Original Research Article

Proposal of unidirectional laminar flow model to black waters lakes in Central Amazonian, Brazil: a case study

ABSTRACT

This case study was conducted in Tupé lake a Ria black water lake in the Negro River basin, Central Amazonian, with historical data from 2001 to 2018. The aim was to propose a unidirectional laminar flow model, relating it to the limnological data, in special temperature and dissolved oxygen in the water column. Climatological, geomorphological and hydrological data as well as general environmental factors were included for the construction and study of the water circulation model. The Tupé lake (3º01'33.5 ”- 3º02'47.8” S; 60º14'57.5 ”- 60º16'1.2” W) is supplied in most of the time by waters coming from forest streams. As a result, the lake has specific properties of circulation and flow of nutrients, being considered a meromictic lake with permanent stratification. Although the statistical test suggests that there is no difference in the average density between the vertical layers of water, the observed pattern confirms exactly the opposite, reinforcing the existence of permanent stratification due to uneven mass densities between the epilimnion and hypolimnion. The continuous and almost permanent unidirectional laminar flow from the forest streams guarantees the state of non-conservation of energy at the bottom of the lake, with constant renewal and variation of this behavior. A laminar flow model was established for the lake, highlighting the partial circulation of water in the epilimnion. The condition of permanent stratification is not common to be observed. Thus, with these results, a model can be established to help identify this behavior in other Ria lakes in the Amazon region.

Keywords: Stratification; fluid dynamic; heat transfer; Negro River; Amazon.

1. INTRODUCTION

The term stratification is used to evidence the existence in a body of water (lentic or lotic) of two or more horizontal layers of water with different physical and chemical characteristics and properties. Stratification can be physical (thermal) or chemical, in this case involving changes in gas concentrations (O_2 or CO_2, for example) or other chemical elements such as organic and inorganic nutrients, ions and minerals. The study of the stratification process in lakes, especially lakes significantly isolated from the drainage basin, is of great importance for understanding the dynamics of the ecosystem, since the phenomenon of stratification and de-stratification interferes directly with the physical, chemical and biological properties of the system. The immediate result of the stratification process is the change in the general properties of water, including density and viscosity, followed by changes in the patterns of solubilization and diffusion of gases, flow of elements, and changes in biological patterns (quantitative and qualitative). The stratification behavior of the water column is variable, even inside a given region or ecosystem, and may be due to autochthonous or allochthonous factors. In the case of a lake ecosystem, the main phenomena involved in the natural stratification process are climatic (solar radiation, winds, rain and cloud cover) and structural, and especially in this case the geomorphological aspects of the system. The average depth, slope, predominant morphometry, main flow of currents, surface area (water mirror), slope of the borders, presence or not of forest protection against the direct action of the winds, are all factors inherent in the stratification process. The chemical composition of the water column is another controlling factor in the stratification process, in which case the connection of the lake with the main lotic system is highly relevant.

The main source of water and nutrients for lakes are their drainage basins, represented by rivers of greater volume and flow, with seasonal variations in the level of the lakes depending on the level of the rivers to which they are connected. In this case, the geomorphology of the connection point and seasonality are fundamental to determine the influence of the river on the lake. This process is relatively evident in the white and clear waters lakes of the Amazon, according to typology established by Sioli [1-3]. However, in black water lakes, often the main contribution of water and nutrients (organic matter) occurs through the forest streams by autochthonous contribution. This is due to several factors, especially geomorphological. This pattern is evident when we consider that for most of the hydrological year, some black water lakes remain isolated from the respective drainage basins. This is a characteristic of Tupé Lake, which is located on the banks of the Negro River (Central Amazonian), and whose connection to the river is through a single flow channel, which even when connected has an almost insignificant river contribution from the point of view of the physical-chemical composition.

As a result, Tupé Lake has very specific properties of circulation and elements, being considered a meromictic lake [4-6], when some water remains partly or wholly unmixed with the main water mass at circulation periods. These properties interfere with the thermal and chemical stratification patterns of the lake. Mathematical models have been improved to study processes and phenomena in water reservoirs and energy generation. Considering that in the hydrological year, Tupé Lake has a very short connection time with its drainage basin, we establish the hypothesis that the lake has a 'natural reservoir' behavior and, therefore, can be studied within some premises established in models for reservoirs. With that, we could have a better view of the laminar flow behavior of the water and the ‘almost’ permanent stratification process of the lake by the phenomenon of meromyxia. The aim of this study was to analyze the stratification profiles of the Tupé Lake for several hydrological years, establishing a mathematical model of flow based on its physical-chemical and morphological characteristics. It is hoped that this will confirm the trend of permanent stratification in the lake, allowing the model to be applied in other lentic systems in the Amazon.

