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Dynamics of Phosphorous in an Amazonian Meromictic Black-Water Lake

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Abstract

This study proposed to find the main pathways of phosphorus (P) to a black water lake shore in Negro River (Central Amazonian), and develop a model of nutrient flow for fluvial-lacustrine ecosystems of black water with a pattern of meromixis water circulation. The levels of P in the compartments water, soil plus litter and sediment were evaluated from 2002 to 2011, and a mapping of distribution of P was developed. The results showed that the Negro River could not supply the black water lakes adjacent with P, leaving the forest streams a significant role in transporting the same, especially in the dissolved form. The flood-pulse of the Negro River does not contribute significantly to elevate levels of oxygen in the hypolimnion, and thus does not favor phosphorous ions precipitation to the sediment. The transport route of P comes from both the forest and streams of the adjacent river system depending on the hydrological period. The particular model for the phosphorous seeks to explain the process flow and the importance of anoxic condition in the hypolimnion to keep up the release of phosphate to the ecosystem.

Keywords: Phosphorus flow, trace metal, mathematical model, water circulation, Amazon.

Introduction

In the Central Amazonian, the variation in the nutrient load in the fluvial-lacustrine systems, especially C, N and P, is directly associated with the flood-pulse of large rivers such as the Solimões River and Negro River. The flood-pulse[1] is responsible for transporting nutrients through the great rivers to the channels, floodplains, streams and lakes in the Amazonian lowlands and, in turn, is associated with the regional hydrological cycle. The flood-pulse concept was reworked by Neiff[2], who pointed out that ebb and flood both periods have equal importance in aquatic ecosystems stability. The variations of water level and flood-pulse causes a number of changes in limnological characteristics of an aquatic ecosystem, such as variations of the transparency, turbidity, pH, electrical conductivity, concentration of gases (O_2, CO_2 etc.), and nutrient content. Therefore, it can be said that the charge that supplies nutritional Amazonian lowlands, coming from the highest parts of the biome as Andean and Pre-Andean regions, depends on the water level of major rivers. In high water periods, the sedimentary material is transported to the floodplain, which responds to this action by developing a high biological diversity included in a vast trophic network. This process is clearly visible in the white water bodies such as Amazon, Solimões, Madeira, Juruá and Purus rivers, where the load of suspended matter is high and rich in ionic elements[3,4] such as Fe^{2+}, Fe^{3+}, Mn^{2+}, Ca^{2+}, Na^{+} and K^{+}. However, in the lakes and channels of black water there is another force of great importance to the aquatic ecosystem called forest streams. These systems transport naturally organic matter and often carry humic substances from upland forest to the lakes and channels, giving to the aquatic ecosystem characteristic acidic water ranging from ocher-colored wine.

There are many issues that need to be better answered as: Have the seasonality significant influence on the flow of nutrients? How to process the flow of phosphorous under the conditions of the hydrological cycle in rivers and lakes of black water of the Amazon? How the flow of nutrients occurs and what the connectivity means to the lake? What is the flood-pulse and forest streams influence on the flow of nutrients in black water lacustrine systems? Does the anaerobic condition identified in Amazon shallow lakes interfere in the flow of phosphorus in the water column? For answer those questions is necessary to understand better the fluvial-lacustrine systems of black water on the limnological aspects.

Based on this complex system of nutrient transport, responsible for biological dynamics in Amazonian ecosystems, this study aims to find the main routes (dynamic) of flow of phosphorus to a black water lake (Tupé Lake) and to develop a model nutritional flow systems for the fluvial-lacustrine black waters, based on observations and interpretation of historical data for hydrological cycles from 2002 to 2011.

Material and Methods

Study area: This study was developed in the Tupé Lake, a black water lake on the banks of the Negro River, which among other advantage is easily accessible, being 25 km from Manaus (Amazonian), and focuses a great deal of research in the areas of limnology, botany and zoology, among others[5-7]. A very comprehensive approach to the physical diversity and specificity of terrestrial and aquatic ecosystems was described[5,8,9]. Tupé Lake is a floodplain lake in Negro River, the largest black water river in the world. Its format is dendritic, with steep banks in a valley in a "*V*" shape, whose main slope moves to the center of the lake, called the central station. In the proximal part of the Negro River, the shores of the lake are predominantly composed of white sandy banks, with low concentration of organic material. As it moves away from the Negro River toward the equatorial forest, it is noted that the lake will present higher concentrations of silt and clay, mixed with litter and decomposed organic matter. The lake is protected from direct action of wind on the water surface, since their margins are higher and mostly surrounded by forest (figure-1). As a typical black water ecosystem, the Tupé Lake has narrow bands of wetlands in headwater areas and in streams and valleys surrounding the same. With hydrological characteristics similar to other lakes in flooded areas of the Amazon, the Tupé Lake is under flood-pulse influence due to local hydrological cycle. So, in this lake until the smallest quota of 19 meters its waters and the waters of the Negro River may have similar level fluctuation[8]. Below that elevation, the lake remains isolated from the river influence receiving only contribution of forest streams and rainfall.

