INFLUENCE OF THE HYDROLOGICAL CYCLE ON PHYSICAL AND CHEMICAL VARIABLES OF WATER BODIES IN THE VÁRZEA AREAS OF THE MIDDLE SOLIMÕES RIVER REGION (AMAZONAS, BRAZIL)

INFLUÊNCIA DO CICLO HIDROLÓGICO SOBRE AS VARIÁVEIS FÍSICO-QUÍMICAS DE CORPOS D'ÁGUA DE VÁRZEA DA REGIÃO DO MÉDIO RIO SOLIMÕES (AMAZONAS, BRASIL)

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KEY WORDS:

Floodplain;

Flood pulse;

Water quality;

Mamirauá;

Water bodies;

Amazon.

ABSTRACT

The variation in water level in the Amazon várzea promotes cyclical isolation or union of various bodies of water. Among these, lakes and channels are the most relevant. Due to their cyclical geographic isolation, and even due to the often distinct origin of their waters, these environments showed limnological features which also vary from those bodies of water located outside the várzea setting. The objective of this study is to demonstrate the differentiation of the types of water bodies present in the Middle Solimões area, inside and outside of the floodplain areas, by segregating their main physical and chemical parameters. It also aims to evaluate the influence of the flood pulse on these parameters in these types of bodies of water. In order to do this, expeditions were conducted monthly from 2004 to 2011, at twelve sampling stations located in different types of water bodies, including canals and lakes within the Mamirauá Sustainable Development Reserve, the Solimões River and the mouth of the Tefé River. The parameters monitored were electrical conductivity, temperature, dissolved oxygen, oxygen saturation, pH and transparency. To analyze the data obtained from this monitoring, descriptive statistics and clustering were used. The temperature of the bodies of water in the Mamirauá RDS showed mean values ranging between 27.1 and 30.8 ° C. Dissolved oxygen concentrations resulted in average concentrations of from 0.3 to 0.6 mg.L-1, with a high standard deviation. Transparency was between 0.4 and 1.6 m. Electrical conductivity ranged between 87 and 204 μS.cm-1 in white waters and 10 - 21 μS.cm-1 in black/mixed waters of the mouth of the Tefé River. From the groupings obtained, it was possible to state that the lakes behave like independent bodies of water in the daught season, and during the season of high water they form a large grouping, suggesting a greater homogenization. An analysis of principal components with the parameters confirmed their relevance in the structuring of groups or types of bodies of water identified in the region. The pH distinguished itself as the main differentiating factor between white and black waters, followed by water transparency. Electrical conductivity was the main parameter responsible for the differentiation of water in different periods of the hydrological cycle, followed by water transparency. The variation in water level during the hydrological cycles evaluated over seven years of monitoring influenced the water quality in the lakes and canals of Mamirauá Sustainable Development Reserve and the Solimões and Tefé Rivers. The parameters transparency, dissolved oxygen, and conductivity varied more markedly between the periods of draught and high water.

PALAVRAS - CHAVE:

Várzea;

Pulso de inundação;

Qualidade da água;

Mamirauá;

Corpos d'água;

Amazônia.

RESUMO

A variação do nível da água nas planícies alagadas da várzea Amazônica promove o cíclico isolamento ou união de vários corpos d'água. Dentre estes corpos, os lagos e canais (ou canos) são os mais relevantes. Devido ao seu cíclico isolamento geográfico, e mesmo à origem muitas vezes distinta de suas águas, estes ambientes apresentaram características limnológicas também variáveis, da mesma forma que são diferentes das características daqueles corpos d'água localizados fora dos domínios da várzea. O objetivo deste estudo é demonstrar a diferenciação dos tipos de corpos d'água presentes na área do Médio Solimões, dentro e fora dos domínios de várzea, por meio da segregação de seus principais parâmetros físicos e químicos. Objetiva também avaliar a influência do pulso de inundação sobre estes parâmetros nestes tipos de corpos d´água. Para tal, foram realizadas expedições mensais, entre 2004 a 2011, a doze estações de coleta, localizadas em diferentes tipos de corpos d'água, incluindo canais e lagos no interior da Reserva de Desenvolvimento Sustentável Mamirauá, o rio Solimões e foz do rio Tefé. Os parâmetros monitorados foram condutividade elétrica, temperatura, oxigênio dissolvido, saturação por oxigênio, pH e transparência. Para analisar os dados obtidos neste monitoramento foram utilizadas a estatística descritiva e de agrupamento. A temperatura nos corpos d'água da RDS Mamirauá mostrou valores médios oscilando entre 27,1 e 30,8 °C. O oxigênio dissolvido resultou em concentrações médias de 0,3 a 0,6 $mg.L^{-1}$, com alto desvio-padrão. A transparência esteve entre 0,4 e 1,6 m. A condutividade elétrica variou entre 87 e 204 $\mu S.cm^{-1}$ nas águas brancas e de 10 a 21 $\mu S.cm^{-1}$ nas águas pretas/mistas da foz do rio Tefé. Dos agrupamentos obtidos, foi possível constatar que, na época seca, os lagos comportam-se como corpos d'água mais independentes, e durante a cheia formam um grande agrupamento, sugerindo uma maior homogeneização. Uma análise de componentes principais com os parâmetros confirmou a relevância deles na estruturação dos grupos ou tipos de corpos d'água identificados na região. O pH destacou-se como o principal fator de diferenciação entre águas brancas e pretas, seguido pela transparência da água. Enquanto a condutividade elétrica foi o principal parâmetro responsável pela diferenciação das águas nos diferentes períodos do ciclo hidrológico, seguida da transparência da água. A variação do nível da água durante os ciclos hidrológicos avaliados ao longo dos sete anos de monitoramento influenciou a qualidade da água nos lagos e canos da Reserva de Desenvolvimento Sustentável Mamirauá e nos rios Solimões e Tefé. As variações mais acentuadas, observadas nos parâmetros transparência, oxigênio dissolvido e condutividade, ocorreram entre os períodos de seca e cheia.

