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Limnological characterization of floodplain lakes in Mamirauá Sustainable Development Reserve, Central Amazon (Amazonas State, Brazil)

Caracterização limnológica dos lagos da planície de inundação na Reserva de Desenvolvimento Sustentável Mamirauá, Amazônia Central (Estado do Amazonas, Brasil)

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Chemical Limnology

Abstract: Aim: This paper examines the spatial and temporal variation of limnological characteristics of floodplain lakes in the Solimões and Japurá confluence, an undisturbed region - the Mamirauá Sustainable Development Reserve (MSDR); **Methods:** We analyzed surface temperature, conductivity, pH, dissolved oxygen, turbidity and transparency, and surface water samples were collected for determination of suspended inorganic and organic matter, chlorophyll-*a*, pheophytin, total nitrogen, total phosphorus, organic and inorganic carbon, in two phases of the hydrograph stage, 2009 high water phase, 2008, 2009 and 2010 low water phases; **Results:** The results showed that the studied water bodies have high variability in all measured variables: a) between hydrograph phases; b) among main rivers; and c) between opposite margins of Japurá River; **Conclusions:** This shows the remarkable influence of the flood pulse and the primary water source on the limnology of this system. The monitoring of physical and chemical limnological variables in Mamirauá will serve as future reference for comparison with disturbed areas, such as the Lower Amazon, and as a baseline for modeling the effects of climate change and anthropogenic influences on Amazon aquatic ecosystem.

Keywords: limnology, undisturbed floodplain lakes, Central Amazon, Mamirauá Reserve.

Resumo: Objetivo: Esse trabalho investiga a variação temporal e espacial de algumas características limnológicas dos lagos da planície de inundação da região de confluência dos Rios Japurá e Solimões, onde está localizada a Reserva de Desenvolvimento Sustentável Mamirauá (RDSM); **Métodos:** Analisaram-se temperatura, condutividade, pH, oxigênio dissolvido, turbidez e transparência da água em três profundidades (superfície, Secchi e no limite da zona fótica) e coletadas amostras de água na superfície para a determinação de material orgânico e inorgânico em suspensão, clorofila-*a*, feofitina, nitrogênio e fósforo total, carbono orgânico e inorgânico dissolvido, em duas fases da hidrógrafa, água alta em 2009, e água baixa em 2008, 2009 e 2010; **Resultados:** Os resultados mostraram que as variáveis medidas possuem uma alta variabilidade nos corpos d'água na região de estudo: a) entre as fases da hidrógrafas; b) entre os rios principais; e c) entre as margens opostas do Rio Japurá, mostrando a importância do pulso de inundação na variação dos parâmetros físicos e químicos e ainda a em relação ao rio principal de alimentação; **Conclusões:** O monitoramento dos parâmetros físicos e químicos em Mamirauá servirá como futura referência para comparação com outras regiões menos preservadas, como o Baixo Amazonas, e ainda como linha de base para modelos sobre efeitos das mudanças climáticas e influências antropogênicas no ecossistema aquático Amazônico.

Palavras-chave: limnologia, planície de inundação não perturbada, Amazônia Central, Reserva Mamirauá.

1. Introduction

The Amazon basin is the largest drainage basin in the world with an area of approximately 6,869,000 km² (Neill et al., 2006). Due to its geological and geomorphological evolution, the basin has a vast floodplain (várzea) which is formed by a complex system of rivers, channels, lakes and islands that are in constant change due to sedimentation and particulate matter transport. This floodplain is seasonally flooded by different water types that vary widely, depending on its origin, soil type and climatic conditions. Sioli (1984) classified the Amazonian waters into three major groups based on suspended and dissolved matter and pH, whereas, black waters are those with high humic contents, low suspended matter and pH between 3.8 to 4.9; white waters has high concentration of dissolved and suspended matter and pH between 6.2-7.2, and clear waters with low turbidity and low content of suspended matter and humic content and pH ranging from 4.5 to 7.8. Furthermore, the periodic flooding changes the proportion of suspended and dissolved components in water by altering its physical-chemical conditions (Melack and Forsberg, 2001) consequently, affects the ecosystem where these waters circulate (Forsberg et al., 1988) and also the ecology and life cycle dynamic of local species (Saint-Paul et al., 2000).

The flood pulse is a key factor in the ecological processes of the várzea, which transforms periodically terrestrial environments into aquatic environments (Junk et al., 1997). This dynamic provides a variety of habitats for many animal and plant species (Junk and Da Silva, 1997), provides food sources, nesting and refuge for many fish species (Sanchez-Botero and Araujo-Lima, 2001). The floodplain is also important for due to its high biodiversity (Junk et al., 2000), high primary productivity of wetland forests (Parolin et al., 2004), aquatic macrophytes (Piedade et al., 1984; Silva et al., 2010), and also provides the main energy source for Amazonian aquatic food chain (Forsberg et al., 1993; Arraut et al., 2010).

The water characteristics and its dynamics are crucial to understand the processes and dynamics that occur between terrestrial and aquatic ecosystems. Several studies have been conducted to assess the spatial and temporal variations of physical and chemical properties of Amazonian waters (Melack and Fisher, 1990; Moreira-Turcq et al., 2003; Aufdenkampe, et al., 2007; McClain and Naiman, 2008; Almeida and Melo, 2009).

However the dynamic nature of the aquatic systems makes it difficult to distinguish between natural variability and anthropogenic influences (Chipps et al., 2006), and even more difficult in the Amazon floodplain lakes, where the flood pulse controls the ecosystem dynamics. Thus the conversion of forest into pasture and agricultural areas in floodplains, especially in eastern Amazon, might affect the water characteristics (Melack and Forsberg, 2001; Tundisi et al., 2002). Therefore, information about water physical and chemical characteristics of undisturbed regions provides a baseline upon which anthropogenic effects on aquatic system may be assessed.

Following this approach this paper examines the spatial and temporal variation of some limnological characteristics of floodplain lakes in the area of confluence of Solimões and Japurá rivers in Central Amazon, where the Mamirauá Sustainable Development Reserve is located. In spite of the fact that it cannot be considered a completely undisturbed várzea due to the human population living there, in this paper, one assumes that it is an almost undisturbed várzea.