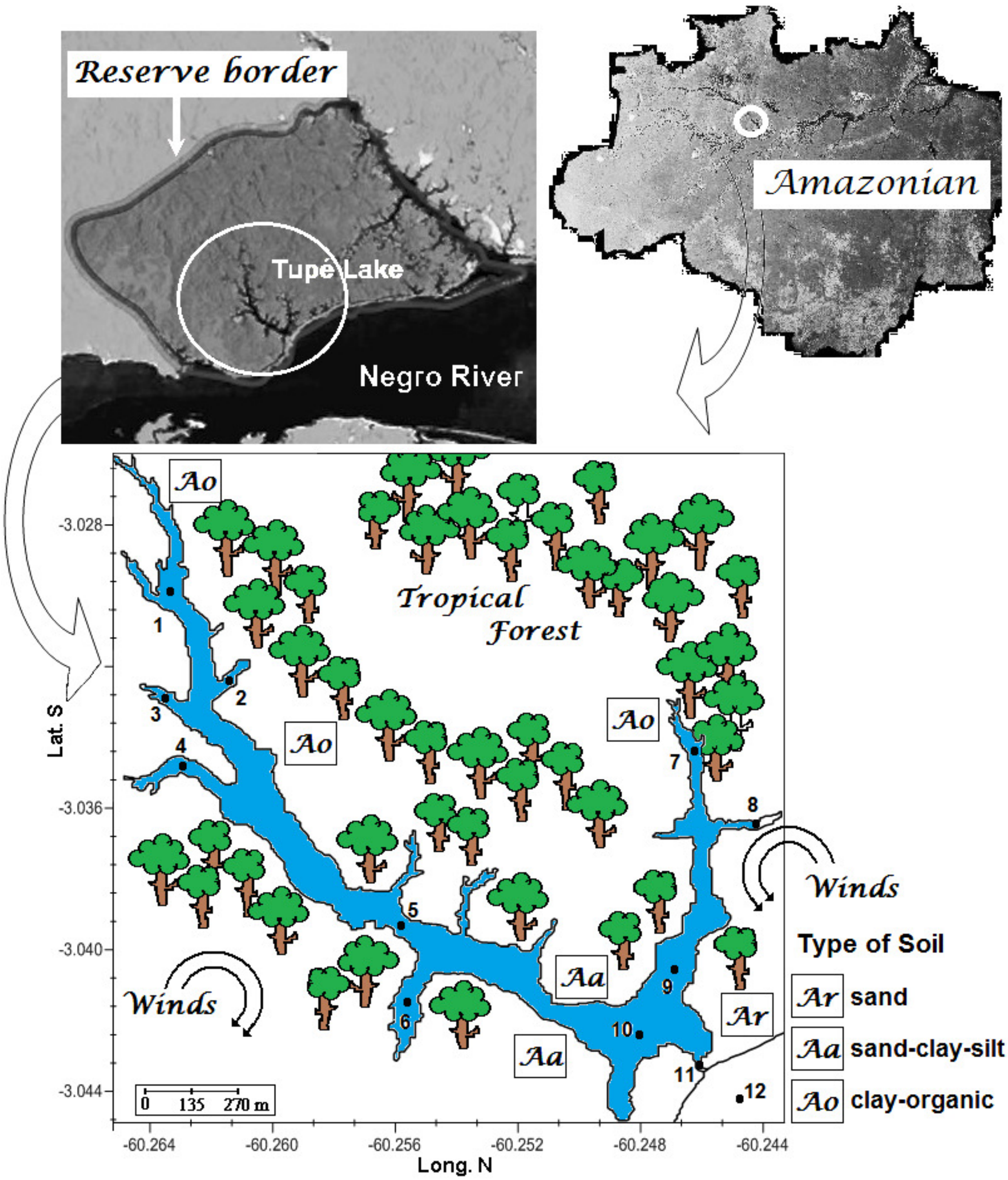

Figure-1
Tupé Lake localization with its sampling stations and type of soils, Central Amazonian

Analytical procedures: For this study limnological data from physical-chemical limits, water, soil plus litter and sediment sampling were collected, as well as information on the rainfall and the fluviometric characteristics of the lake were obtained bimonthly during the hydrological cycle from 2002 to 2011 in twelve sampling stations. Bathymetry was developed in the dry and flood periods with a bathymetry-sonar Eagle model with GPS connected. The models generated in this study were obtained from the analysis and interpretation of results for the flood, flood-peck, ebb and dry sampled periods. The lake was compartmentalized so that they could determine the direction and senses the nutritional flow, and was considered for analysis compartments water, soil plus litter and sediment. All limnological determinations followed international protocols referred for collection and conservation[10]. The variable temperature (°C), dissolved oxygen (DO ppm), oxygen saturation (O_2%) and pH were determined in horizontal and vertical profiles (every 0.5 m) with portable WTW probe to find the presence or absence of processes of stratification physical (thermal) and/or chemical (O_2 saturation) in lake system, as well as interference possibility from the pH in the immobilization process of the ions. That information is very important for models construction, as well as for to explain the flow of phosphorus. Transparency (m) with euphotic limit (Z_{eu}) in meters was determined with Secchi disc, and attenuation coefficient ($K=4.59/Z_{eu}$) was calculated from Secchi disc results. Density ($kg.m^{-3}$) was calculated from temperature date. In laboratory were performed the analysis of phosphorous in the forms total (ppm P_t), dissolved (ppm P_d) and particulate (ppm P_p), organic matter (%OM) and Fe^{3+} levels (%) in the respectively compartments. Phosphorus was determined by method of extraction of the ascorbic acid with spectrophotometer at 725 nm, according to methodological adequacy[11], OM concentrations were determined by relation with organic carbon from COD analysis, and trivalent iron level was determined by the AAS method according proceedings from sections 3500-Fe B, 3111B and C[12], respectively. The results were statistically analyzed by applying the Pearson's correlation matrix; multiple linear regression and *F*-test for: i. to find out the degree and direction of association between the variables studied; and ii. to determine the co-dependence on a variable with the group, especially phosphorous in relation to their reason.

Model construction: The model was based on conceptual and compartmental (mass balance) models. Differential equations and a flow model for phosphorus were presented from the limnological and geochemical studies, using the Tupé Lake as a basis for understanding the behavior of the flow of nutrients in lakes of black water of the Amazon. For developing the model, however, it was necessary to better understand the existing degree of seasonality in the region studied, and how to process the physical and chemical limits, especially water temperature, dissolved oxygen and density. Thus, it wanted answers to some basic questions highlighted over a decade of research on the Tupé Lake, answers those very important to building of the flow model: i Does the flood-pulse of the Negro River contribute much to elevated levels of oxygen in the hypolimnion of the lake, favoring ions phosphorus immobilization by organic compounds and iron ions (Fe^{3+}), and benefited by acidic pH? ii. What is the Negro River and forest streams contribution in the supply of nutrients for the metabolism of lentic ecosystems of black waters? iii. Does the degree of each contribution to depend on the period of the hydrological cycle?

