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Pairing Quantitative and Qualitative Analyses during Flooding Event in Mamiá Lake (Amazon River)

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Authors' contributions

This work was carried out in collaboration between all authors. All authors participated of the samples collection, date and statistical analysis and wrote the first draft of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Aims and Place: The variable transparency, temperature, dissolved oxygen, conductivity, pH, total suspended solids (TSS), turbidity and ion balance (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^- + CO_3^{2-} and SO_4^{2-}) were measured in surface waters of the Amazon River and Mamiá Lake during the hydrological cycle 2008 – 2009 in order to understand the influence of fluvial-lacustrine connectivity in lentic systems of the Amazon floodplain.

Methodology: International standards methods of collection, transportation, preservation and analysis were used in this research and the results were statistically analyzed (Cluster and PCA) to verify the existence of seasonality, interference of the flood pulse and similarities between the sampling sites.

Results and Conclusion: A standard mixing and movement of water was identified for the Amazon River and its channel of connection, while the lake remained stratified throughout the study period. Statistical analysis confirmed seasonality in fluvial-lacustrine system, especially during periods of flooding (F) and ebb (E), when there was a significant change in the waters chemical composition of the lake and channel. Principal Components Analysis (PCA) identified the parameters conductivity, TSS and turbidity as indicator variables of the existence of flood pulse from the Amazon River to the Mamiá Lake.

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Keywords: Ionic balance; seasonality; connectivity; flood pulse; Ria lake; Amazon floodplain.

1. INTRODUCTION

Generally, in floodplains the fluvial-lacustrine systems show high variation of the abiotic and biotic parameters, which are consistent with seasonal variations in the hydrometric levels of the main rivers, which Junk et al. [1] designated flood pulse. This phenomenon results in significant changes in the physical and physic-chemical composition of water from the floodplain lakes and also seasonal changes in diversity and dynamics of aquatic organisms [2].

In most of continental water systems the conductivity and ionic composition are highly correlated and are determined mainly by the cation calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}) and potassium (K^{+}), and anions bicarbonate ($HCO_3^{-)}$, carbonate (CO_3^{2-}), sulfate (SO_4^{2-}) and chloride (Cl^{-}) all vital to physiological and biochemical processes in plants and animals, and participating directly or indirectly of the chemical equilibrium of the water.

As there are pronounced differences in the chemical composition of the waters of the various integrated compartments (river, lake, channel, rainwater, sediment etc.) conductivity and the total ions have an important function as indicator of changes in the chemical composition of the lakes associated to the hydrological periods [3,4]. The ionic concentration helps to understand the effect of the flood pulse in the lakes, since it is subject to annual hydrological variations. As a result of periodic change, the water chemistry of floodplain lakes is mainly determined by the supply of dissolved substances and organic matter from the main river, and depends on the deposition and resuspension of the lake sediments [5,6].

In Ria lakes the ionic content is influenced mainly by the contribution of its former river and forest streams from upland that drain their basins. Besides, all set depends on the geology of the fluvial drainage area, as well as precipitation that is also seasonal. Little is known about the hydrochemical amount resulting of influence of the flood pulse on Amazon floodplain lakes. The knowledge of this abiotic dynamic is of fundamental importance for the understanding of biotic processes, and essential for the preservation and management of aquatic fauna. The main scientific contribution of this research is that this is the first study conducted in a large Ria lake in the Western Amazon. Thus, the objective of the study was to show the seasonality and variation in the chemical composition of fluvial-lacustrine waters under the influence of the flood pulse.

2. MATERIALS AND METHODS

2.1 Study Area

The Mamiá Lake is a Ria lake located on the right bank of the Amazon River, in the Coari City, State of Amazonas (04º06'19,8"S – 63º00'04,0"W), distant 350 km west of the Manaus City. It has about 50 km long and 3 km width, and an area of approximately 150 km^2. The lake is permanently connected to the Amazon River (Fig. 1) by a channel of 120 m width and 12 km length. The lake receives water from forest streams that drain the upland.

2.2 Analytical Procedures

Water samples were collected in eight sampling sites distributed: three on the Amazon River, three in Mamiá Lake and two in the channel of connection during periods of flooding (F 13.1 m), flood-peck (Fp 15.7 m), ebb (E 8.9 m) and early-flood (eF 7.8 m) of the hydrological cycle 2008 – 2009 (Fig. 2). The parameters temperature (ºC), dissolved oxygen (DO mg/L), conductivity (EC μS_{25}/cm) and pH were measured in situ with portable probes. The analytical determinations are summarized in Table 1 and were carried out at the Chemical Laboratory of Water/CBIO/INPA, based on the recommendations of the International Biological Program aquatic environments [7], and followed the analytical procedures described by [8-12]. It was also considered the analytical adjustments and calibration curves used by [13].