2. Material and Methods

The study area is situated in western Amazon, near Tefé municipality (570 km distant from Manaus), in Amazonas State. It is located in Mamirauá Sustainable Development Reserve (MSDR), which was established in 1990 by state government, and it has an area of 1,124.000 ha approximately (Figure 1). The region is formed by “várzea”, a floodplain inundated by sediment-rich whitewater rivers of the Amazon River with a complex mosaic of seasonally inundated forests, lakes and channels, with an annual water level variation of 12 m (Ayres, 1993; Henderson, 1999; Queiroz, 2005; Queiroz, 2007; Ramalho et al., 2009).

According to the hydrological monitoring data system of the Eastern Amazon, in the hydrological period of 2008/2009 the flooding reached the highest water level of the last 107 years (CPRM, 2009) at Negro/Solimões River system, near Manaus municipality.

In Mamirauá study area the hydrological period of 2008/2009 corresponded to the second highest record (38.33 m above sea level) in the historical data (from 1990 to 2010). The highest one occurred in 1999, when in the water reached 38.55 m above sea level (m.a.s.l.) (Ramalho et al., 2009). Nonetheless, during the drought of 2010, water level reached the

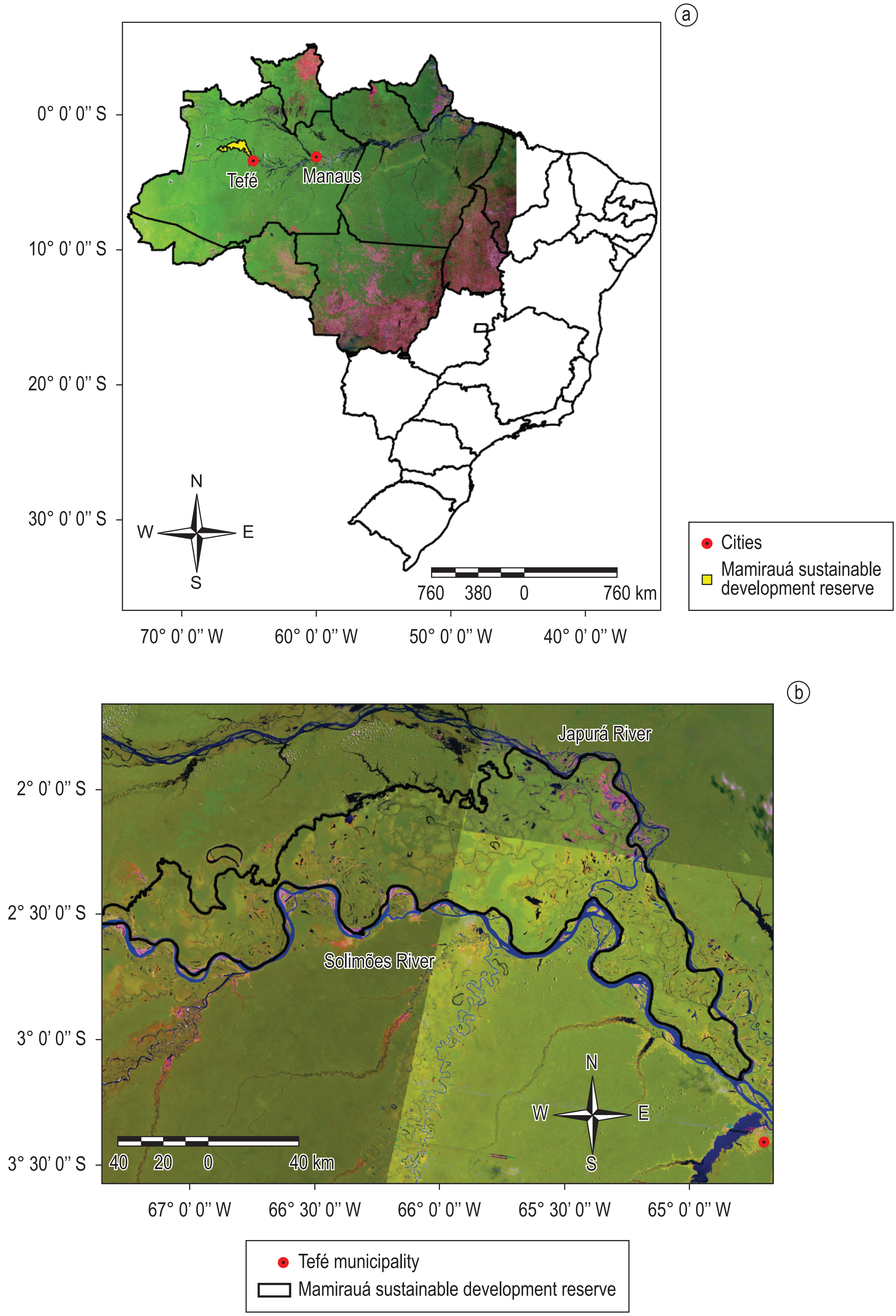

Figure 1. Study area. a) Location of study area in Brazil. Tefé and Manaus municipality and Mamirauá Sustainable Development Reserve (MSDR) are shown; b) Complete Landsat TM image view of MSDR. Japurá and Solimões Rivers are shown.

lowest level for the last 108 years, lower than 1963 or 2005, when water during the droughts reached 13.64 and 14.75 m.a.s.l., respectively, at Manaus. In Mamirauá study area, however, the 2010 low water phase was considered as one of the driest in in the historical data, with the minimum water level of 24.4 m. The driest ever for the time series available for Mamirauá occurred in 1995 when the water level reached 21.71 m.a.s.l., followed by the 1991, 1992 and 2005 droughts (with 23.45, 23.41 and 24.09 m.a.s.l., respectively) (Ramalho et al., 2009). Thus this paper presents limnological data about two historical, extreme and opposite events, and also presents data of regular events.

Field samples were distributed among floodplain lakes, located on the right and left margins of Japurá River, and also in the main rivers (Japurá and Solimões Rivers) in 2008 (low water phase), 2009 (high and low water phase) and 2010 (low water phase) (Figure 2 and 3). Water temperature (°C), dissolved oxygen (mg.L^{-1}), turbidity (NTU), electrical conductivity (µS.cm^{-1}) and pH were measured on the surface using an YSI multi-parameter probe. Surface water samples were also collected for determination of the following parameters in the laboratory: suspended inorganic and organic matter (mg.L^{-1}); chlorophyll-*a* (µg.L^{-1}), pheophytin (µg.L^{-1}), total nitrogen (mg.L^{-1}), total phosphorus (µg.L^{-1}), organic and inorganic carbon (mg.L^{-1}).