2. STUDY AREA

The black water rivers have their sources in the shields of Guyana and Central Brazil, or in the tertiary sediments of the Amazon basin. The relief of these basins is flat, resulting in a slower flow of water, indicating low erosion processes. According to the Sioli classification [1-3], black water rivers and lakes have good transparency (up to 3 meters), color ranging from olive-brown to coffee-brown water, almost total absence of suspended material, low concentrations of Ca and Mg, acidic waters with pH between 3.5 and 4.5 and electrical conductivity below 10 μS_{25}/cm. The catchment area of the black water basins is inserted in a large flood forest (igapós), so that the decomposing organic material releases soluble humic substances (humic and fulvic acids). Due to these physical and chemical properties, the flooding area of the Negro River differs from the floodplains of the Amazon River.

Lake Tupé (3º01'33.5” - 3º02'47.8” S; 60º14'57.5” - 60º16'1.2” W; Fig. 1), is a shallow lake of black waters, of the type “Ria”[7], in the shape of a 'T' that occupies a shallow depression between rows of Pleistocene soils containing reserved tertiary and clay sediments. The lake is located on the left bank of the Negro River (Central Amazonian), located 25 km from the city of Manaus, and from the confluence of the Negro and Amazon rivers. According to Köppen classification, the local climate is "*Am*" equatorial hot and wet, with temperatures between 25 and 30 ºC, concentrated rains between January and May, and average annual rainfall of 2200 mm/y. Lake Tupé is connected to the Negro River by a narrow and shallow channel, which receives the waters of the Negro River only when the river level exceeds the elevation of 19 meters above sea level (a.s.l.), the rest of the hydrological year remaining isolated from the river waters. The lake basin has steep margins, with a triangular cross-section ("V" shape), slightly dislocated to the right, and very well protected from the action of the winds by dense tree vegetation. A detailed description of the region, including information on geology, geomorphology, geochemistry and limnology, can be found in other studies [4-9].

3. MATERIALS AND METHODS

To establish the model of physical and chemical stratification in Tupé Lake, data of temperature (ºC), dissolved oxygen (DO mg/L) and oxygen saturation (OS %) determined with WTW OXI-197 probe with coupled thermistor were used. Eleven sampling sites, including the main streams and the connection channel with the Negro river (Fig. 1), in the interval between 2001 and 2018 were measured. Measurements were taking vertically every 0.5 m between the surface and the bottom of the lake, for periods of flood, flood-peak (high waters), low and dry (low waters). Two nichtemeral samples (24 hours) were also performed within this period, with an interval of three hours at the deepest site of the lake (central station – site 10), in the periods of flood and ebb. Considering the variations in the volume and depth of the lake during the study period, the total sampling frequency (N) was 2416 data for each parameter analyzed. Speed (U_w m/s) and wind direction data were estimated using a portable anemometer and local observations of current flow on the surface of the water column. The results of the bathymetry were obtained in the low water period with Eagle sonar probe with GPS connected, and maps developed from images generated with Global Mapper 11.01© 2009 and Google Earth© 2017 for the high and low waters periods were considered for the model [5,6]. Transparency data (Z_{ds} m), incident radiation index, reflected and refracted radiation were obtained with Quantum Radiometer LI-COR Li-250 probe and sub-aquatic sensor LI-COR Li-192SA. Euphotic zone (Z_{eu} m) and the attenuation coefficient (K m) were also considered [4-6]. The results were used for the construction of the model, which mean data (mean ± SD) were applied. The density of water at depth Z (p_z) was determined considering the respective temperature at each meter in the water column. For this, a relationship between the values described by Birge [10] and the density calculated from equation 1 [11] was established. The salt content present in the water samples was estimated from the sum of the main ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^-/CO_3^{2-}), and a linear regression equation was established for determination of specific conductivity (EC_S; equation 2). The density was then correlated with the salt content, considering that 1 g/L of salt increases the density by 0.00085 g/cm [12]. Total density (*p*) was plotted against EC_S to determine its trend. A correlation analysis between temperature and PAR radiation was performed to establish an association with local seasonality. Once the amount of light incident on the water surface (L_{obt}) was obtained using a radiometer, the refraction curve and the calculation of the luminous radiation decay (L_{calc}) were determined, applying the fundamental decay of the solar radiation by the Lambert -Beer Law (equation 3) [13,14]. A summary of the hydraulic and radiological data proposed by Aprile [5,6] is shown in Table 1.