2.3 Statistical Analysis

The results were analyzed using descriptive statistics, Cluster and Principal Component Analysis (PCA) with PC-ORD® Software 6.0, to observe significant differences and seasonal clusters between sampling sites, as well as to confirm the flood pulse influence. Considering the irregularly spaced data, a geostatistical gridding method denominated *Kriging* [15] was applied to determine the connectivity between Amazon River and Mamiá Lake using Secchi, TSS and turbidity as variables and Software Surfer® 9.11. The results were normalized based on the equation 1, and a connectivity index (CI) was obtained based on the most significant hydrological period for the flood pulse (eF).

$$CI = \frac{TSS + Turbidity - Secchi}{TSS + Turbidity} \tag{1}$$

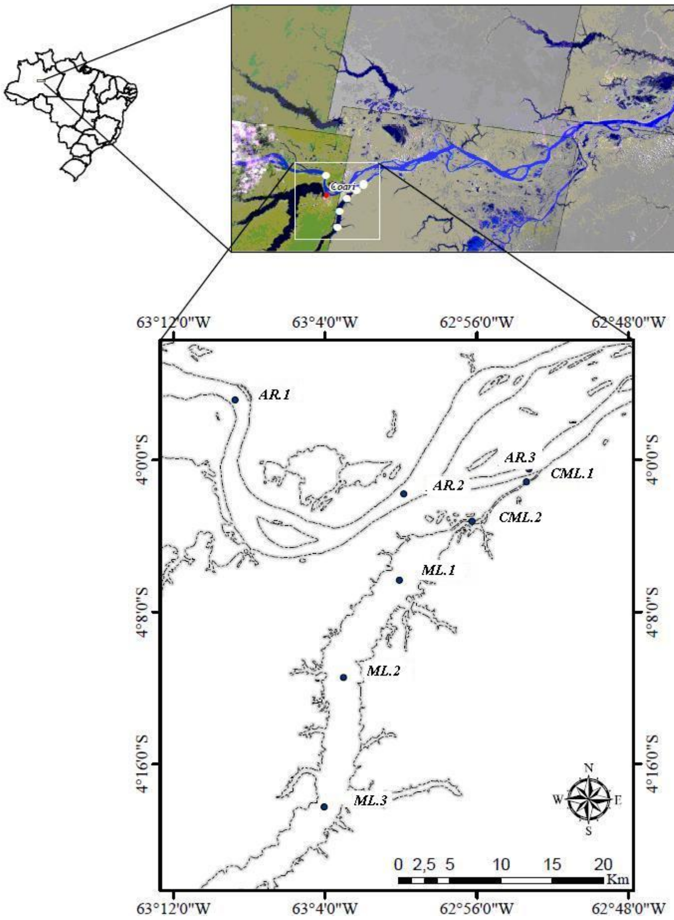


Fig. 1. Mamiá Lake and Amazon River with their sampling sites
(Source: LANDSAT/INPE – 2010)

Table 1. Summarized methodology

Parameter	**Method**
Temperature (ºC)	Potentiometric WTW Model 197
Dissolved oxygen (DO mg/L)	
Electric conductivity (EC μS_{25}/cm)	
pH	
Transparency (m)	Secchi disk
Turbidity (NTU)	Turbidity Orbeco-Hellige Digital Model 966
Total suspended solids (TSS mg/L)	Gravimetric [a]
HCO_3^- (mg/L)	Potentiometric titration [b]
Cl^- (mg/L)	Titration with $Hg(NO_3)_2$ [c]
SO_4^{2-} (mg/L)	Spectrophotometer (Model FEMTO 700S) [d]
Na^+, K^+, Ca^{2+} and Mg^{2+} (mg/L)	Atomic Emission Spectroscopy (EPA 3015) [e]

[a,b,c] [7]; [a,b] [9]; [a,b] [11]; [a,c,d,e] [12]

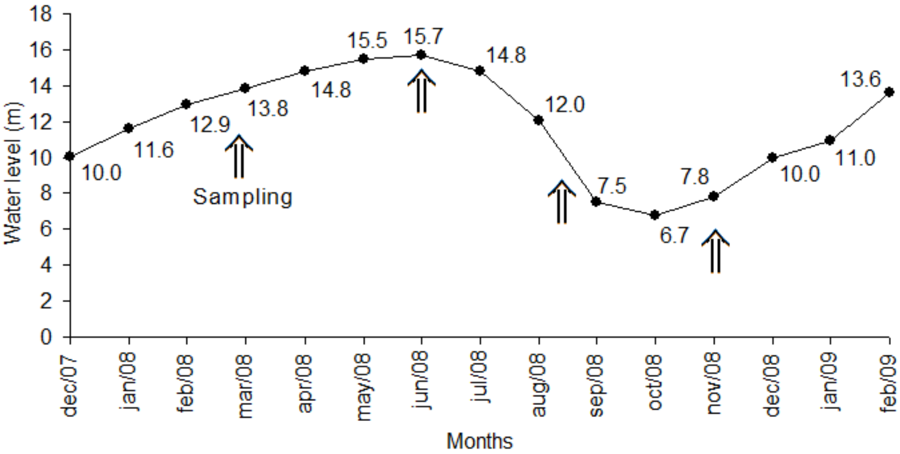


Fig. 2. Annual quota of the Amazon River level (m) in Itapeuá Station (04°3'28.08''S-61°1'40.08''W), adapted from the National Information System on Water Resources [14]