For chlorophyll-*a*, pheophytin and suspended inorganic and organic matter, water samples were filtered (Whatmann GF/C fiberglass filter (0.5-0.7 mm)) and stored in silica gel at 0 °C until further analysis in laboratory according to Nush (1980) and Wetzel and Likens (1991) methodology, respectively. Total phosphorus and nitrogen were determined through Valderrama (1981) and Golterman et al. (1978), in that order, and organic and inorganic carbon according to Eaton et al. (1995).

The number of samples varied in different hydrograph phases (Table 1) as the open water extent changed from one phase to other, limiting the access to some lakes and regions. For the lakes located on the left margin of Japurá River, samples were taken only during 2009 high water phase, because of the limited access during low water phase campaigns.

There were two types of sampling stations: 1) Complete sampling: both surface water samples

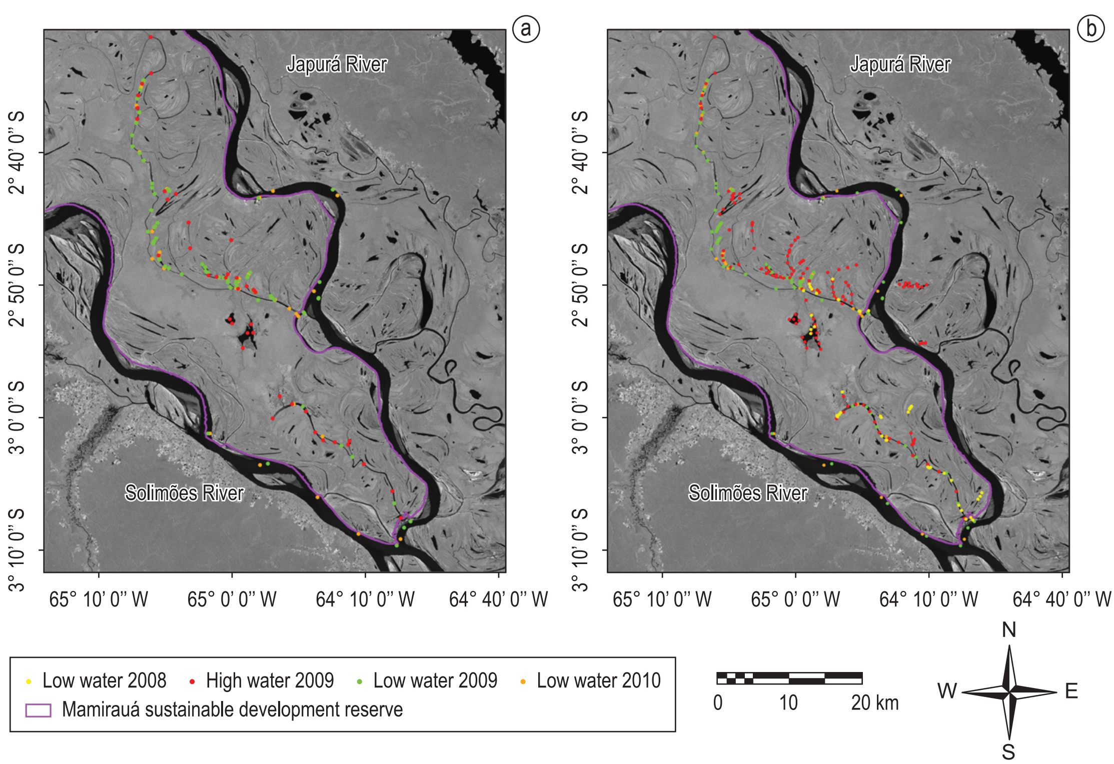

Figure 2. Complete (a) and incomplete (b) sampling stations at study area, whereas, 2008 low water sampling points are show in yellow dots, 2009 high water in red, 2009 low water in green and 2010 low water in orange. Japurá and Solimões river are shown.

and YSI measurements, and 2) Incomplete sampling: only YSI probe measurements.

Limnological data were submitted to a two-sample non-parametric test Kolmogorov-Smirnov ($p < 0.01$) (Siegel, 1975) to investigate if there were statistically significant differences in water properties among samples collected in: i) different phases of the flood pulse (flood and drought), ii) different margins of the Japura River, iii) Solimões and Japurá Rivers, and also, iv) distinct drought events.

The two-sample Kolmogorov-Smirnov test uses the maximal distance (Dmax) between cumulative frequency distributions of each two samples, and, if the Dmax is greater than the critical value (Dcrit), which is obtained from a table, than these samples come from different distribution.

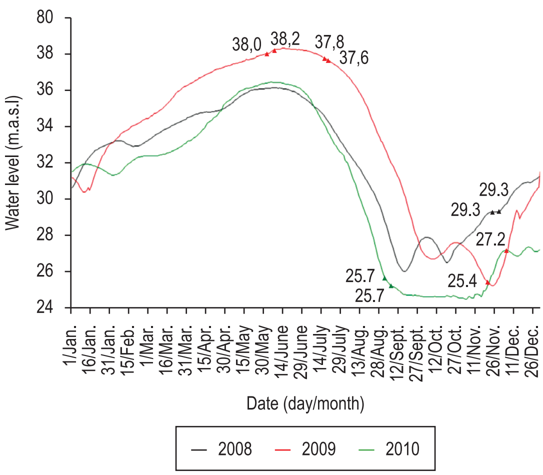

Figure 3. Water level variation (above sea level) during 2008, 2009 and 2010 field campaigns and the respective water level in the beginning and end of each field mission.

3. Results

In general, the magnitude of all variables was higher in drought (or low water phase – LWP) than in rainy season (or high water phase – HWP), except for water transparency (Tables 2 to 5). The lakes located on the right margin of Japurá River had higher transparency, pH and electrical conductivity values than those on the opposite margin, during high water phase. The left margin lakes were warmer, more turbid and with higher oxygen concentration in the same season. The two-sample Kolmogorov-Smirnov tests (K-S test) showed that the differences reported were statistically significant, as described in Tables 6 to 9.