A flow model based on the behavior of the mass balance of the phosphorous was developed, it designed for contextualize the flow of nutrients between the different compartments in the fluvial-lacustrine ecosystem.

Results and Discussion

Physical-chemical data: Within the hydrological cycle from 2002 to 2011, the results of water temperature showed a greater oscillation of the more superficial layers, with an interval between 27.9ºC and 32.4ºC and annual average 30.1±0.6ºC. The deeper water layers, however, did not show the same intensity oscillation along the hydrological cycle, ranging from 27.0ºC to 27.5ºC and annual average of 27.3±0.02ºC. Saturation of oxygen had a behavior very similar to the water temperature, with high O_2 saturation in the upper layers ranging between 37.6% and 148.6% with an annual average of 81.0±8.9%, and low variation in the deeper layers of the lake hovering between 0.0% (anoxic condition) and 8.0% with annual average of 1.7±1.8%. Table-1 shows the results of this monitoring effort seasonality. In Tupé Lake there was always a totally anoxic layer of water at certain periods of the hydrological cycle, an important fact to explain the behavior of ions phosphorous in modular system.

Seasonality was quite clear in the Tupé Lake, especially with regard to changes in temperature and DO. It should be mentioned that in stations 9 and 10, in the central station and deepest of the lake (figure-1 and figure-2), which reaches up to 15 meters in flood-peck, the highest concentrations of O_2 saturation always occurred during the dry periods, when the O_2 reached its highest values and remained between 100-120%. It was also during dry periods than at other stations the saturation remained high between 80-100%, including the monitoring station on the Negro River (station 12). In contrast, in periods of flood-peck, the O_2 saturation in the surface layers has always remained close to 80%. This marked difference between hydrological periods (dry and flood-peck) diametrically opposite of temperature and oxygen values reinforces the question there was influence of the seasonality in the nutrients flow, since both oxygen solubility as the temperature value in the water are directly associated with the processes of stratification and redox potential.

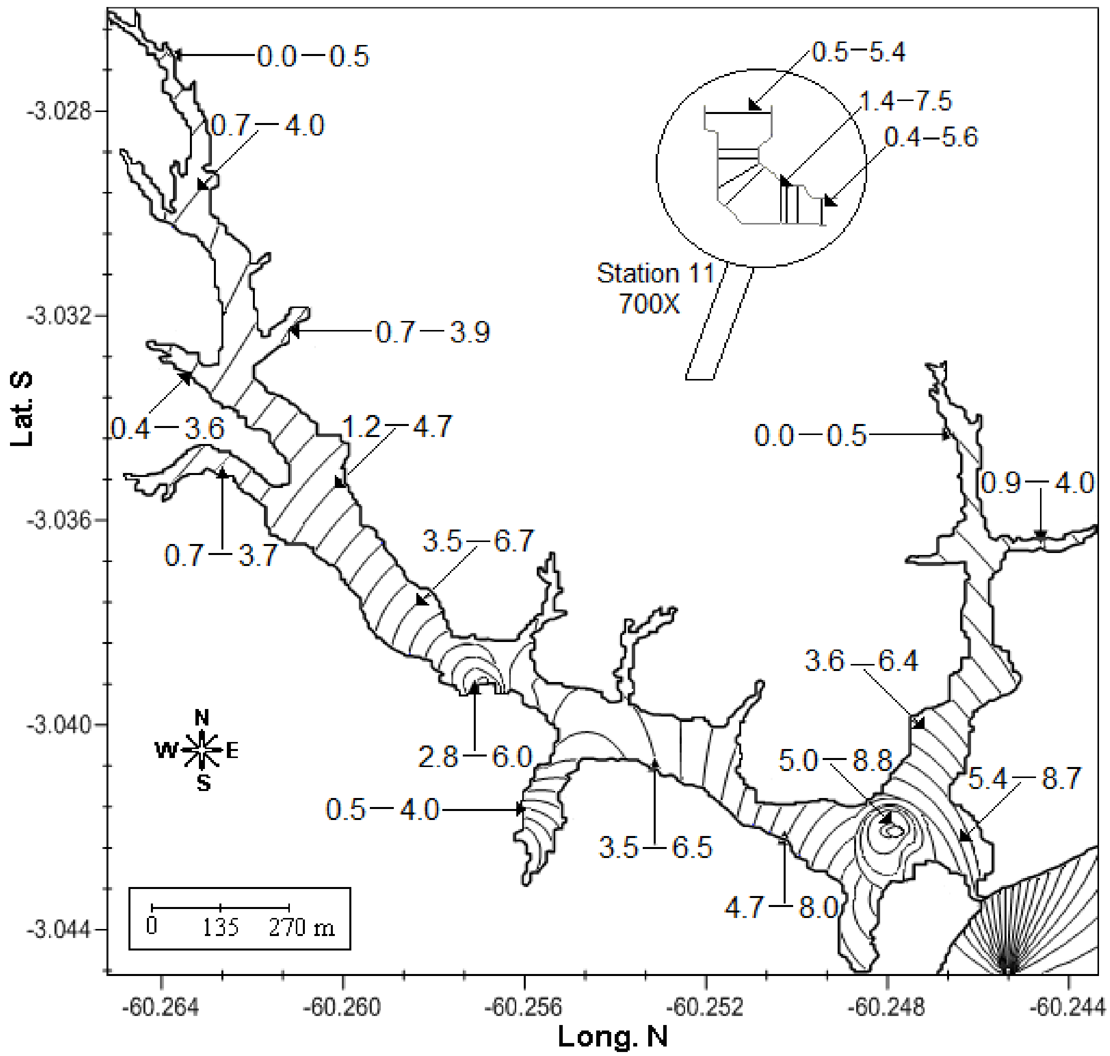

Figure-2

Bathymetry of the Tupé Lake in the Negro River basin, Central Amazonian, Interval variation for dry and flood periods, respectively