3. RESULTS AND DISCUSSION

3.1 Limnology Parameters

Water transparency (Secchi) ranged from 0.15 (F) to 0.32 (E) meters in the Amazon River and 1.23 (eF) to 2.40 (E) meters in Mamiá Lake. In the same period the concentration of TSS in the Amazon River ranged from 169.7 (F) to 50.0 (E) mg/L, demonstrating an inverse correlation (p= -0.7822) in relation to water transparency. However, this correlation was not evident to Mamiá Lake (p <0.24), where the concentration of TSS ranged from 13.7 (eF) – 7.3 (E) mg/L. In this case, it is evident that the lentic hydrodynamic, which is variable depending on the flood pulse and of the influence of forest streams, is interfering in maintaining the solids in suspension. Turbidity confirmed the pattern of seasonal variation in both systems (lotic and lentic) with values 57.4 (Fp) – 173.3 (F) NTU in Amazon River, and 1.5 (Fp) – 15.6 (eF) NTU in Mamiá Lake (Tab. 2). High TSS and turbidity levels are commonly observed in lakes of the Amazon plain influenced directly by the flood pulse, as shown studies of [1,16,17]. The connection channel plays an important role between the fluvial and lacustrine ecosystems, especially in periods of high hydrodynamics (flooding and ebb), influencing the load of sedimentary material transported on the river-lake direction during the flood periods.

The lower TSS and turbidity levels observed in F and E periods reflect mutually the sedimentation in the period and the higher contribution of the waters of forest streams from upland, which drain the lake basin. In the Amazon River this variation is a result of excess leaching before of the high-waters and the reduction of rainfall in the ebb period. That interaction associated with the water level that occurs between the drainage basin and the floodplain lakes, is decisive to the maintenance of trophic chains and biodiversity, as demonstrated by Casali et al. [17] for phytoplankton community of lakes in the Amazon plain and by Aprile and Darwich [6] in studies of water-forest interactions in the Catalão Lake. Melack and Fisher [18] reported that during the low-waters periods in the Calado Lake (Middle Amazon River) the resuspension of sediment increased the turbidity, increasing the supply of nutrients for the biological communities. In general, in Amazon floodplain lakes turbidity and TSS are controlled by the: 1) water into the Amazon River; 2) length and sinuosity of the channel of connection; 3) morphometry of the lake, and rainfall. Besides, it is also important the re-suspension of sediments in the low-waters periods influenced by winds. All these factors also have a strong influence on the TSS, turbidity and transparency levels in Mamiá Lake. The next area to the channel of connection is under greater influence of the sediments load transported by Amazon River, especially in eF periods. The connectivity index (CI), obtained from the equation 1, showed strong relationship in the river-lake system during the study period, with CI 0.6188 in Fp; 0.7334 in E; 0.8163 in F and 0.9502 in eF. From the highest CI (eF periods) the results were applied to the isovalues chart with geostatistical analysis (Fig. 3).

Table 2. Average values of transparency (Secchi), TSS and turbidity in the waters of the Amazon River (AR), channel of connection (CML) and Mamiá Lake (ML) in the hydrological year 2008 – 2009

Period	Site	Depth	Secchi (m)	TSS (mg/L)	Turbidity (NTU)
F	AR	Surface	0.15 (±0.00)	169.67 (±26.39)	173.27 (±11.91)
	CML	Surface	1.25 (±0.07)	9.00 (±1.41)	3.90 (±0.00)
	ML	Surface	1.57 (±0.12)	6.00 (±1.00)	2.63 (±0.42)
	ML	Bottom	-	-	-
Fp	AR	Surface	0.27 (±0.03)	52.00 (±15.52)	57.43 (±17.31)
	CML	Surface	0.75 (±0.07)	3.50 (±0.71)	2.20 (±0.49)
	ML	Surface	2.17 (±0.23)	5.67 (±3.79)	1.55 (±0.36)
	ML	Bottom	-	-	-
E	AR	Surface	0.32 (±0.03)	50.00 (±11.53)	57.87 (±7.15)
	CML	Surface	1.45 (±0.21)	8.00 (±4.24)	5.65 (±1.77)
	ML	Surface	2.40 (±0.00)	7.33 (±2.08)	1.67 (±0.47)
	ML	Bottom	-	-	-
eF	AR	Surface	0.20 (±0.00)	152.00 (±32.51)	132.57 (±14.50)
	CML	Surface	0.20 (±0.00)	90.50 (±17.68)	91.75 (±7.00)
	ML	Surface	1.23 (±0.76)	13.67 (±11.72)	15.60 (±19.93)
	ML	Bottom	-	-	-