Japurá River had lower values than Solimões River in all variables, except for dissolved oxygen and chlorophyll-*a*, during LWP. Kolmogorov-Smirnov (K-S test) tests showed that turbidity (in 2009) and dissolved oxygen (in 2010) values displayed differences statistically significant between those rivers, during low water phases. When comparing drought events (2009 × 2010), conductivity, temperature, turbidity and pH measured at Japurá river displayed statistically significant differences, and for the Solimões River, only turbidity and dissolved oxygen were statistically different (Tables 6 to 9).

When comparing the 2008 to the 2009 and 2010 drought events, the electrical conductivity, pH and turbidity distributions were statistically different (Tables 6 to 9). Dissolved oxygen was

Table 1. Number of sampling points collected per sampling type in different hydrograph phases/year.

Hydrograph phase	2008 low water	2009 high water	2009 low water	2010 low water
Sampling date	24/11 to 29/11	20/05 to 11/06	11/11 to 10/12	29/08 to 07/09
Complete	NA	41	74	45
Incomplete	50	136	97	64

NA: Not applicable. It was not collected water surface samples during this field work.

Table 2. Mean, minimum (Min), maximum (Max), coefficient of variation (Coeff.var.) and number of samples (N) of variables measured during 2008 low water field mission.

Variables	Mean	Min	Max	Coeff.Var.	N
Transparency (m)	0.56	0.15	1.20	54.94	50
Temperature (°C)	31.31	29.24	33.60	4.59	50
pH	6.99	6.60	8.17	4.38	50
EC (μS.cm^{-1})	156.21	61.00	300.90	38.40	50
Turbidity (NTU)	23.82	3.92	158.90	125.49	50
DO (mg.L^{-1})	4.23	0.77	10.32	60.33	50

EC: Electrical conductivity; DO: dissolved oxygen.

statistically different when comparing two different drought events: 2008 (a mild drought episode) and 2010 (an extreme drought event).

The 2009 and 2010 low water phase events were statistically different for water transparency, dissolved oxygen, chlorophyll-*a*, pheophytin, nitrogen, phosphorus, and inorganic and organic dissolved carbon (Tables 6 to 9).

Mean water transparency (Secchi depth) were higher during HWP (1.58 m than in drought events when ranged from 0.32 to 0.44 m, with a maximum value of 1.2 m in 2008 and the minimum transparency of 0.05 m in 2009 (Tables 2 to 5). Right margin lakes were more transparent than left margin lakes during HWP and also than main rivers during LWP. Solimões and Japurá Rivers had the lowest mean values, with less than 0.2 m of water transparency in both dry periods.

The lowest water temperature was recorded during HWP (26.5 °C) and the highest occurred in 2010 drought (34.7 °C). Mean values during LWP varied from 31.22 (2009) to 31.33 (2010). Mean temperature of right margin lakes (27.08 °C) were lower than left margin lakes (28.04 °C) during HWP, but higher (31.55 °C) than main rivers (30.12 °C) during LWP (Tables 2 to 5).

Table 3. Mean, minimum (Min), maximum (Max), coefficient of variation (Coeff.var.) and number of samples (N) of variables measured during 2009 high water field mission.

Variables	Mean	Min	Max	Coeff.Var.	N
Transparency (m)	1.58	0.60	2.80	33.24	136
Temperature (°C)	27.18	26.50	28.92	1.90	136
pH	6.79	6.35	7.01	1.69	136
EC (µS.cm^{-1})	105.21	50.00	123.00	18.92	136
Turbidity (NTU)	8.74	0.50	31.30	76.88	136
DO (mg.L^{-1})	2.36	0.86	6.98	33.13	136
SIM (mg.L^{-1})	0.92	0.05	3.02	87.21	41
SOM (mg.L^{-1})	1.17	0.24	2.00	37.61	41
Chlorophyll-*a* (µg.L^{-1})	0.29	0.11	0.81	45.89	41
Pheophityn (µg.L^{-1})	0.24	0.00	0.64	66.48	41
Nitrogen (mg.L^{-1})	0.18	0.03	0.31	34.64	41
Phosphorus (µg.L^{-1})	105.11	50.68	179.42	29.68	41
DIC (mg.L^{-1})	8.16	3.56	9.58	15.23	41
DOC (mg.L^{-1})	4.62	2.02	6.31	20.87	41

EC: Electrical conductivity; DO: dissolved oxygen; SIM: suspended inorganic matter; SOM: suspended organic matter; DIC: dissolved inorganic carbon; DOC: dissolved organic carbon

Table 4. Mean, minimum (Min), maximum (Max), coefficient of variation (Coeff.var.) and number of samples (N) of variables measured during 2009 low water field mission.

Variables	Mean	Min	Max	Coeff.Var.	N
Transparency (m)	0.32	0.05	1.00	66.53	96
Temperature (°C)	31.22	27.98	33.91	3.80	96
pH	7.28	6.21	8.79	6.42	96
EC (µS.cm^{-1})	174.42	54.00	378.00	59.11	96
Turbidity (NTU)	60.42	2.70	565.00	135.04	96
DO (mg.L^{-1})	5.65	0.72	14.02	49.31	96
SIM (mg.L^{-1})	57.68	1.52	590.39	169.49	75
SOM (mg.L^{-1})	21.14	4.47	202.96	121.59	75
Chlorophyll-*a* (µg.L^{-1})	113.03	2.90	2,061.29*	211.06	75
Pheophityn (µg.L^{-1})	18.38	1.63	73.32	72.32	75
Nitrogen (mg.L^{-1})	1.62	0.04	10.31	83.35	75
Phosphorus (µg.L^{-1})	220.99	38.05	1,094.89	95.00	75
DIC (mg.L^{-1})	16.06	0.49	40.04	69.64	75
DOC (mg.L^{-1})	11.47	1.71	23.39	53.87	75

*Phytoplankton bloom. EC: Electrical conductivity; DO: dissolved oxygen; SIM: suspended inorganic matter; SOM: suspended organic matter; DIC: dissolved inorganic carbon; DOC: dissolved organic carbon.