Analyzing the data of temperature and O_2 saturation in the water inside a vertical profile (surface to bottom) and space-time distribution for the hydrological cycle, it is noted that the results confirmed the trend behavior of the curve by Darwich et al.[8]. The authors suggested that there is a physical (thermal) and chemical (DO) stratification across the lake and throughout the hydrological cycle. Oxygen saturation in the hypolimnion of the lake were always reduced due to stratification, however, although the profile of the lake is stratified, there is laminar flow presence (figure-3) towards the headwaters to its mouth, in Negro River, which could have an important role in the nutrients distribution from the sediment compartment to the water column. Once in the lake its shores are high and partially surrounded by the tropical rainforest there is little direct influence of winds on its lake (figure-1). The result of this phenomenon is almost absent formation of "waves of the lake", which reduces possibility complete mixing of the water column, contributing to the lake stratification. Moreover, this process is of fundamental importance to consider the difference in water density with temperature variation. Especially in that area where temperatures in the epilimnion can reach high values (34ºC or up). Thus, small differences in the Amazonian region can set temperature stratification (physical and chemical) stable. The amount of energy required mixing stratified water masses between 32ºC and 33ºC is 40 times greater than that needed to mix the same masses between 4ºC and 5ºC. In Tupé Lake, the water column presented temperature range of about 6ºC in low water periods and nearly 3ºC in the flood-peck periods. In this temperature range the water column during the dry is about two times more stable than the flood-peck. If these data are compared with temperature variations of the temperate region, it appears that the water column in Tupé Lake would be about seven times more stable than the same column of water between 4ºC and 10ºC (same temperature range). During these years of study was noted there is only a partial mixing of the upper layers (figure-3).

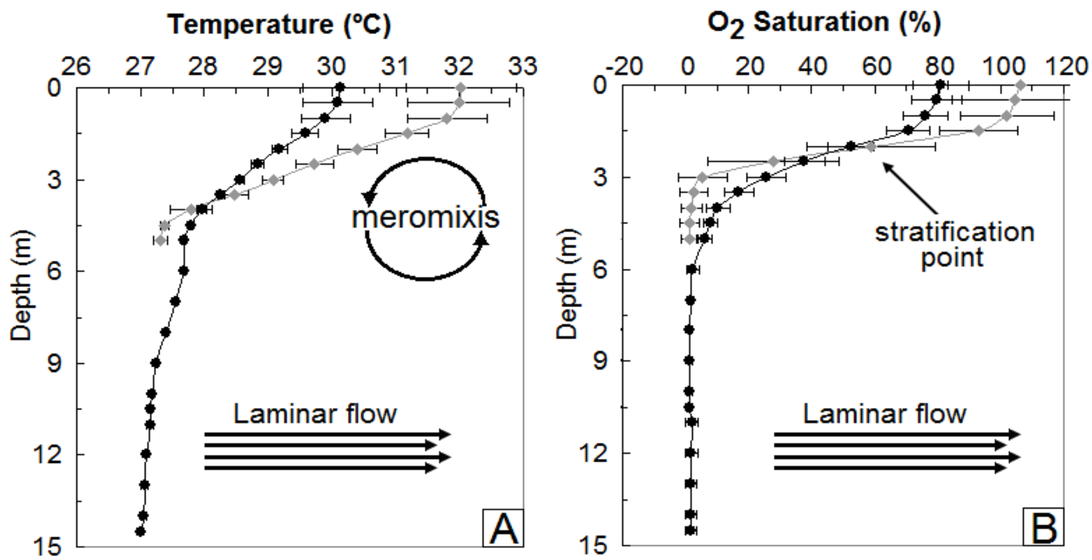

Figure-3

Profile of A) physical stratification (thermal) and B) chemical (DO) in the water column of Tupé Lake with average data for the 2002-2012 hydrological cycles. Black line means flood-peck and gray line means dry period

The Tupé Lake is a lake with difficult movement, with only mixed evidence of the more superficial layers in all periods of the hydrological cycle, which characterizes it as a meromictic lake (figure-3), unlike many of polymictic lakes of the Amazonian. The lake is permanently stratified contributed to answer the question that the flood-pulse of the Negro River, during the periods of flood and flood-peck, does not contribute much to elevate levels of oxygen in the hypolimnion, and thus does not help the precipitation of ions phosphorous to the sediment. Total P in water, soils and sediment ranged according to table-1 values in the three layers (epilimnion, metalimnion and hypolimnion). The results showed higher concentrations always in the surface water layers of the lake, demonstrating that there is a flux or source of P from the forest streams to the lake.

Based on the concentrations of phosphorous of the compartments studied a map of distribution was elaborated by the method of kriging (figure-4). The highest phosphorous concentrations found remained off the stretch of the stations 9 and 10. The sampling stations in forest streams had a greater representation for the phosphorous also highlighting the stations 2, 3, 7 and 8 in the forest streams. Total phosphorous at the channel connection (station 11) and Negro River (station 12) always presented for all compartments low concentrations of P. The evidence were obtained through chemical analysis and confirmed by analysis of isovalues (figure-4). More that the lake remains almost permanently stratified, reinforce that the Negro River alone could not supply black water lakes adjacent with nutrients, and so the forest streams have a role in transporting the same for the lake water column, especially in the dissolved forms. Thus, the results refute the possibility that the Negro River plays an important role to offer phosphorous to the lakes through the flood-pulse. The route of transmission of nutrition comes from both streams forest and the adjacent river system, depending on the period of the hydrological cycle.

