lake, with circulation model of water to the high and low waters periods

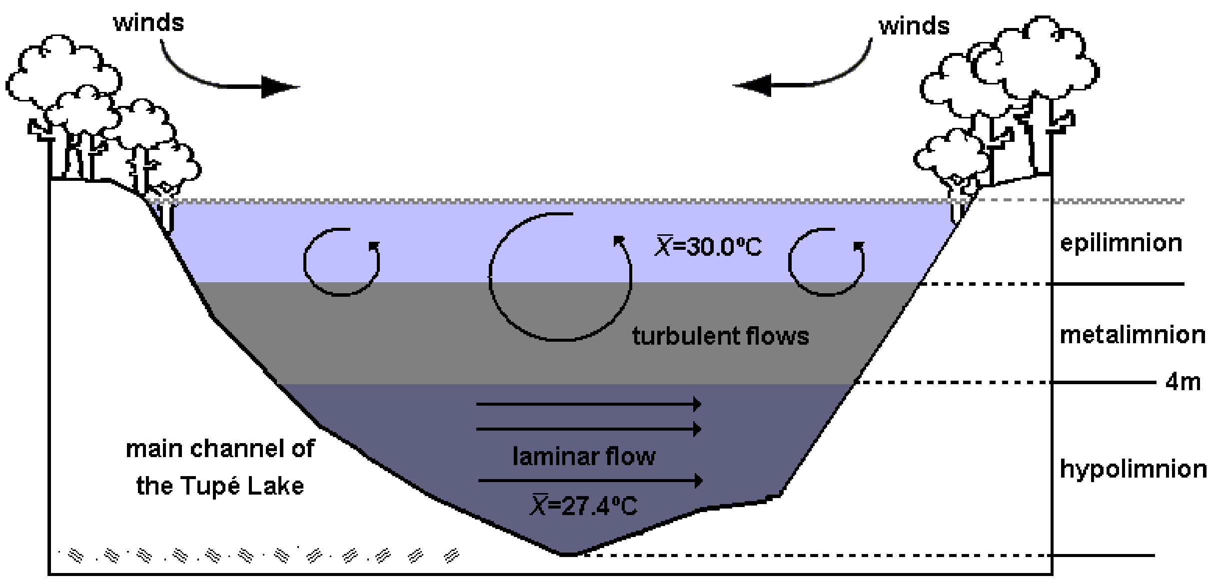

Figure-4
Physical stratification trend to the Tupé Lake

In situations where the stratification is fragile or the input of turbulent kinetic energy is high, enough work is available to exceed the buoyant forces due to stratification and mix the water column. However, during periods of stronger stratification, as it that occurs in the Tupé Lake, when natural mechanics are not capable to completely mix the water column, the lower layer of the water column becomes isolated from the atmosphere, and chemical and biological gradients can be develop[15]. In general, the winds produce turbulent kinetic energy (TKE) and currents at the water surface that mix the superficial water (epilimnion). However, when the warmest water is floating near the surface, the wind cannot easily mix it with the underlying more cold water from forest-rivers. Furthermore, the morphology of the lake with a lengthened shape and boundaries protected by igapós and forest-rivers reducing the winds influence, including in the high waters periods, when the winds are stronger (table-2). The inundated forest contributes as a shield in opposition to the winds action. In the Tupé Lake were evidenced three types of vegetation associated to the flood-pulse lake: non-flooded forest, occasionally flooded forest, and occasionally flooded low vegetation. There is an increase of the resistance to mixing from the hypolimnion to the shallow so, the physical and chemical stratification maintains constant.