Table 5. Mean, minimum (Min), maximum (Max), coefficient of variation (Coeff.var.) and number of samples (N) of variables measured during 2010 low water field mission.

Variables	Mean	Min	Max	Coeff.Var.	N
Transparency (m)	0.44	0.10	1.00	55.22	64
Temperature (°C)	31.33	28.80	34.70	4.26	64
pH	7.06	6.46	7.62	3.61	64
EC (µS.cm^{-1})	151.25	35.00	313.00	56.79	64
Turbidity (NTU)	96.46	6.00	527.20	95.17	64
DO (mg.L^{-1})	5.24	1.86	9.70	25.86	64
SIM (mg.L^{-1})	27.15	1.60	122.19	106.58	45
SOM (mg.L^{-1})	10.69	2.31	27.86	47.92	45
Chlorophyll-*a* (µg.L^{-1})	148.07	1.13	2,589.23*	330.02	45
Pheophityn (µg.L^{-1})	15.67	1.35	95.59	87.35	45
Nitrogen (mg.L^{-1})	1.17	0.17	4.07	72.39	45
Phosphorus (µg.L^{-1})	210.78	59.68	701.81	67.65	45
DIC (mg.L^{-1})	15.19	3.58	31.60	63.11	45
DOC (mg.L^{-1})	8.44	1.85	22.55	57.89	45

*Phytoplankton bloom. EC: Electrical conductivity; DO: dissolved oxygen; SIM: suspended inorganic matter; SOM: suspended organic matter; DIC: dissolved inorganic carbon; DOC: dissolved organic carbon.

Table 6. Two-sample Kolmogorov-Smirnov test (Dmax) between hydrograph phases and main rivers for temperature, water transparency and electrical conductivity and inorganic and organic dissolved carbon. Sig 1% indicates the variables that display different distributions.

Parameter	Hydrograph phase	Water body	Year comparison	Dmax	Dcrit.	Sig.1%
Temperature	High	RM x LM	2009	0.91	0.45	Yes
	High x low	RM	2009 x 2008	1.00	0.27	Yes
			2009 x 2009	0.96	0.23	Yes
			2009 x 2010	0.99	0.27	Yes
	Low	RM	2008 x 2009	0.21	0.29	-
			2008 x 2010	0.23	0.32	-
			2009 x 2010	0.12	0.28	-
		Japurá x Solimões	2009	0.83	0.91	-
			2010	0.80	1.03	-
		Japurá	2009 x 2010	1.00	0.95	Yes
		Solimões	2009 x 2010	0.80	0.99	-
Water transparency	High	RM x LM	2009	0.95	0.49	Yes
	High x low	RM	2009 x 2008	0.95	0.48	Yes
			2009 x 2009	0.95	0.33	Yes
			2009 x 2010	0.93	0.38	Yes
	Low	RM	2008 x 2009	0.31	0.45	-
			2008 x 2010	0.24	0.49	-
			2009 x 2010	0.42	0.34	Yes
		Japurá x Solimões	2009	0.80	1.09	-
			2010	0.80	1.03	-
		Japurá	2009 x 2010	0.60	1.03	-
		Solimões	2009 x 2010	1.00	1.09	-
Electrical conductivity	High	RM x LM	2009	1.00	0.45	Yes
	High x low	RM	2009 x 2008	0.72	0.27	Yes
			2009 x 2009	0.55	0.23	Yes
			2009 x 2010	0.44	0.27	Yes
	Low	RM	2008 x 2009	0.37	0.29	Yes
			2008 x 2010	0.32	0.32	Yes
			2009 x 2010	0.18	0.28	-
		Japurá x Solimões	2009	0.83	0.91	-
			2010	0.80	1.03	-
		Japurá	2009 x 2010	1.00	0.95	Yes
		Solimões	2009 x 2010	0.80	1.03	-

Rm: lakes of the right margin of Japurá lakes, LM: Left margin of Japurá River. High: high water phase (flood), Low: low water phase (drought).

Table 7. Two-sample Kolmogorov-Smirnov test (Dmax) between hydrograph phases and main rivers for pH, turbidity and dissolved oxygen and inorganic and organic dissolved carbon. Sig 1% indicates the variables that display different distributions.

Parameter	Hydrograph phase	Water body	Year comparison	Dmax	Dcrit	Sig. 1%
pH	High	RM x LM	2009	0.98	0.45	Yes
	High x low	RM	2009 x 2008	0.48	0.27	Yes
			2009 x 2009	0.74	0.23	Yes
			2009 x 2010	0.60	0.27	Yes
	Low	RM	2008 x 2009	0.47	0.29	Yes
			2008 x 2010	0.35	0.32	Yes
			2009 x 2010	0.26	0.28	-
		Japurá x Solimões	2009	0.55	0.91	-
			2010	1.00	1.03	-
		Japurá	2009 x 2010	1.00	0.95	Yes
		Solimões	2009 x 2010	0.43	0.99	-
Turbidity	High	RM x LM	2009	1.00	0.45	Yes
	High x low	RM	2009 x 2008	0.50	0.27	Yes
			2009 x 2009	0.76	0.23	Yes
			2009 x 2010	0.85	0.27	Yes
	Low	RM	2008 x 2009	0.30	0.29	Yes
			2008 x 2010	0.53	0.32	Yes
			2009 x 2010	0.28	0.28	-
		Japurá x Solimões	2009	1.00	0.91	Yes
			2010	0.60	1.03	-
		Japurá	2009 x 2010	1.00	0.95	Yes
		Solimões	2009 x 2010	1.00	0.99	Yes
Dissolved oxygen	High	RM x LM	2009	0.88	0.45	Yes
	High x low	RM	2009 x 2008	0.60	0.27	Yes
			2009 x 2009	0.72	0.23	Yes
			2009 x 2010	0.85	0.27	Yes
	Low	RM	2008 x 2009	0.26	0.29	-
			2008 x 2010	0.35	0.32	Yes
			2009 x 2010	0.35	0.28	Yes
		Japurá x Solimões	2009	1.00	0.91	Yes
			2010	0.80	1.03	-
		Japurá	2009 x 2010	0.71	0.95	-
		Solimões	2009 x 2010	1.00	0.99	Yes

Rm: lakes of the right margin of Japurá lakes, LM: Left margin of Japurá River. High: high water phase (flood), Low: low water phase (drought).