The results of the Pearson's correlation for phosphorus (table-2) respond statistically the question on the influence of flood-pulse and forest streams in the flow of nutrients in black water lakes, in the same time that confirmed the route of nutrients comes from both the transport of forest streams and of the Negro River. However, the principal participation of supplying nutrients is from the forest streams. The correlations between the lake area and the forest streams were strongly positive, with Pearson's r over 0.92 to $p < 0.0001$. The results show also there is no significant contribution of phosphorus from the river to the lake compartments. In fact, as already discussed, the hypolimnion stratification and low concentrations of suspended solids in the Negro River reduce any contribution chance of this for the sediments of the lake. The exception was the channel of connection (station 11), that had a strong correlation with the Negro River (station 12) because present for all compartments of low phosphorous concentrations with similar composition and grain size, contends basically sand without OM. The clearest correlation between lake and river, in terms of differentiation, was also due to the sediment compartment, because differently of the river's sediment in the lake the sediments are predominantly formed by mud (rich in clay plus OM). On other hand, in both lake and forest streams the sediments are composed of organic matter in various states of decomposition, mineral particles and an inorganic part of biogenic origin. Form the substrate unbound in the bed of streams and lake both represent a fundamental compartment as the cycling of matter and energy flow in water systems. They reproduce the activities of environmental parameters and offer a record of local dynamics.

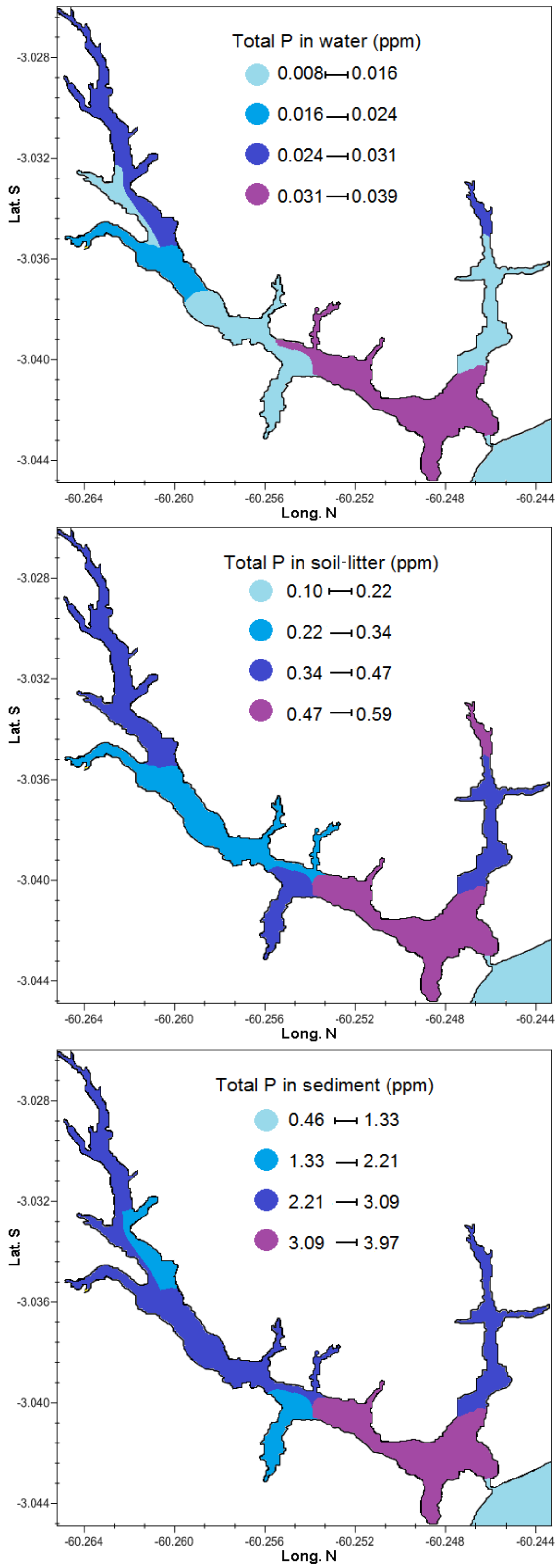

Figure-4

Isovalues total phosphorous determined from the average for the compartments water, soil plus litter and sediment in the Tupé Lake, Central Amazonian

Table-1
Mean values ± SD for the environmental variables used to P flow model construction

Period		**Temp** (ºC)	**Satur** (%)	**pH**	**Z_{eu}*** (m)	**K^a** (1/m)	**D_z** (kg/m^3)	**OM** (%)	**Fe^{3+}** (%)	**P_{water}** (ppm)	**P_{soil}** (ppm)	**$P_{sediment}$** (ppm)
flood	E	28.7±0.1	23.8±24.3	3.9±0.4			0.994		0.50±0.07	0.01±0.02	0.12±0.06	0.87±0.21
	M	28.0±0.3	18.7±12.3	4.0±0.2	4.45	1.03	0.994	80.5±3.8	0.43±0.04	0.02±0.01	0.09±0.03	0.43±0.11
	H	27.3±0.2	2.1±5.8	4.0±0.1			0.994		0.22±0.04	0.01±0.01	0.23±0.11	2.35±0.44
flood-crest	E	28.4±0.1	27.5±14.9	4.1±0.3			0.994		0.50±0.13	0.02±0.02	0.15±0.21	1.18±0.61
	M	28.0±0.1	19.3±7.5	4.1±0.2	3.00	1.24	0.995	82.2±5.4	0.44±0.07	0.01±0.02	0.12±0.11	0.97±0.58
	H	27.4±0.3	2.6±5.9	4.0±0.1			0.995		0.28±0.06	0.04±0.01	0.22±0.10	1.54±0.22
ebb	E	30.8±0.4	17.6±25.5	4.5±0.2			0.995		0.51±0.06	0.03±0.02	0.32±0.21	2.36±1.12
	M	29.1±0.6	18.2±15.2	4.3±0.2	3.42	1.11	0.995	84.1±5.2	0.46±0.03	0.01±0.01	0.16±0.12	1.11±0.88
	H	27.6±0.4	1.8±2.3	4.0±0.1			0.996		0.29±0.07	0.03±0.01	0.42±0.21	3.13±0.45
dry	E	31.7±0.4	101.4±17.9	4.4±0.1			0.996		0.52±0.06	0.02±0.01	0.51±0.11	3.27±0.68
	M	29.1±1.0	19.3±25.8	4.2±0.1	3.48	1.32	0.996	85.1±8.9	0.46±0.06	0.01±0.02	0.18±0.09	1.55±1.01
	H	27.4±0.1	1.3±2.8	3.9±0.2			0.996		0.33±0.07	0.04±0.01	0.61±0.02	3.91±0.31