Since we consider that Tupé Lake presents itself for most of the hydrological year in isolation or with a minor contribution from the Rio Negro, from a physicochemical point of view (temperature, pH, alkalinity, conductivity, total solids, etc.), we suggest that the limnological characteristic of the lake is primarily due to metabolic activities and autochthonous processes. Thus, we could establish calculations of residence time and flow for the lake, as if it were a natural reservoir. Considering that the diffusion coefficient of solar radiation, responsible for the heating and heat exchange process between the underlying water layers, is assumed to be constant and not turbulent, as will be discussed in due course, we established the integrated energy balance model as the most suitable for Tupé Lake. From these premises, we established that the physical (thermal) stratification process followed the one-dimensional transient non-turbulent heat transfer process, defined in equation 5 [15], and that presents variations for deep lake environments (reservoirs). For this, where it assumes that the cross-sectional area is constant.

$$p_Z = \left[1 - \frac{T + 288.9414}{508929.2\,(T + 68.12963)}(T - 3.9863)^2\right] \qquad \text{(eq. 1)}$$

Where: p_Z (g/cm^3) is water density; and T (ºC) is temperature.

$$EC_S = 1.6559x\;[major\;\;ions] + 26.917 \qquad R^2 = 0.9661 \qquad \text{(eq. 2)}$$

Where: EC$_S$ (μS/cm) is the specific conductivity.

$I_z = I_0\,.\,e^{-kz}$ (eq. 3) can be written as; $I_z = (1-\beta)\,I_0\,.(1-\alpha_W)\,e^{-kz}$ (eq. 4)

Were: I$_o$ (μE/m^2.s) is the light radiation in the air near the surface water; *K* (m) is the attenuation coefficient; *Z* (m) is the depth (for z>0); *β* is the proportion of absorption of short-wave solar radiation on the water surface; and αW is the albedo of water.

$$A_Z\left[\frac{\partial T}{\partial t} + V\frac{\partial T}{\partial z}\right] = \frac{\partial}{\partial z}\left[A_Z\,(K_M + K_H)\frac{\partial T}{\partial z}\right] - \frac{1}{p_Z c}\frac{\partial (A_Z I_{\mathrm{B}Z})}{\partial z} \qquad \text{(eq. 5) [15]}$$

Were: A$_Z$ (m^2) is the area of the cross section as a function of the depth z, which in this case was considered constant, adopting the average depth ($\bar{z}$ m) at each sampling site; T (ºC); V (m/s) is the vertical speed; K$_M$ (m^2/s) is the molecular diffusion coefficient and K$_H$ (m^2/s) is the turbulent diffusion coefficient for heat; *p*$_Z$ (kg/m^3) is water density in the depth Z; c (J/Kg ºC) is the specific heat of the water; I$_{βZ}$ (W/m^2) is the short-wave solar radiation absorbed internally along the water column.

Considering the bottom laminar flow as a unidirectional flow (see item 5.1 Finite Diffusion Model), which follows the main channel of the lake, in the direction of the headwaters to the lake-river connection channel (Fig. 1), a comparison of the results was established with the modeling of thermal stratification phenomena, which normally uses the dimensionless number of Froude (equation 6) [16], which represents a relationship between forces of inertia and gravitational forces. The Froude number is a dimensionless value, which brings together the main characteristics of stratification and morphometry, being widely used to know the behavior of a reservoir before the start of its operation [17]. Besides, the Fr value is applied in mathematical models compatible with the future physical conditions of the system, and is also used to establish predictions about the behavior of the future reservoir.

$$Fr = \frac{U_0}{\left(|g|\,D\,\frac{|\Delta p|_{\max}}{p_0}\right)^{1/2}} \qquad \text{(eq. 6) [16]}$$

Were: U_0 (m/s) is the average speed of the water, taking into account the flow and the main channel area in the period; g (m/s^2) is the acceleration due to gravity; D (m) is the diameter of the 'tubular figure' closest to the reality of the laminar flow channel; Δp (10^{-3} g/cm^3) is the difference between the water mass densities of continuous strata; p_0 (10^{-3} g/cm^3) is the water density.