On the other hand, pH mean values were similar between hydrograph phases, but minimum and maximum values ranged from acid to basic waters. During HWP, the pH ranged from 6.35 to 7.01, with a mean of 6.79. Right and left margin lakes presented acid waters with mean values of 6.82 and 6.56, respectively. During LWP, pH values varied from 6.21 (2009) to 8.79 (2009), with mean values ranging from 6.99 (2008) to 7.28 (2009). Solimões presented the highest mean values in 2009 (7.39) and 2010 (7.32) drought events; however the maximum value was registered in right margin lakes in 2009 drought (8.79) (Tables 2 to 5).

Electrical conductivity ranged from 50 to 123 $\mu S.cm^{-1}$, with mean values of 105.21 $\mu S.cm^{-1}$, in HWP. During LWP the condutivity varied from 35 $\mu S.cm^{-1}$ (2010) to 378 $\mu S.cm^{-1}$ (2009), with mean values ranging from 151.25 $\mu S.cm^{-1}$ (2010) to 174.42 $\mu S.cm^{-1}$ (2009). Conductivity of the right margin lakes was two times higher than that of the left margin in HWP. During LWP, Japurá had the lowest mean values, below 75 $\mu S.cm^{-1}$ (2009) while right margin lakes and Solimões River had the highest values, above 162.81 $\mu S.cm^{-1}$ (2010) and 100.83 $\mu S.cm^{-1}$ (2009), respectively (Tables 2 to 5).

Turbidity ranged from 0.5 NTU to 31.30 NTU, with a mean of 8.74 NTU in HWP, and from 3.92

Table 8. Two-sample Kolmogorov-Smirnov test (Dmax) between hydrograph phases and main rivers for total suspended matter, suspended inorganic and inorganic matter, chlorophyll-*a* and pheophytin and inorganic and organic dissolved carbon. Sig 1% indicates the variables that display different distributions.

Parameter	Hydrograph phase	Water body	Year comparison	Dmax	Dcrit	Sig.1%
Total suspended matter	High x low	RM	2009 x 2009	1.00	0.32	Yes
			2009 x 2010	1.00	0.38	Yes
	Low	RM	2009 x 2010	0.32	0.34	-
		Japurá x Solimões	2009	0.75	1.09	-
			2010	0.60	1.03	-
		Japurá	2009 x 2010	0.80	1.03	-
		Solimões	2009 x 2010	0.60	1.09	-
Suspended inorganic matter	High x low	RM	2009 x 2009	0.94	0.32	Yes
			2009 x 2010	0.87	0.38	Yes
	Low	RM	2009 x 2010	0.32	0.34	-
		Japurá x Solimões	2009	0.75	1.09	-
			2010	0.60	1.03	-
		Japurá	2009 x 2010	0.80	1.03	-
		Solimões	2009 x 2010	0.60	1.09	-
Suspended organic matter	High x low	RM	2009 x 2009	1.00	0.32	Yes
			2009 x 2010	1.00	0.38	Yes
	Low	RM	2009 x 2010	0.31	0.34	-
		Japurá x Solimões	2009	0.80	1.09	-
			2010	0.80	1.03	-
		Japurá	2009 x 2010	0.40	1.03	-
		Solimões	2009 x 2010	1.00	1.09	-
Chlorophyll-*a*	High x low	RM	2009 x 2009	1.00	0.32	Yes
			2009 x 2010	1.00	0.38	Yes
	Low	RM	2009 x 2010	0.35	0.34	Yes
		Japurá x Solimões	2009	0.75	1.09	-
			2010	1.00	1.03	-
		Japurá	2009 x 2010	0.80	1.03	-
		Solimões	2009 x 2010	0.40	1.09	-
Pheophytin	High x low	RM	2009 x 2009	1.00	0.32	Yes
			2009 x 2010	1.00	0.38	Yes
	Low	RM	2009 x 2010	0.48	0.34	Yes
		Japurá x Solimões	2009	1.00	1.09	-
			2010	1.00	1.03	-
		Japurá	2009 x 2010	0.80	1.03	-
		Solimões	2009 x 2010	1.00	1.09	-

Rm: lakes of the right margin of Japurá lakes, High: high water phase (flood), Low: low water phase (drought).

NTU to 565 NTU in LWP. Mean values during drought events ranged from 23.82 NTU, in right margin lakes in 2008, to 218.42 NTU in Solimões River in 2010. Left margin lakes were four times more turbid than right margin lakes, during HWP. Solimões and Japurá Rivers were more turbid than right margin lakes during LWP (Tables 2 to 5).

Dissolved oxygen mean concentration varied from 4.23 $mg.L^{-1}$ (2008) to 5.65 $mg.L^{-1}$ (2009) in LWP. In 2009 high water phase, it presented the lowest mean value (2.36 $mg.L^{-1}$). During HWP mean oxygen concentrations were higher in left margin lakes (3.33 $mg.L^{-1}$) than in right margin lakes (2.24 $mg.L^{-1}$). During 2009 drought event, dissolved oxygen was higher in right margin lakes than in main rivers. However in 2010 Solimões and Japurá had more oxygenated waters (Tables 2 to 5).

Suspended inorganic matter (SIM) varied from 0.05 to 3.02 $mg.L^{-1}$ with a mean value of 0.92 $mg.L^{-1}$, during HWP. During LWP inorganic fraction varied from 1.52 to 590.39 $mg.L^{-1}$, with mean values of 57.68 $mg.L^{-1}$ (2009) and 27.15 $mg.L^{-1}$ (2010). The maximum concentration was found in right margin lakes (590.39 $mg.L^{-1}$)

Table 9. Two-sample Kolmogorov-Smirnov test (Dmax) between hydrograph phases and main rivers for nitrogen, phosphorus, total dissolved carbon and inorganic and organic dissolved carbon. Sig 1% indicates the variables that display different distributions.