*Z_{eu} euphotic zone for 1% of light; [a] attenuation for $k=4.59/Z_{eu}$; E= epilimnion, M= metalimnion and H= hypolimnion.

Table-2
Pearson's correlation analysis for total phosphorous in the lacustrine-river system of the Negro River, Central Amazonian (*n*=290)

		Lake x Streams		**Lake x River**		**Streams x River**	
	stations	Pearson's r	*p* <	Pearson's r	*p* <	Pearson's r	*p* <
Water	1 x 2	0.96	0.0001				
	1 x 3	0.94	0.0001				
	5 x 6	0.92	0.0001				
	7 x 8	0.98	0.0001				
	10 x 12			0.56	0.0001		
	11 x 12			0.88	0.0001		
	2 x 12					-0.33	0.0001
	6 x 12					-0.42	0.0001
	8 x 12					0.28	0.0001
Soil + litter	5 x 6	0.88	0.0001				
	7 x 8	0.89	0.0001				
	9 x 12			0.47	0.0001		
	11 x 12			0.78	0.0001		
	8 x 12					-0.42	0.0002
Sediment	1 x 2	0.87	0.0001				
	1 x 3	0.86	0.0001				
	5 x 4	0.74	0.0001				
	7 x 8	0.98	0.0001				
	10 x 12			-0.46	0.0001		
	11 x 12			0.91	0.0002		
	6 x 12					0.36	0.0033
	8 x 12					0.42	0.0286

Flow model: The flood-pulse contribution to the Tupé Lake is limited to the surface layers of water, especially with regard to oxygen and the supply of phosphorous, and not for the system due to the permanent stratification of the lake. Thus, one must understand the river flow (V_f) is a force directed preferentially to the epilimnion, which in this case may bring fractions of nutrients during high waters (flood and flood-peck), and this way will be consumed by the planktonic communities of the lake. This modeling has been suggested that in the epilimnion (V_eB_e) acting preferably non-conservative forces, since both DO and temperature fluctuate daily (24 hours) and seasonally (hydrological cycle), while in the forest stream ($V_{fs}S_{fs}$) and hypolimnion (V_hS_h) acting predominantly conservative forces, since it is permanently stratified and anoxic, serving as the receptor of nutrients from the sediment compartment. It was also suggested that the allochthonous nutrient contribution from the soil, particularly the litter contribution, is not conservative ($V_{sp}B_{sp}$), since the rains that cause leaching are seasonal.

Flow models interpretation of P took into consideration: i. the concepts of ecosystem, structure and trophic dynamics, ii. the law of conservation of mass, iii. law of the minimum Leibig and iv. the laws of thermodynamics. The model developed related the flow and inflow of P between compartments associated (figure-5), from environmental variables interference: density, temperature, pH, DO and redox potential. Were also indicated in the model the process of assimilation and release of nutrients by biota (V_bS_b), considering that once the law of conservation of mass and law of the minimum go through the process of increasing biomass (assimilation) followed by senescence, with release of nutrients back into the system. Simultaneous with the conservative forces inclusion, the nonconservative forces are acting on the system transport mechanisms with uptake and release/decomposition, such as leaching of soil and litter ($V_{sp}B_{sp}$). Both depend on rain action and of the changes occurred in the epilimnion (V_eB_e), by the variations of light intensity and rainfall, which in turn alter the temperature and DO concentrations in this layer of water. In practice, part of the nutritional elements can be stored indefinitely in compartments called stocks, such as sediment, and its release into the water column depends on the environmental variables. The phosphorous flow in fluvial-lacustrine ecosystems at the Amazon black water showed a pattern of water circulation of type "meromictic", depends on input and output loads variation of the sediment and soil plus litter compartments, as well as the physical-chemical conditions of the hypolimnion. There was a not conservative way (*VB*) for sediment and soil plus litter compartments, and a conservative way (*VS*) to the hypolimnion and sediment compartments. Precipitation part was included in the model due to its existence in the system. However the same was not computed to be defined the degree of its contribution. Finally, the flow model developed had as aim trying to explain flow pathways and the crucial role of anoxia in the hypolimnion to keep up the release of phosphate to the fluvial-lacustrine ecosystems of black water at the Amazonian, according to Equation 1 developed for figure-6.