Table 1: Hydraulic and radiologic data of the Tupé 'Ria' Lake – Amazon for the period between 2001 – 2017 [5,6].

Aspect	Value	Aspect	Value
Surface area^1 (A km^2)	0.67	Wind (U_w m/s) low waters	6±1.2
Volume^1 (V m^3)	1.44×10^6	$Z_{eu}{}^3$ (m) hw	3.0 – 4.5
Max depth^2 (Z_{max} m)	5.60	K^4 (1/m) hw	1.0 – 1.3
Mean depth^2 ($\overline{Z}$ m)	2.10	$p_z{}^5$ (kg/m$^{3)}$) hw	0.994
Max declivity (α_{max} m/km)	4.10	Z_{eu} (m) lw	3.4 – 3.8
Total declivity (α_{total} m/km)	1.90	K (1/m) lw	1.1 – 1.3
Wind (U_w m/s) high waters	31±3	p_z (kg/m$^{3)}$) lw	0.996

[1]To the low waters; [2]to the central station (site 10); [3]Z_{eu} euphotic zone for 1% of light; [4]attenuation for $k=4.59/Z_{eu}$; [5]water density in Z depth.

4. RESULTS

Figure 1 shows the results of the analysis of wind direction and surface (e) and bottom (h) currents, predominant in the hydrological year. The bottom lake currents, responsible for the formation of the laminar flow in the hypolimnion, originate at the headwaters of the forest streams, and come from the north and northeast regions of the lake. The influence of the prevailing winds in the most exposed areas, without marginal vegetation, establishes a continuous flow of surface currents (e) in the final portion of the lake, before its connection with the Negro river through the connection channel. This section coincides with the deepest and inverted cone shape of the lake, called 'central station', where there is an intersection of the two largest channels that form Lake Tupé. The consequence of this, previously studied, is the accumulation of fine sedimentary material in the lake bed, with higher rates of organic matter and elements C, N and P [6,8,9,18].