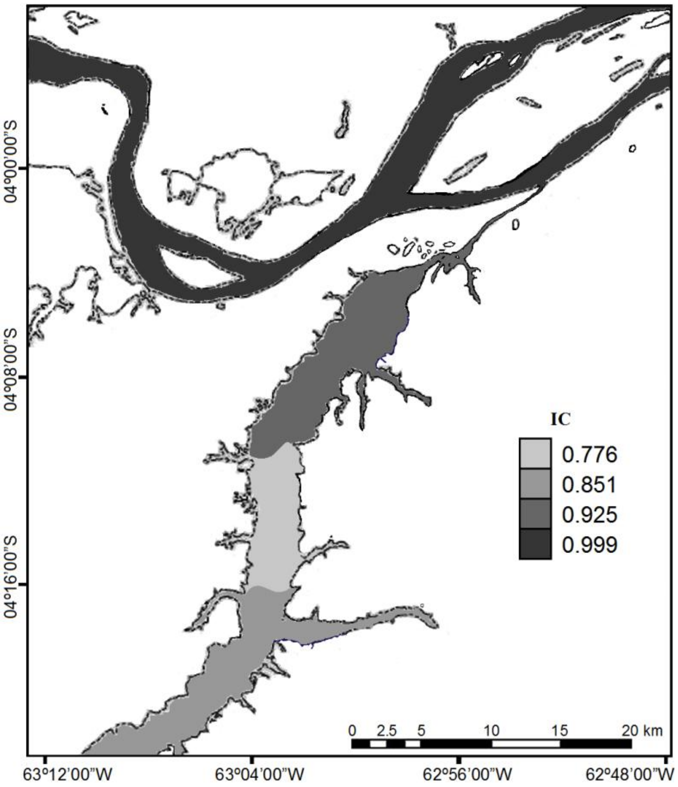


Fig. 3. Isovalues chart for CI in the fluvial-lacustrine system Amazonas – Mamiá for the hydrological period 2008 – 2009

Temperature, dissolved oxygen, conductivity and pH were homogeneously distributed in water column of the Amazon River, due to factors such as turbulence and currents flow, which promote the mixing of the water column. In Mamiá Lake the thermal (°C) and chemical (DO) stratification were evident throughout the study period (Fig. 4). The water temperature values in the lake showed slight seasonal variation. However, the vertical profile of temperature showed higher amplitude, with differences between surface and bottom of 2.2 ºC Fp; 1.9 ºC E and 1.5 °C eF. Daily stratification and destratification processes observed in Mamiá Lake have been documented for several lakes of white-waters and black-waters at the Amazonian floodplain [13,19-22]. In high-waters periods (F and Fp) was observed chemical stratification with oxiclina between 5.0 and 7.0 m and anoxia in the lake bottom. The increase of the turbidity in lakes at the Amazon floodplain in eF period can be interfering in the concentration of DO in the water column. The large amount of organic material constantly decomposed by bacteria and fungi in the deeper water layers in these lakes consumes the available oxygen, also contributing to the registered anoxia conditions. The DO vertical profile in Mamiá Lake showed a pattern of chemical stratification correlated with thermal stratification, revealing a clinogrado profile decreasing with the depth, similar to those found in other lakes of the Amazon [19,22,23].

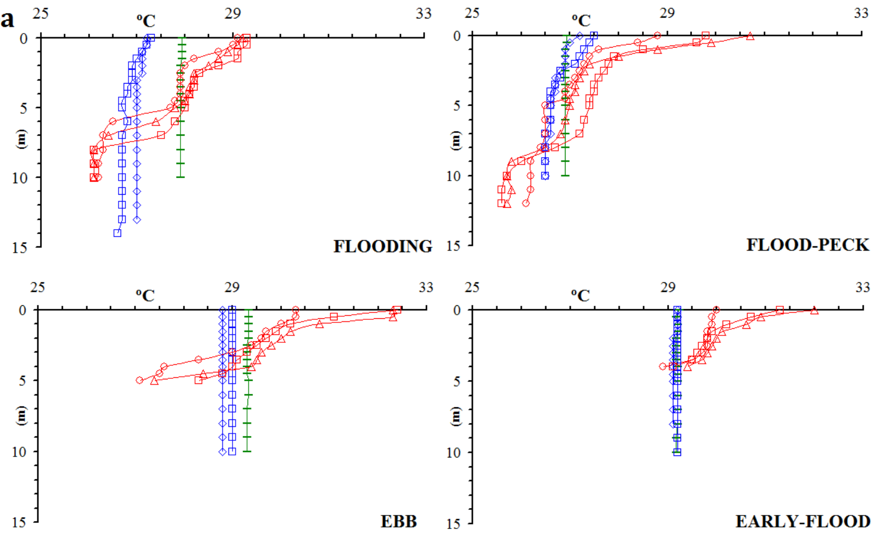
The conductivity profile (Fig. 4) showed a tendency to vertical homogeneity of the water column in the fluvial-lacustrine system, confirmed by the low standard deviations, which ranged in the Amazon River from 0.0 to 0.3, meanwhile that in Mamiá Lake the values ranged from 0.1 to 4.2. However, it should be noted that a significant seasonal variation of conductivity, especially in the channel and the first sampling site of the lake (ML1 – Fig. 1). The conductivity of the channel ranged from 11.4±4.5 (F, Fp and E) to 106.7±1.9 in eF, meaning an increase of 167% in the last period. These results corroborate the analysis presented in the isovalues chart for CI in the fluvial-lacustrine system (Fig. 3), confirming the influence of the flood pulse on the floodplain lakes. Isolated events related to the abrupt increase in conductivity in some sampling sites of the lake, especially during eF, may have been caused by the resuspension of sediment in the low-waters, as was also reported by [16,20] to Amazon floodplain lakes.