Conditions: Layers definition ⇒ variables (temp + Z_{eu} + K + D_z), Direction ⇒ from epilimnion to hypolimnion
P-flow ⇒ variables OM and Fe^{3+} in determined conditions of pH and DO

$$\frac{d(VS)}{dt} = \sum_{i=1}^{\infty} (V_{in}S_{in} - V_{out}S_{out}) = VS \quad and \quad \frac{d(VB)}{dt} = \sum_{i=1}^{\infty} (V_{in}B_{in} - V_{out}B_{out}) + \Delta B \quad \therefore$$
$$B(t) = \left[(\Delta V_s B_s + \Delta V_{sp} B_{sp} + \Delta B)(1 - e^{-(\frac{k}{V})t})\right] + \left[B(\Delta V_s S_s + \Delta V_{fs} S_{fs} (e^{-(\frac{k}{V})t})\right] \tag{1}$$

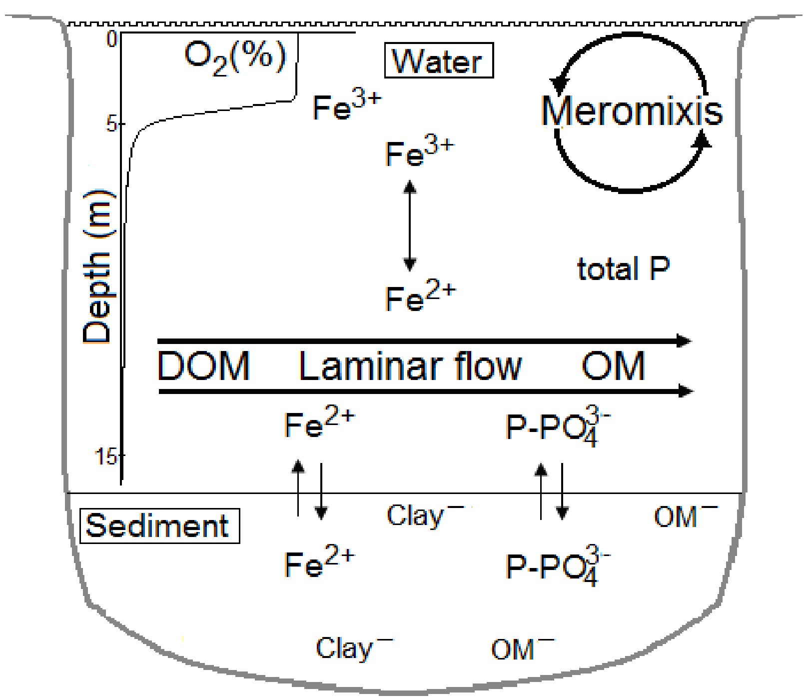

Figure-5
Model of phosphorous flow pathways and their components to the black water lakes of the Central Amazonian

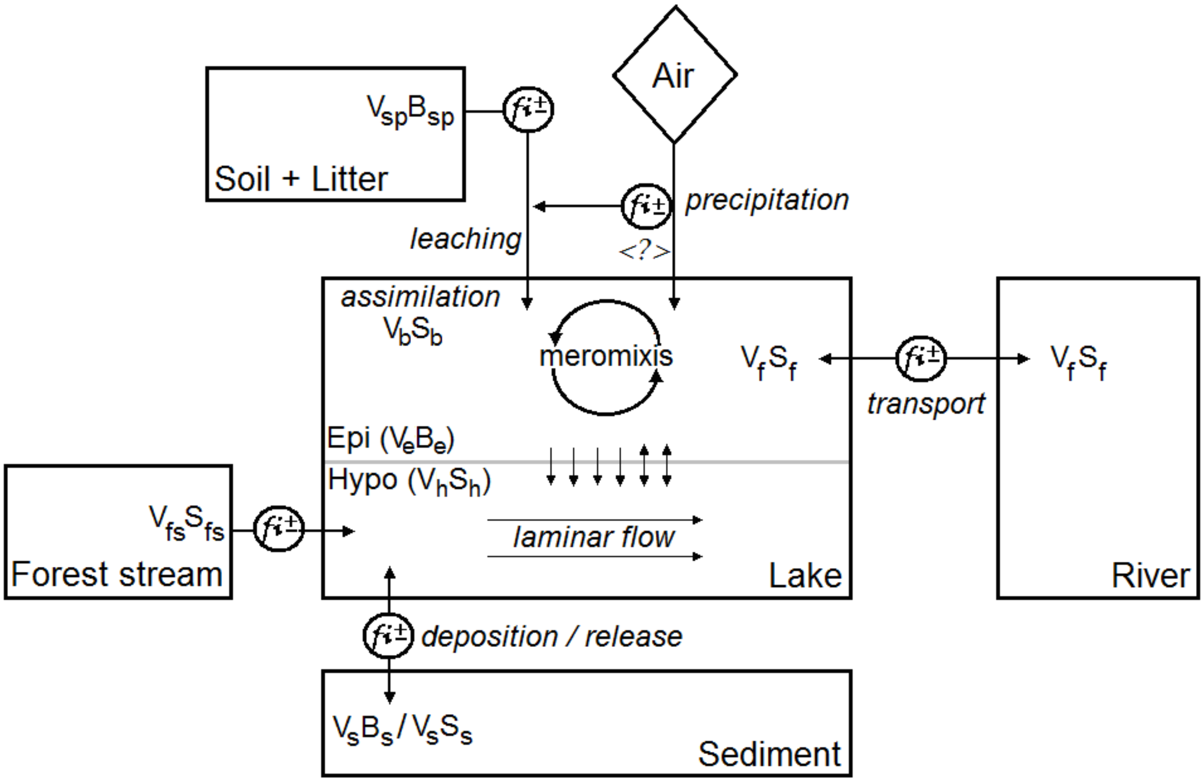

Figure-6
Dynamics of phosphorous in anaerobic conditions in black water lakes of the Amazon, OM = organic matter and DOM = dissolved organic matter