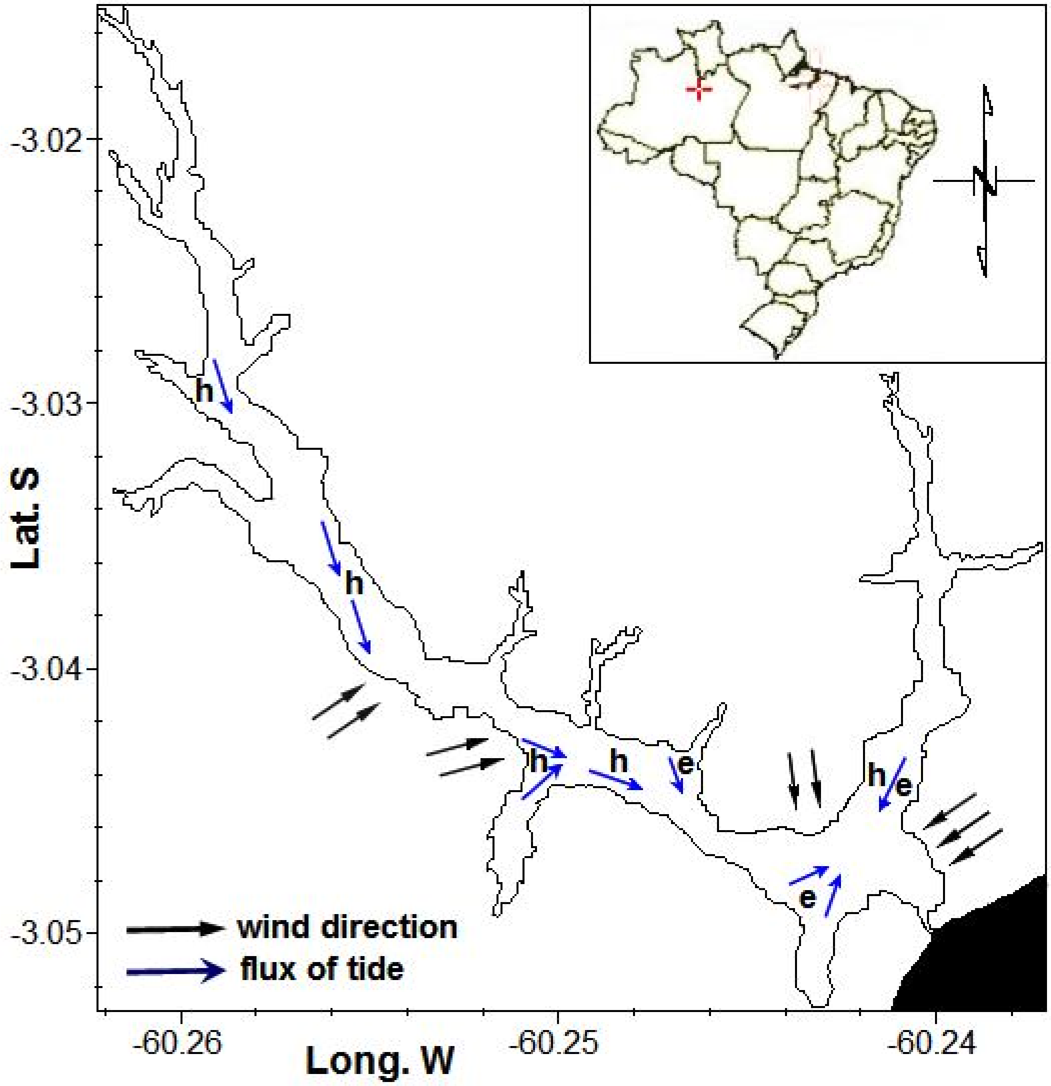

Figure 1: Lake Tupé in the Rio Negro basin. Detail for vectorization of the main currents of winds and tides throughout the hydrological year. Surface currents (e) and bottom currents (h).

The water cycle establishes four stages for the hydrological region: periods of flood, flood-peak, ebb and dry. Despite this, in the region two important moments can really be evidenced, the period of connection of the lake and river waters (lake - river), and the period of isolation of the lake. At first, there is a contribution of water (by volume) from the Negro River, without major changes in the physical-chemical and consequently biological composition of the lake, only a slight dilution factor in the concentration of certain elements, such as P and N, as it has been observed previously [6,8,9]. In the second hydrological moment, there is an absolute isolation of the lake waters, with the contribution only of the forest streams. It is in this period that we can observe the real composition of the black water lakes. Thus, we can briefly establish two moments for this type of lake: period of high waters (with connection to the river) and low waters (without connection with the river). From the water temperature point of view, the high water period is marked by a greater range of variation between the maximum and minimum daily in the epilimnion, while the temperature fluctuation in the same layer during low water shows a greater regularity in behavior. In the hypolimnion, the water temperature has a lower oscillation at both times (high and low waters), due precisely to the continuous laminar flow in the lake (Fig. 2). Still analyzing the Figure 2, we can observe that in the high waters the oxygen both dissolved (mg/L) and in the saturation factor (%) has strong daily amplitude in the upper layers (epilimnion) and almost imperceptible variation (limit tending to zero) in the deepest layers. The daily oxygen amplitude model also suggests that saturation improves slightly during periods of low waters, although stratification remains unchanged. This is not due primarily to the gas exchange in the water column, but to the better oxygenation of deep waters from the forest streams. We must also consider that within the range of observation and analysis from 2001 to 2018, there were at least two periods of significant influence of climatic phenomena in the Amazon, resulting from the currents of El Niño. In most of the floodplain in Central Amazonian, the volume of water in rivers and, consequently, in lakes has been reduced by this global climatic phenomenon. Despite this, the pattern and tendency for permanent stratification of black water lakes does not appear to change.