Parameter	Hydrograph phase	Water body	Year comparison	Dmax	Dcrit	Sig.1%
Nitrogen	High x low	RM	2009 x 2009	0.97	0.32	Yes
			2009 x 2010	0.98	0.38	Yes
	Low	RM	2009 x 2010	0.47	0.34	Yes
		Japurá x Solimões	2009	0.55	1.09	-
			2010	0.40	1.03	-
		Japurá	2009 x 2010	0.80	1.03	-
		Solimões	2009 x 2010	0.80	1.09	-
Phosphurus	High x low	RM	2009 x 2009	0.56	0.32	Yes
			2009 x 2010	0.70	0.38	Yes
	Low	RM	2009 x 2010	0.47	0.34	Yes
		Japurá x Solimões	2009	0.35	1.24	-
			2010	0.60	1.15	-
		Japurá	2009 x 2010	1.00	1.15	-
		Solimões	2009 x 2010	0.75	1.24	-
Total dissolved carbon	High x low	RM	2009 x 2009	0.67	0.32	Yes
			2009 x 2010	0.91	0.38	Yes
	Low	RM	2009 x 2010	0.47	0.34	Yes
		Japurá x Solimões	2009	0.80	1.09	-
			2010	0.80	1.03	-
		Japurá	2009 x 2010	0.60	1.03	-
		Solimões	2009 x 2010	0.60	1.09	-
Dissolved inorganic carbon	High x low	RM	2009 x 2009	0.62	0.32	Yes
			2009 x 2010	0.88	0.38	Yes
	Low	RM	2009 x 2010	0.47	0.34	Yes
		Japurá x Solimões	2009	0.80	1.09	-
			2010	0.80	1.03	-
		Japurá	2009 x 2010	0.80	1.03	-
		Solimões	2009 x 2010	0.80	1.09	-
Dissolved organic carbon	High x low	RM	2009 x 2009	0.80	0.32	Yes
			2009 x 2010	0.93	0.38	Yes
	Low	RM	2009 x 2010	0.47	0.34	Yes
		Japurá x Solimões	2009	0.75	1.09	-
			2010	0.60	1.03	-
		Japurá	2009 x 2010	0.40	1.03	-
		Solimões	2009 x 2010	0.75	0.98	-

Rm: lakes of the right margin of Japurá lakes, High: high water phase (flood), Low: low water phase (drought).

during LWP. Solimões and Japurá rivers mean concentrations were higher than that of the right margin lakes, and Solimões River presented the highest mean concentration (134.6 $mg.L^{-1}$) which was more than two times the right margin lakes SIM mean concentration (51.1 $mg.L^{-1}$) (Tables 2 to 5).

Suspended organic matter (SOM) varied from 0.24 to 2 $mg.L^{-1}$, with a mean value of 1.17 $mg.L^{-1}$ during HWP. During drought events SOM varied from 2.31 to 202.96 $mg.L^{-1}$, with mean concentrations of 21.14 $mg.L^{-1}$(2009) and 10.69 $mg.L^{-1}$ (2010). Right margin lakes presented the highest mean concentration in both drought events, with 22.2 $mg.L^{-1}$ (2009) and 11.2 $mg.L^{-1}$ (2010). Japurá had lower mean concentration in 2009 (9.9 $mg.L^{-1}$) and higher in 2010 (10.7 $mg.L^{-1}$) compared to Solimões River in the same period (17.2 $mg.L^{-1}$ in 2009 and 7.4 $mg.L^{-1}$ in 2010) (Tables 2 to 5).

During HWP, chlorophyll-*a* and pheophytin were lower than 1 $\mu g.L^{-1}$ in all samples. Nonetheless during LWP chlorophyll-*a* mean concentration was three hundred times higher in 2010 LWP (148 $\mu g.L^{-1}$) than in 2009 HWP, and in 2009 drought the mean chlorophyll-*a* concentration was 113.03 $\mu g.L^{-1}$. Solimões and Japurá mean concentration during LWP was lower than 10.2 μg.L^{-1} while right margin lakes mean concentration was higher than 127.3 μg.L^{-1}. Maximum chlorophyll concentration occurred in right margin lakes in 2010 drought with 2589.23 μg.L^{-1}, where there was a phytoplankton bloom. Pheophytin varied from 1.35 μg.L^{-1} to 95.59 μg.L^{-1} during LWP. Mean concentration in HWP was 0.2 μg.L^{-1}. In LWP, mean concentrations were 18.38 μg.L^{-1} (2009) and 15.67μg.L^{-1} (2010). Right margin lakes had the highest mean (20.1 μg.L^{-1} in 2009) and Solimões river the lowest one (2.6 μg.L^{-1} in 2009) during LWP (Tables 2 to 5).

Mean phosphorus concentration was 105.11 μg.L^{-1}, during HWP, varying from 50.68 μg.L^{-1} to 179.42 μg.L^{-1}. During LWP total phosphorus mean concentrations were two times higher (220.99 μg.L^{-1} in 2009 and 210.78 μg.L^{-1} in 2010) than in flood period, with a maximum concentration of 1094.89 μg.L^{-1} in 2009. Right margin lakes had highest mean values during HWP and LWP than the main rivers in 2009 LWP. However during 2010 LWP, Solimões River presented the highest mean value with 233.8 μg.L^{-1} (Tables 2 to 5).

Nitrogen concentration was lower than 0.32 mg.L^{-1} in HWP, with a mean value of 0.18 mg.L^{-1}. During LWP, nitrogen varied from 0.04 mg.L^{-1} to 10.31 mg.L^{-1}, with mean values of 1.62 mg.L^{-1} (2009) and 1.17 mg.L^{-1} (2010). Right margin lakes had the highest mean values during LWP. In 2009, those lakes had six times more nitrogen than Japurá and 4 times than Solimões mean values. In 2010, both Japura and Solimões had almost 5 times less nitrogen than the lakes located in the right margin of Japurá River (Tables 2 to 5).

Dissolved inorganic carbon was higher during droughts with mean concentrations of 16.06 mg.L^{-1} (2009) and 15.19 mg.L^{-1} (2010). In HWP mean concentration was 8.16 mg.L^{-1} with a maximum value of 9.58 mg.L^{-1}. The highest inorganic carbon mean concentration was observed in right margin lakes and in Solimões River in both years. Japurá River values during LWP were even lower than the concentrations found during HWP in right margin lakes (Tables 2 to 5).