In the sampling sites from Amazon River, the pH was the parameter with the lowest oscillation within the study period, ranging from 6.7 to 7.3 (average 7.0±0.2). This variation indicates good buffering capacity with equilibration of acids and bases by the presence of carbonate ions (HCO_3^- + CO_3^{2-}). The same trend has not occurred in the channel and Mamiá Lake, which showed variation from 4.8 to 7.3 (average 5.8±0.9) and 4.9 to 7.2 (average 5.5±0.6), respectively. In the channel was observed most seasonal oscillation of pH from acid to neutral due to the mixture of slightly alkaline waters from the river with the acidic waters of the lake, especially in the flooding period. Mamiá Lake without the direct influence of the Amazon River is a typical Ria lake of slightly acidic water due to geology of its drainage basin, as well as the presence of organic compounds in various stages of decomposition. The brief neutralization of acids present in the waters of the channel at the end of the dry season and the beginning of the flood (eF) is another evidence of the flood pulse influence on the Amazon floodplain lakes. The pH seasonal dynamics was marked by lower values in F and Fp and higher values in E and eF periods. The higher pH values observed in the lake can be associated with increase of the photosynthetic activity, which increases the pH due to the CO_2 removal from the system.

3.2 Ionic Balance

Table 3 summarizes the concentrations of major ions in the fluvial-lacustrine system. The waters of the Amazon River were characterized as neutral (pH≈ 7.0) and high levels of ions, according to the following order of dominance: $Ca^{2+}> Na^+> Mg^{2+}> K^+$ and $HCO_3^-/CO_3^{2-}> Cl^-> SO_4^{2-}$ in all periods, except in the flooding (F), when for the cations the order was $Ca^{2+}> Mg^{2+}> Na^+> K^+$. The ionic content of the Amazon River reflects the chemical conditions of the water and soil of the Andean and Pre-Andean regions, rich in electrolytes and nutrients [24]. Seasonally, the highest average concentrations of major ions were found in the periods F and eF, reflecting the high concentration of ions at the drainage area of the Andean Region. Contrary to the trend observed in the Amazon River, the Mamiá Lake was chemically characterized as waters slightly acidic (pH≈ 5.5) and with low ionic content, according to the following order of dominance: a) for the cations $K^+> Na^+> Ca^{2+}> Mg^{2+}$ in all periods except at the eF when the ordinance was $K^+> Ca^{2+}> Na^+> Mg^{2+}$; b) for the anions $HCO_3^-/CO_3^{2-}> Cl^-> SO_4^{2-}$ in all periods except at the Fp, when the ordinance was $SO_4^{2-}> Cl^-> HCO_3^-/CO_3^{2-}$. The ionic content of the Mamiá Lake reflected the chemical conditions of the waters of the Central Amazon [6,24], which are under the influence of the flood pulse.