Discussion: Once in the water column, phosphorous starts to circulate between the plants and animals to return the rock matrix. For its ability to form water-soluble compounds, the phosphorous can easily be transported by rainfall, soil and litter action to water bodies, causing eutrophication of the environment. The increase of phosphorous in aquatic ecosystems can degrade water quality, since high concentrations of this element stimulates algae growth and accelerate the eutrophication process[13]. The development followed by the decomposition process of algae, in a short time, causes drastic decrease in the levels of DO in the water column, especially due to oxygen consumption in the process decomposition. This phenomenon result the killing of several aerobic organisms, especially fish such as occurs in lakes and coastal lagoons of urban centers. The growth of algae can be followed by the uncontrolled growth of aquatic macrophytes, and both contribute to water transparency reduction. The low transparency associated with increased total suspended solids hinders light penetration in the water column, reducing the process of photosynthesis, which in turn causes the death of more algae, followed by decomposition and further reduction in oxygen levels the ecosystem. This process remains active until there is a permanent reduction in the levels of dissolved nutrients and the system returns to equilibrium. Most often, however, the phosphorous can act as a limiting factor of the system, act directly in regulating the growth of primary producers of the food net. In the black water of the Amazon the levels of inorganic nutrients are always very low. Studies have suggested that there is a seasonality associated with the distribution and concentration of phosphorous in aquatic ecosystems[3,14]. According to these authors, total phosphorous concentration is about 11 times higher in the waters of the Amazon River than in the Negro River. That is explained by the fact of in the white water the high load of silt and clay, transported in the form of suspended material, is often associated with the phosphorous soluble in water. But then, how to process the flow of phosphorous forms under the conditions of the hydrological cycle in the Tupé Lake and so, in others black water lakes? What is the role of the flood-pulse and forest streams in the flow of the lake? To understand the process it is necessary to know that several physical, chemical and physical-chemical cycles can interfere with phosphorous in the water column, especially in their precipitation and mobilization, and for the conditions of the lakes of black water of the Amazon stood out the following factors: concentration of humic substances and soluble iron ions, temperature, pH and DO levels in addition to the conditions generated by them in the redox process. Humic substances, represented by fulvic and humic acids, formed from the decomposition of plant material from the forest, controlling the pH levels, which ranged in Tupé Lake along the hydrological cycle between 4.1 and 4.5 ensuring favorable conditions for solubilization of ferrous ion (Fe^{2+}) and precipitation of ferric iron (Fe^{3+}), which is soluble only at pH less than 3-3.5. The temperature interferes directly in the process of physical stratification of the water column, while the pH and dissolved oxygen have a strong influence on ionic activity, especially in waters having a low concentration of suspended matter, such as the black waters. Both control the oxidation state of iron ions (Fe^{2+}/Fe^{3+}), which in turn, has great action on the dynamics of phosphate in the aquatic environment. This is a cyclical type reaction of cause and effect, where the different variables involved influence and are influenced by other factors. The process begins when iron and manganese are present in the water column. What will control the redox process is precisely the environmental variables action: pH, DO and organic compounds. In black waters, and especially in certain conditions of meromixis in Tupé Lake, the conditions of oscillating pH within the range of acidic to slightly acidic ($3.5 \leq pH \leq 4.5$) and low oxygen concentrations and potential redox, favoring ferric to ferrous reduction, which is soluble in the ionic form and/or bicarbonate [$Fe(HCO_3)_2$]. In addition, the ferrous ion may also remain associated with humic substances, absorbing other ionic elements. Once there is no oxidation of the iron from Fe^{2+} to Fe^{3+}, that in the pH conditions of the Tupé Lake precipitate and/or stay complexed to the sediment, and because the deeper layers of the lake remain permanently with low levels of oxygen, is not formed an oxidative layer in the border area between the water and sediment compartments. This layer has the role to keep P in the sediment as long as oxidative conditions in the hypolimnion. In continental tropical waters it is usual to see the phenomenon of adsorption followed by total deposition of P, once in these waters there is higher concentration of ferric iron (Fe^{3+}) than phosphate ion ($P\text{-}PO_4^{3-}$). Thus, the Fe^{3+} adsorb to the particles of iron hydroxide all soluble forms of phosphorous, transporting it to the sediment, which in these conditions presents a brownish, typical of limonite presence. In the black waters, however, the reductive condition is prevalent to oxidative condition, especially in the deeper layers of the water column, preventing the oxidation of Fe^{2+}, which in association to dissolved organic compounds remains part of phosphorous in the water. Thus, it is concluded that precipitation and immobilization of phosphorous forms and its consequent removal of metabolic processes that control the dynamics of aquatic ecosystems, does not occur in great magnitude in the Tupé Lake (figure-6). This phenomenon could be extended to all the lakes of black water with meromixis in the Amazonian, what would answer the question that speculate if the anaerobic condition present in Amazon shallow lakes interferes in the flow of phosphorus in the water column.

One of the most striking characteristics of the floodplain and wetlands is the high content of organic matter accumulated in soil and sediment, which account for the high productivity in these ecosystems[15-18]. A significant part of this material comes from the forest streams, which contribute mainly with dissolved nutrients. In the description of the study area was mentioned that most of the soils that make up the lake shore are composed of clay and silt, rich in organic matter from the litter produced by equatorial forest. The litter is a key source of supply of nutrients to water systems. The annual production of litter depends on the type of vegetation and its response to seasonal variations, and in the rain forests, such as the Amazon, the hydrological cycle has greater influence on the seasonality of production. This plant material is leached and transported by the rains and the waters of the lake during periods of flood, going to make up the lake sediment. This fact was confirmed by Aprile et al.[5] to study aspects of geochemistry and sediment dynamics of the Tupé Lake. The main property of the sediment is their ability to accumulate organic matter, to store nutrients, especially P, and act as active matrix in biochemical processes of transformation of substances[19,20]. Sediment rich condition in organic matter and clay makes this compartment a supplier of phosphorous to the water column in an anaerobic condition (figure-6). In addition, the sediments of wetlands have great importance as an electron acceptor and receiver, especially for phosphate and nitrogen forms.

Conclusion

The study showed that the main source of phosphorus in the lake comes from the forest streams and not from the Negro River, as previously thought. Another important conclusion is that contrary to what occurs with the white water lakes of the Amazon floodplain, in the Negro River basin the lakes are not controlled by the flood-pulse. Amazonian black water lakes with circulation pattern type meromictic present specific features of trophy, especially for limiting nutrients such as phosphorus, and knowledge of flow pattern is fundamental to understand the relationships of richness and abundance of species of the study environment.

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