The organic fraction was also higher during LWP with mean concentrations of 11.47 mg.L^{-1} (2009) and 8.44 mg.L^{-1} (2010), and during HWP the mean value was 4.62 mg.L^{-1}. The lakes located on the right margin presented the highest values. Solimões and Japurá River concentrations during the LWP were lower than the organic carbon concentration of the right margin lakes during HWP (Tables 2 to 5).

4. Discussion

The results showed that the studied water bodies have high variability on all measured chemical and physical variables between hydrograph phases, among main rivers and between opposite margins of Japurá River.The limnological variability among hydrological phases, and also between lakes on opposite margins and between main rivers points to the influence of several factors, such as, water volume, main river input, lake morphometry and connection to the main channel/river.

The seasonal flood homogenizes the water masses, all the lakes are interconnected with the main channels and rivers, receiving a huge volume of water, and thus promoting the lowest amplitudes for all variables were observed during high water phase. During the drought the lakes are isolated with poor or no connection to the main channels and rivers and can be considered as single units or actual lentic systems, influenced by their local immediate environment. This condition may explain the fact that they displayed the highest values and amplitudes of all variables during the low water period. This pattern was already observed elsewhere in the Amazon (Carvalho et al., 2001; Abdo and Silva, 2004; Almeida and Melo, 2009), and also in Mamirauá lakes, where Henderson (1999) and Queiroz (2007) noted similar patterns for conductivity, temperature, dissolved oxygen and water transparency, with lower values during flood and higher during drought (except for water transparency). Water volume in lakes and channels, during dry season, is much lower than in other seasons, thus many of them might remain isolated from the main channel and more turbid. Therefore the surface irradiance increases the water column temperature (Alcântara, 2010). However, during the rainy season, the large volume of flowing water in the floodplain turns the lakes into almost lotic system since they gain direction and flow, and thus, smaller residence time, increased turbulence and changes in water-air interface, which also contributes to lower the temperature. Besides that, the water column is more transparent, which favors light penetration and, consequently, the energy dissipation within a higher water volume. This enlarged water volume in the high water also explains the lower temperatures in this season. In addition, the flood period of this region is characterized by low solar radiation, increased cloud cover and high precipitation, opposite to the dry season (Ceballos et al., 2004; CPTEC, 2009; NASA, 2009).

During low water season, the lakes and channels are shallower and are primarily fed by channels bearing inorganic matter from main rivers. Furthermore, they are more affected by wind (because they are shallow), causing sediment re-suspension. Nevertheless, during high water phase the lakes are fed by a huge water volume which comes in a diffuse way to the lakes throughout the forest and channels. Particulate material is deposited along the way, and when the water reaches the lakes there is almost no suspended matter and with probable low turbidity.

Similar to other variables, electrical conductivity was higher during droughts because during that period the lakes are isolated from main channels, with less water volume (shallower, higher solar incidence, and consequently, higher temperature and evaporation) with higher residence time, and consequently an intense ion exchange with the substrate. Inversely during high water phase those values are lower than that of the low water phase.

Barbosa et al. (2010) showed that Curuaí floodplain, Pará State (Lower Amazon) has higher magnitudes of pH, turbidity, chlorophyll-*a* and dissolved organic carbon during high water phase, than in Mamirauá floodplain. During HWP, Curuaí water was alcaline, more turbid, and with higher chlorophyll and organic carbon concentrations than in Mamirauá at the same period. However during LWP, this situation was inverse, with exception of turbidity when Curuai reached extreme mean values of 769 NTU while in Mamirauá mean turbidity were 23.82 (2008), 60.46 NTU (2009) and 96 NTU (in 2010). Mean dissolved inorganic carbon was almost two times higher in Mamirauá and chlorophyll-*a* mean concentration was three times higher in Mamirauá than in Curuai during LWP. Water characteristics are dependent on local climate, soil, surrounding vegetation, human influence, and exhibited temporal and spatial variations due to internal and external processes (Maybec and Helmer, 1992; Wetzel, 2001). Curuai floodplain is located in eastern Amazon, 510 km distant from Manaus, in Pará State. There are 20,000 rural inhabitants living in 96 communities within the floodplain. This region is formed by 4 municipalities and has a strong rancher tradition with 234,678 cattle heads and 373,608 inhabitants (IBGE, 2006). According to Renó (2010), around 3,600 km^2 of flooded forest were removed from the lower Amazon várzea between 1975-1981 and 2008, which represents 56 % of that region.

On the other hand Mamirauá Sustainable Development Reserve, where human intervention is kept to minimum and deforestation is practically nonexistent. It is a highly conserved floodplain area where only 6,500 inhabitants are divided in 64 communities. The municipalities around the Reserve (6 in total) have up to 134,558 inhabitants and 8,677 cattle heads according to 2006 Census (IBGE, 2006).

Notwithstanding the limited (two hydrograph phases) and the large inter-annual variability of the hydrology forcing functions in those regions, it suggest that those differences between limnological conditions at Mamirauá and Curuai might be originated from anthropogenic activities and will in turn affect considerably those water properties and may pose a threat not only to human health but also for aquatic fauna and flora

This study showed the temporal (intra and interannual) and spatial (opposite margins and main rivers) variations that occurred in Mamirauá floodplain, and related them with the different phases of the hydrologic pulse. And this study also points out to the fact that less disturbed areas as Mamirauá Sustainable Development Reserve might be considered as future reference for comparison with more disturbed areas, and for modeling the effects of climate change and anthropogenic influences on Amazon aquatic ecosystem.

5. Conclusions

Limnological patterns of Amazon floodplain lakes are highly dependent on the flood pulse, and consequently on the surrounding environment, the main river input, and geographic location. Mamirauá floodplain lakes, an undisturbed Amazon region, can vary from an oligotrophic, with low primary productivity, during high water phase to a hyper eutrophic environment, high productivity, in low water phase. These changes, although highly contrasting shows how undisturbed regions respond to natural variance in such a diverse environment. The Amazon region is under anthropogenic pressure since the 70´s and the consequences of these changes in the aquatic system is barely know. Thus these data will be fundamental for assessing not only human impact on aquatic systems but can also give support to future analyses on the effects of global climate changes in their biogeochemical cycles.

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