4a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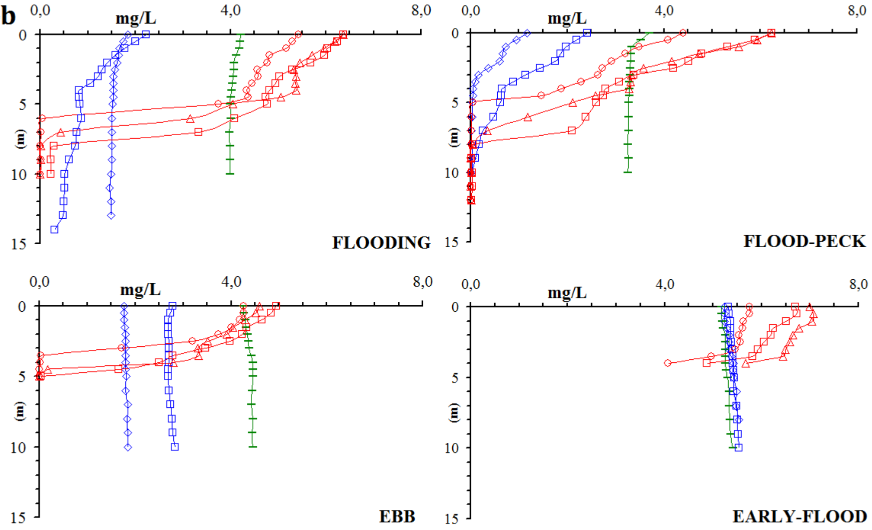
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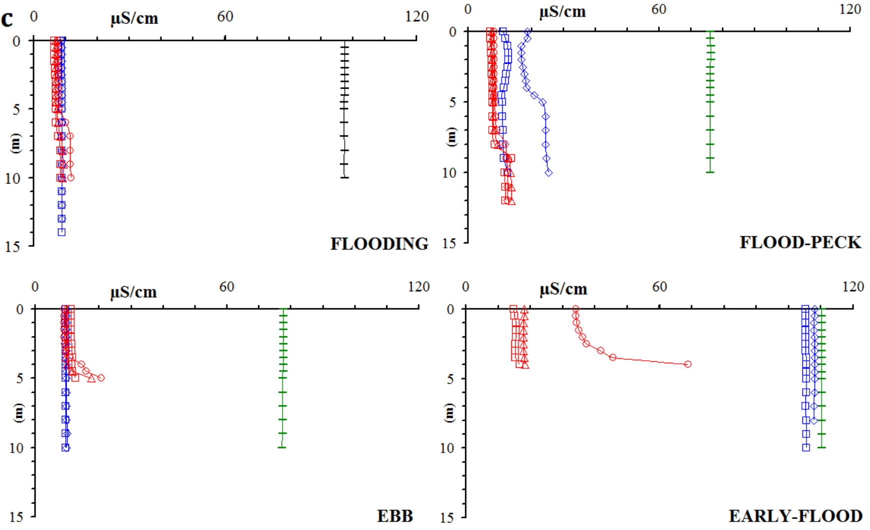
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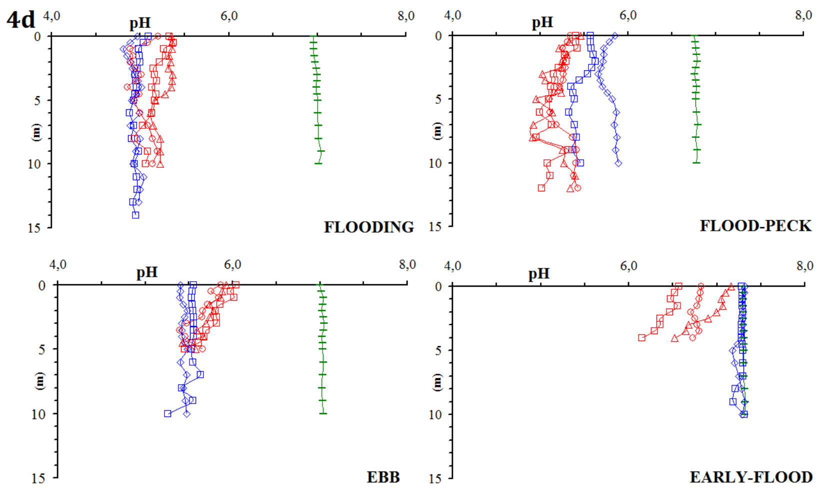

Fig. 4. Vertical profile for 4a) temperature (°C), 4b) DO (mg/L), 4c) conductivity (μS$_{25}$/cm) and 4d) pH in the Amazon River, channel and Mamiá Lake

Table 3. Average of the ion concentration (mg/L) in surface waters of the Amazon River, channel and Mamiá Lake during the hydrological year 2008 – 2009

Period	Site	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-/CO_3^{2-}	SO_4^{2-}	Cl^-
F	AR	1.4±0.1	0.9±0.1	12.9±0.3	1.5±0.0	42.9±3.9	2.3±0.2	5.4±0.4
	CML	0.5±0.1	0.5±0.1	0.2±0.0	0.2±0.0	1.5±0.4	2.3±0.0	2.8±04
	ML	0.2±0.1	0.4±0.1	0.2±0.1	0.1±0.0	6.9±2.5	2.2±0.1	2.6±0.3
Fp	AR	1.3±0.0	0.8±0.0	9.1±0.4	1.0±0.1	31.7±1.6	2.2±0.1	6.1±0.3
	CML	0.4±0.0	0.5±0.0	1.3±0.6	0.3±0.1	9.5±3.9	2.8±0.0	3.2±0.2
	ML	0.3±0.0	0.5±0.0	0.2±0.1	0.1±0.0	2.2±0.9	2.9±0.2	2.5±0.2
E	AR	1.7±0.1	0.7±0.0	8.5±0.8	1.0±0.1	32.1±1.5	1.7±0.3	5.3±0.5
	CML	0.3±0.1	0.6±0.0	0.3±0.1	0.1±0.0	8.5±0.9	2.1±0.1	2.0±0.4
	ML	0.4±0.1	0.7±0.1	0.3±0.1	0.1±0.0	7.7±1.3	1.9±0.1	1.8±0.0
eF	AR	3.2±0.5	1.0±0.1	10.5±0.3	1.4±0.0	42.5±0.7	2.3±0.5	7.5±0.1
	CML	2.6±0.2	1.0±0.0	10.8±0.0	1.4±0.0	43.9±0.0	1.8±0.2	7.0±0.1
	ML	0.9±0.4	1.2±0.3	1.6±0.6	0.3±0.1	11.4±3.4	2.2±0.2	2.8±0.9