Conclusion

The Tupé Lake has characteristic of Meromictic Lake with permanent physical and chemical stratification for all hydrological cycle. Basically, the thermal stability of the lake was explained by three factors associated: i. density differences between upper and lower strata, due to the bottom water flux from forest-rivers; ii. a typical morphology of a "*Ria*" lake basin occupying a shallow depression in Negro River; and iii. the protection of the inundated forest in opposition to action of the winds in the region. Morphology of the Tupé Lake has influence on its limnological characteristics, such as residence time of water, sedimentation processes, and continuous stratification of the hypolimnion. The stratification trend showed to Amazonian black-waters lakes can explain diverse physical, chemical and biological processes that are depending greatly of the temperature and oxygen. Information of this nature can offer valuable contribution in the research of fish's ecology in the Amazonian.

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References

1. Meade R.H., Rayol J.M., Da Conceicão S.C. and Natividade J.R.G., Backwater effects in the Amazon River basin of Brazil, *Environ. Geology and Water Sciences*, **18(2)**, 105–114 **(1991)**
2. Dorea J.G., Barbosa A.C. and Silva G.S., Fish mercury bioaccumulation as a function of feeding behavior and hydrological cycles of the Rio Negro, Amazon, *Comparative Biochemistry and Physiology*, **142**, 275–283, **(2006)**
3. Lorens M., Sáez J. and Soler A., Influence of thermal stratification on the behaviour of a deep wastewater stabilization pond, *Water Res.*, **26(5)**, 569-577, **(1992)**
4. Lampert W. and Sommer U., Limnoecology: the ecology of lakes and streams, Oxford University Press, Oxford/ New York, 382, **(1997)**
5. Sterner R.W. and Grover J.P., Algal growth in warm temperate reservoirs: kinetic examination of nitrogen, temperature, light, and other nutrients, *Water Res.*, **32(12)**, 3539-548, **(1998)**
6. Rai H. and Hill G., Physical and chemical studies of lago Tupé: a Central Amazonian Black Water, Ria Lake, *Int. Revue ges. Hydrobiol.*, **66(1)**, 37-82, **(1981)**
7. Aprile F.M. and Darwich A.J., Geomorphologic models to the Tupé Lake. In: Santos-Silva E.N., Aprile F.M., Scudeller V.V. and Melo S. (Orgs.), BioTupé: Physical environmental, biologic diversity and social and cultural of the down Negro River, Central Amazon, pp.3-17, INPA editora, Manaus, **(2005)**
8. Scudeller V.V., Aprile F.M., Melo S. and Santos-Silva E.N., Sustainable Development Reserve: general characteristics, In: Santos-Silva E.N., Aprile F.M., Scudeller V.V. and Melo S. (Orgs.), BioTupé: Physical environmental, biologic diversity and social and cultural of the down Negro River, Central Amazon, pp.XI-XXI., INPA editora, Manaus, **(2005)**
9. Birge E.A., The work of the wind in warming a lake, *Trans. Wisconsin Acad. Sci. Arts and Lett.*, **18(2)**, 341-391, **(1916)**
10. Martin J.L. and McCutcheon S.C., Hydrodynamics and Transport for Water Quality Modeling, Lewis Publications, Boca Raton - Florida, **(1999)**
11. Rai H. and Hill G., Primary production in the Amazonian aquatic ecosystems. In: Sioli H. (Ed.), The Amazon, 311-335, Dr. W. Junk Publishers, Dordrecht, **(1984)**
12. Henry R., Heat budgets, thermal structure and dissolved oxygen in brazilian reservoirs, In: Tundisi J.G. and Straskraba M. (Eds.), Theoretical reservoir ecology and its applications, pp.125-152, International Institute of Ecology, Backhuys Publishers and Brazilian Academy of Sciences, **(1999)**
13. Birge E.A., An unregarded factor in lake temperatures, *Trans. Wisconsin Acad. Sci. Arts and Lett.*, **16(2)**, 989-1004 **(1910)**
14. Hutchinson G.E., A contribution of the limnology of arid regions, *Trans. Conn. Acad. Arts. Sci.*, **33**, 47-132 **(1937)**
15. Wetzel R.G., Limnology: Lake and River Ecosystems, Academic Press, San Diego - California, **(2001)**