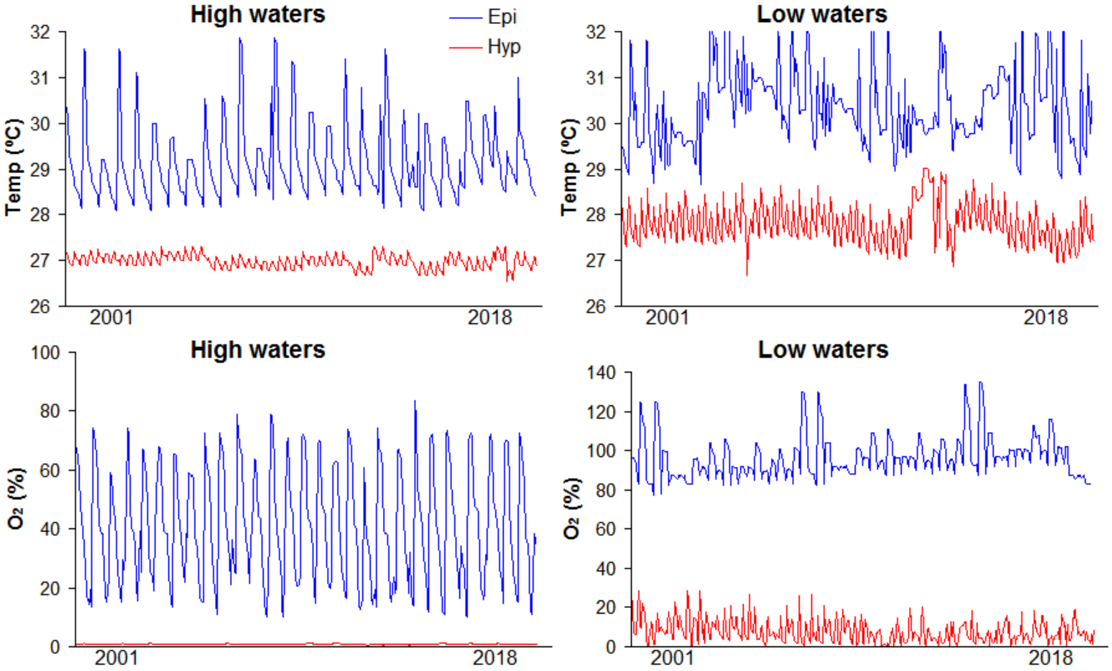

Figure 2: Spatial-temporal variation (2001 - 2018) of temperature (ºC) and oxygen saturation (%) for the hydrological year in Tupé Lake, Negro River basin - Amazonian (N= 2415).

By establishing a standard curve model for water density in the vertical column of Tupé Lake, we obtained distinctly significant patterns between the upper layers, which make up the epilimnion, from the lower layers, which form the hypolimnion. From a numerical point of view, the difference in water densities between the two layers (epilimnion and hypolimnion) may seem insignificant, on the order of |0.0009| in the high waters period and |0.0004| in the low waters. The application of the t-test of significance even suggests that the means are not different, as shown in Table 2. Despite this, Pearson's correlation analysis was very low between the respective means, suggesting that there is no correlation between the results. In fact, the general trend observed in Figure 3 reinforces the existence of a physical 'barrier' (density) between the surface and deep waters of the lake. This phenomenon is intensified when is considers not only density (numerical value), but also ionic concentration (main ions). Considering the data analysis period of almost two decades (2001 – 2018), with interference and influence of various climatic events throughout the period, e.g. El Niño, La Niña, intense rains, strong winds on the surface lake and the 'coldness' (friagem), a regional phenomenon in Central Amazonian that causes momentary retention of cooler air masses close to the surface of lentic water bodies, the trend observed brings to the research strong confidence in the results. For the establishment of the curve model, the values of the cross-sectional area of the main channel of the lake (Eq. 5) were calculated with result estimated at A_Z= 24.3 m^2. The average depth of the hypolimnion and Froude number obtained from equation 6, whose average value ranged between 0.21 and 0.27, also were considered. The results showed that Tupé Lake presents a highly stratified reservoir behavior, according to the classification suggested by Nogueira [19]. Based on the historical results evaluated in this study, we reaffirm the model of circulation of water masses from Tupé Lake, proposed in Figure 4, and which is not an exception, but a trend to "Ria" black waters lakes initially established by [7] in the Amazon region.

Table 2: Pearson's correction test and significance of means (student's t).

	Average	SD	N	df	r	t_{obt}	t_{crit}	*P* ,05
HEp vs HHy	0.9959	0.0003	2416	2414	0.0054	0.03	1.96	0.98
LEp vs LHy	0.9957	0.0003	2416	2414	0.0689	0.29	1.96	0.77

SD= standard deviation; df= free degree; t_{obt}= t obtained; t_{crit}= t critic.