In Mamiá Lake there was predominance of anions over cations for most of the hydrological year. The HCO_3^-/CO_3^{2-} was the most abundant element in the lake in all periods, except during the Fp, and there was no seasonal variation in the concentrations of Cl^- e SO_4^{2-}, and only observed higher concentrations through the eF period. Two factors can be interfering with the HCO_3^-/CO_3^{2-} balance in fluvial-lacustrine system: 1) dilution factor, due to the increase in water catchment in periods of high-waters that are preceded by higher rainfall; 2) ratio respiration/photosynthesis (R/P) associated with variation of the load of suspended solids containing organic compounds. Although the forest streams contribute with low ionic content to the lake during high-waters periods, the main ion contribution comes from the Amazon River, which has high load of adsorbed electrolytes in sedimentary particles, and containing several ions including iron, which interfere with the algal bloom. In this condition, the excess of waters rich in mudstones and siltstones associated to organic matter can be changing the balance R/P toward photosynthesis. As result, the CO_2 free is removed of the system increasing content of carbonates (HCO_3^-/CO_3^{2-}) in the water, which are associated with H^+ establishing higher alkalinity and, thus raising the pH, as noted at the beginning of the flood (eF). The excess of carbonate can also associate with calcium ($CaCO_3$), as shown in the Fig. 5. The Pearson correlation between the total concentrations of HCO_3^-/CO_3^{2-} and pH was 0.8800, confirming there is strong similarity in the variation seasonal to both parameters.

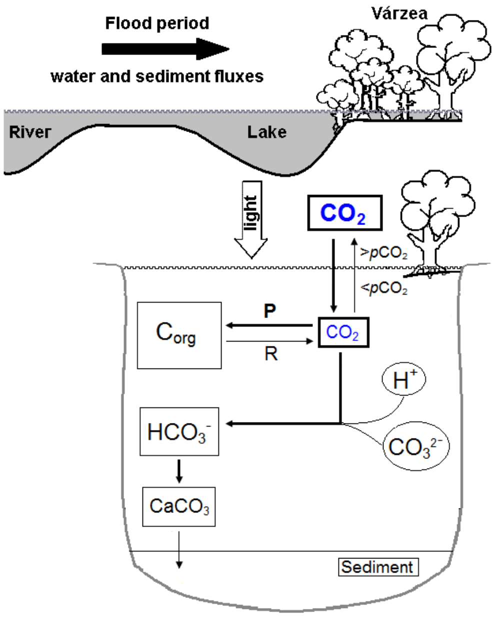

Fig. 5. Via carbonate formation in the Mamiá Lake during increased of photosynthetic productivity in the eF period

Cluster showed the formation of two groups, one consisting of all the sampling sites of the Amazon River and channel in the latter eF period, and the other group formed by sampling sites from the lake and the sites of the channel in F, Fp and E periods. The group formed by the Amazon River presented 90% homogeneity and the group formed by the Mamiá Lake 95%. The concentrations of major ions confirm similarities between the channel of connection and lake, and distinguish them of the Amazon River in the most part of time, except during the eF period (Fig. 6). The PCA compiled from the concentrations of ions (Fig. 7) provided by two components (axes 1 and 2) explain 87.7% of the total variance of the data. According to the variables that correlate with the components, the axes 1 explained 73% of the variation substantially represented by variables Na^+, Ca^{2+}, Mg^{2+}, HCO_3^- and Cl^-, while the axes 2 explained 14.7% of variation represented by the ions K^+ and SO_4^{2-}. Both groups confirmed that the concentrations of major ions in the Amazon River are different of the concentrations of ions determined in Mamiá Lake (Table 4).