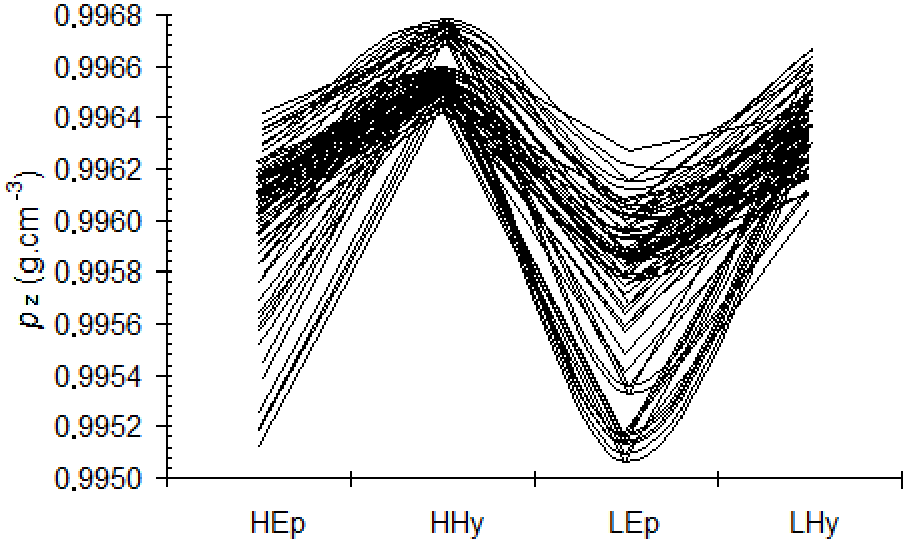

Figure 3: Spatial-temporal distribution of water density based on temperature and charge of the main ions (Σ mg/L) in Tupé Lake for the hydrological year. H= high waters; L= low Waters; Ep= epilimnion and Hy= hypolimnion (N = 2416).

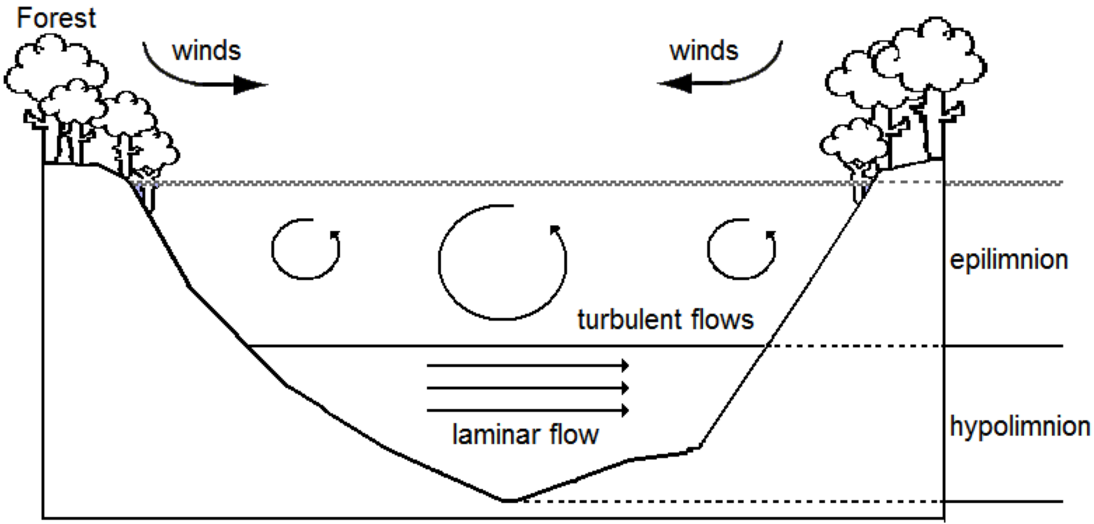

Figure 4: Laminar flow model to Tupé Lake (Central Amazonian, Brazil).

5. DISCUSSION

In the case of thermal stratification, the mechanisms of heat exchange in the water column occur preferentially at the air-water interface, although there are side and bottom exchanges (water-sediment interface), both of which are less representative. This reinforces the importance of climatic components, such as the action of winds and precipitation, for the stratification phenomenon. As already defined, stratification implies evident differences in temperature or concentration of elements (for example, gases or ions) in two or more adjacent water layers. Several studies have established that vertical heat transfer can follow two trends: the integrated energy balance model, whose layers are generally well-defined and homogeneous (epilimnion, metalimnion and hypolimnion), as the proposed model for water circulation in meromictic lakes [5], and the turbulent diffusion model, whose main characteristic would be the absence of homogeneity of the water column [20,21]. Unlike white water lakes, whose concentration of suspended material and nutritional elements (C, N, P, K, Ca, Mg etc.) are moderately variables and distinct in the vertical column, generally increasing their concentrations with the depth of the reservoir or lake, at the same time as an internal circulation is manifested with swirling evidence [22], in Tupé Lake the condition of meromyxia is intense and predominant in the hydrological year, establishing parallel flows of water but with homogeneity in the conductivity, salinity, pH, and nutrients in general. For this reason, the integrated energy balance model remains the most suitable for the studied lake system, with a thermocline inside the metalimnion, an unclear layer, and characterized by a maximum temperature gradient, reinforced by the dispersion of heat in the bottom by the laminar flow action.

5.1 Finite Diffusion Model (FDM)

The thermal stratification model used in this study is generally applied to reservoirs based on meteorological data from the lake. In this sense, the main factor considered in the calculation of the system's thermal regime is the result of heat exchanges, which occur at the air-water interface, and which is dependent on the interaction between incident light radiation (I_0), radiation emitted by the surface of the water (I_z), loss of energy by evaporation, and variation of energy by sensitive heat. It should be noted that the side heat sources, heat dissipation and heat flows from the deep layers were originally neglected. Speed and direction of the wind are also parameters used to estimate the heat exchange coefficient. Other models also consider the function of wind speed to be fundamental to estimate latent heat flow, sensitive heat flow and heat exchange coefficient [23]. In this case, the surface area of the lake and the height at which the wind speed is measured are important for the adjustment of the speed function, since this function is defined for specific bodies of water.

Despite the resistance imposed by the adjacent forest, acting as a natural barrier to the action of winds on the surface of Tupé Lake, it is possible to observe some agitation in the water mirror. Thus, the first layer of water was established as isothermal, conditioned by climatic factors, and with a mixture caused by the wind action. From the second layer of water, evidenced by the gradual change in temperature and oxygen concentration, the heat diffusion process begins. However, unlike other models found in the literature, the deeper layers do not have a state of energy conservation, since cooler waters from the forest streams flow horizontally at the bottom of the lake. This statement is confirmed by the results for the vertical temperature and dissolved oxygen profile presented above. The continuous and almost permanent unidirectional laminar flow from the forest streams guarantees the state of non-conservation of energy at the bottom of the lake, with constant renewal and variation of this behavior. Studies developed by the authors to assess the sedimentary load accumulated in Tupé Lake over the years, even suggest a large discrepancy in the values of organic matter and organic carbon between the superficial and deep layers of the lake, of 30 to 100 units.

5.2 Diffusion of temperature and oxygen

In the work carried out by Antonopoulos and Gianniou [24], the vertical temperature distribution for Vegoritis Lake, in Greece, was estimated so that its implication in the distribution of dissolved oxygen strengthens the existence of temporal patterns of thermal stratification. In the respective study, these two water quality parameters were estimated using numerical models. The study showed that in stratified lakes, the thermocline became a barrier for the transfer of oxygen from epilimnion to hypolimnion. Therefore, the availability of oxygen was confined to the epilimnion, as noted by the authors. On the other hand, there was a decrease in the oxygen dissolved in the hypolimnion, motivated by the breathing of aerobic organisms. These characteristics proved to be very dependent on the stratification cycle for the lake. This same pattern had already been observed in previous studies on Tupé Lake by Aprile et al. [4,5]. Heat exchanges through the air-water interface were considered by [25] to be the most important factors that govern water temperature. The authors presented a mathematical linearization model and developed a physical interpretation for the heat exchange coefficient and the equilibrium temperature at the air-water interface, in order to justify the application of this method in energy balance models in body's waters.

5. CONCLUSION

This study, since it was started in 2001, has already shown the trend confirmed in this historical monitoring of almost two decades. The "Ria" type lakes, with black waters in the Negro River basin, exhibit both thermal and chemical permanent stratification (meromyxia) intensified by geomorphological characteristics, the flow of laminar currents from the forest streams and the structure of barriers to wind in the water surface. The consequences of this permanent stratification are the lack of exchange of gases and nutrients between the water layers, consequently interfering in the biological pattern of aquatic organisms, especially the benthic groups. In fact, the continuous and almost permanent unidirectional laminar flow from the forest streams guarantees the state of non-conservation of energy at the bottom of the lake, with constant renewal and variation of this behavior. The unidirectional laminar flow model for the Tupé Lake, and extrapolating to the Amazonian black water lakes, was the best explanation for the presented trends. The laminar flow model established for the lake highlighted the partial circulation of water in the epilimnion. The condition of permanent stratification is not usual to be observed. The model, generally applied to natural reservoirs, proved to be appropriate for the studied lake (case study). Thus, the results can be used in the study of other lakes of Ria in the Amazon region.

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