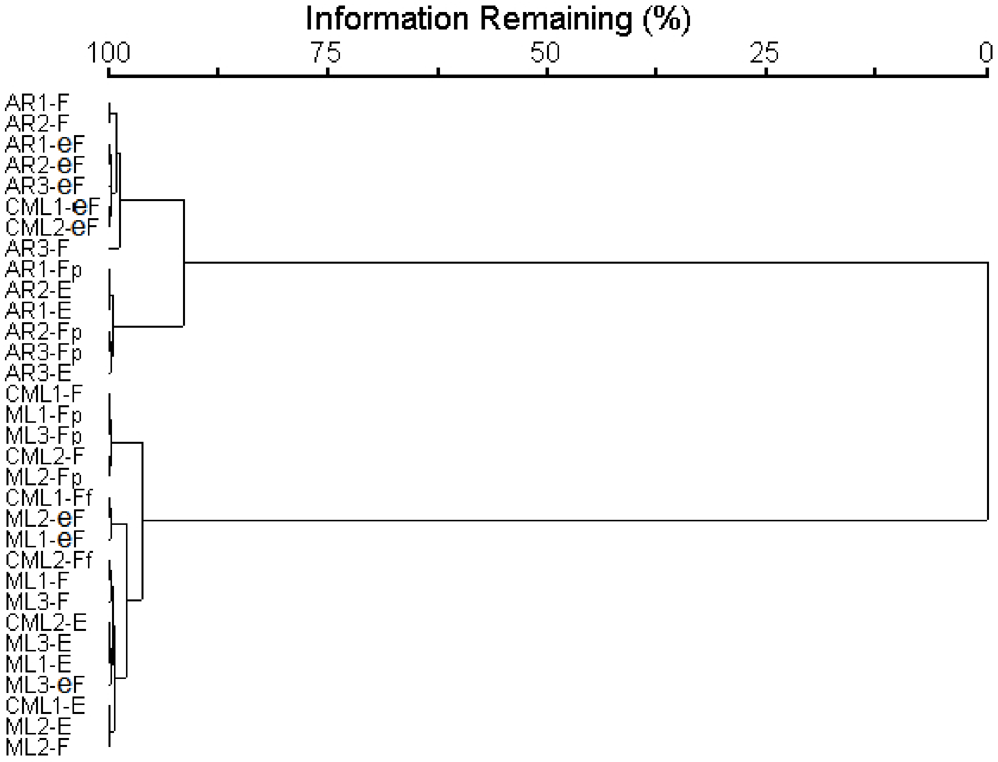

Fig. 6. Cluster analysis of the ion concentrations in the fluvial-lacustrine system for the sampling period from 2008 – 2009 (linkage: Ward's method)

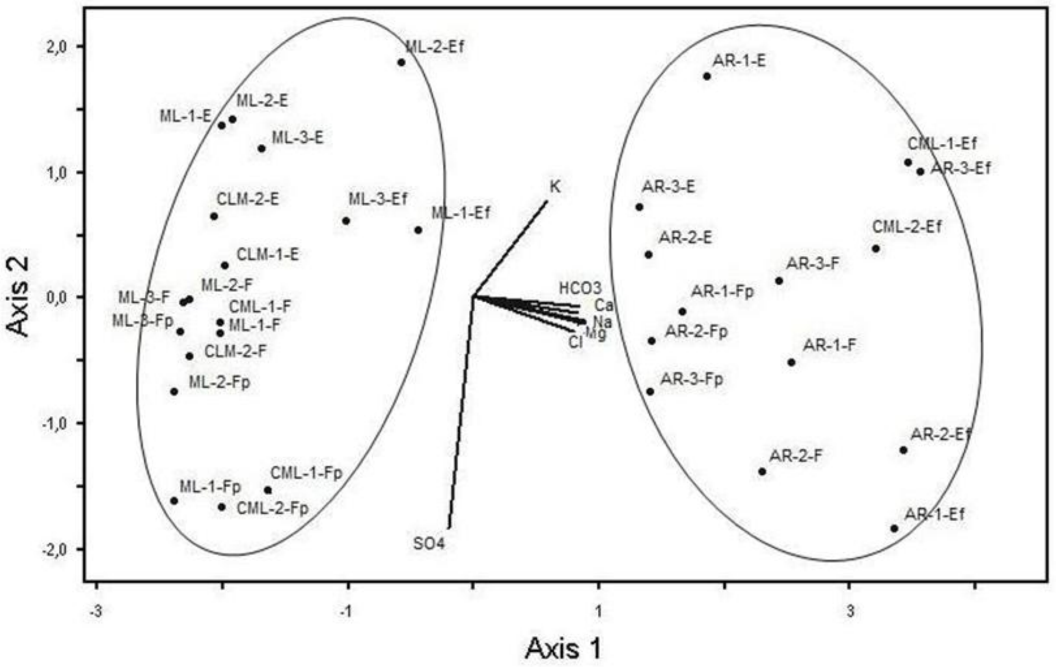

Fig. 7. Graph of the main components in relation to the concentrations of major ions in the Amazon River, Mamiá Lake and its channel in the hydrological period 2008 – 2009

Table 4. Eigenvalues and variation of the axes of PCA for hydrological year 2008 – 2009

Axis	Eigenvalues	Variation (%)	Variation acumulated (%)	Variable	Axis 1 (73%)	Axis 2 (87.7%)
1	5.11	73.03	73.03	Na^+	0.406	-0.086
2	1.03	14.66	87.69	K^+	0.287	0.416
3	0.55	7.93	95.61	Ca^{2+}	0.426	-0.122
				Mg^{2+}	0.431	-0.130
				HCO_3^-	0.434	-0.066
				SO_4^{2-}	-0.143	-0.868
				Cl^-	0.420	-0.170

4. CONCLUSION

The flood pulse of the Amazon River has great influence on the chemical composition of the Mamiá Lake and its channel of connection, especially during the eF period. In this hydrological period the influence is direct, and the fluvial waters modify the physical-chemical structure of the lake. In high-waters (Fp) the remarkable influence is the damming of the Amazon River on the channel, with strong consequences for chemical and biological composition of the lake. During the flooding (elevation 25 m), with direct influence of the river on the lake, the average transparency of the channel is about eight times higher than in the Amazon River and transparency of lake is about ten times. The flux of TSS from Amazon River to the channel and lake is significant especially during the high-waters periods. The food pulse contributes also with the increase of the dissolved inorganic ions amount in the water column of the lake, which interfere in the euphotic zone and phytoplankton production of the ecosystem. Results confirmed seasonality for the almost all variables measured in that research, suggesting that the present information can be extrapolated to the vast number of Amazonian floodplains lakes.

CONSENT

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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