INTRODUCTION

The Solimões-Amazonas River Basin, which includes forests, rivers, creeks, *igarapés*, lakes, canals, swamps, swaths of savannah, and sandy beaches (AYRES, 2006), is the largest flood basin in the world, spanning seven countries and covering an area of 6,869,000 km² (NEIL et al, 2006; JUNK, 1997).

Its hydrology is subject to natural and regular variations in water level. Due to the complex dynamics of the flood pulse, there is a cyclical formation of extensive flooded areas known as várzeas (flooded with white water) and igapós (flooded with black water) (AYRES, 2006; JUNK et al., 2010b; JUNK et al., 2011).

Junk et al. (2010a) argue that the fact that the flood pulse is monomodal, predictable, and large in scale favors the adaptation of plants and animals to the land and aquatic environments, allowing the organisms to use the resources that exist in these floodable areas. The flood pulse concept itself suggests that the main selection pressure on the great biodiversity of flooded areas is the change in water level, generating an alternation between drougthand flooded phases, and causing the water in the rivers to invade the adjacent floodable plains (JUNK et al., 1989).

As a result of the variation in water level on these plains, the local water bodies may join together or become isolated. Principal among these are the lakes and canals, which due to their isolation or even the origin of the water they contain, may present great variation in their water quality parameters, generating distinct limnological characteristics.

There is extensive literature about the limnology of Amazonian waters and their seasonal variations. McClain et al. (2008) show the influence of the Andes on the physical, chemical, and ecological characteristics of the Amazon River. Almeida et al. (2009) present limnological variables that better characterize the lake environment than a floodplain. More recent work has been conducted on this theme by Darwich et al. (2005); Aufdenkampe et al. (2007); Thomaz et al. (2007); Alcântara (2010); Barbosa (2010) and Ruddorf et al. (2011), among others. Limnology studies in the Mamirauá Sustainable Development Reserve - MSDR, were conducted by Henderson (1999); Jardim-Lima et al. (2005); Queiroz (2007); Affonso et al. (2011); Ruddorf et al. (2011); and Trevisan et al. (2012), among others.

The objective of this study is to describe some physical and chemical parameters of different types of water bodies in the MSDR and its surroundings, to verify if there are similar characteristics between them that allow them to be grouped into categories of water bodies, and to assess the influence of the seasonal flood pulse on the characteristics of the local waters, and on the groupings that may be made with these water bodies.

METHODOLOGY

Study area

This study was conducted in the Middle Solimões region of Central Brazilian Amazonia. Fixed collection stations were established on the water bodies that are representative of the area. These stations, or fixed points in the aquatic environment, were monitored monthly from the beginning of the study, when information was collected about the characteristics of the water there, and continue to be visited monthly.

The location of these collection points is shown in the map in Figure 1. Ten of the sample points are located within the MSDR. This state conservation unit has a total area of 1,240,000 ha that is periodically flooded, and is bordered by the Solimões, Japurá, and Auati-Paranã Rivers (INSTITUTO..., 2010). The area includes the Solimões River basin; the river itself is sedimentary in origin, and drains white water that originates in the Andes.

The hydrological cycle of the region of this study was described by Ramalho et al. (2009). The lakes and canals within the RDSM receive waters from the Solimões and Japurá Rivers during high water periods (HENDERSON, 1999). Although the lower course of the Japurá River receives a significant inflow of white water from the Solimões River, these two rivers differ in relation to the quality of their water (HENDERSON, 1999; INSTITUTO..., 2010).

Collection methods

Monthly collection of the data presented in this study began in July 2004 and continues until today. However, this project presents only information collected until July 2011.

The parameters collected in this study were: electrical conductivity, temperature, dissolved oxygen, oxygen saturation, and pH, always using a multi-parameter measuring probe. The measurements at each station were conducted at depths of one half (0.5), one (1.0), two (2.0), and three and a half (3.5) meters. The transparency values at each point were also taken at each fixed point using a Secchi disk.

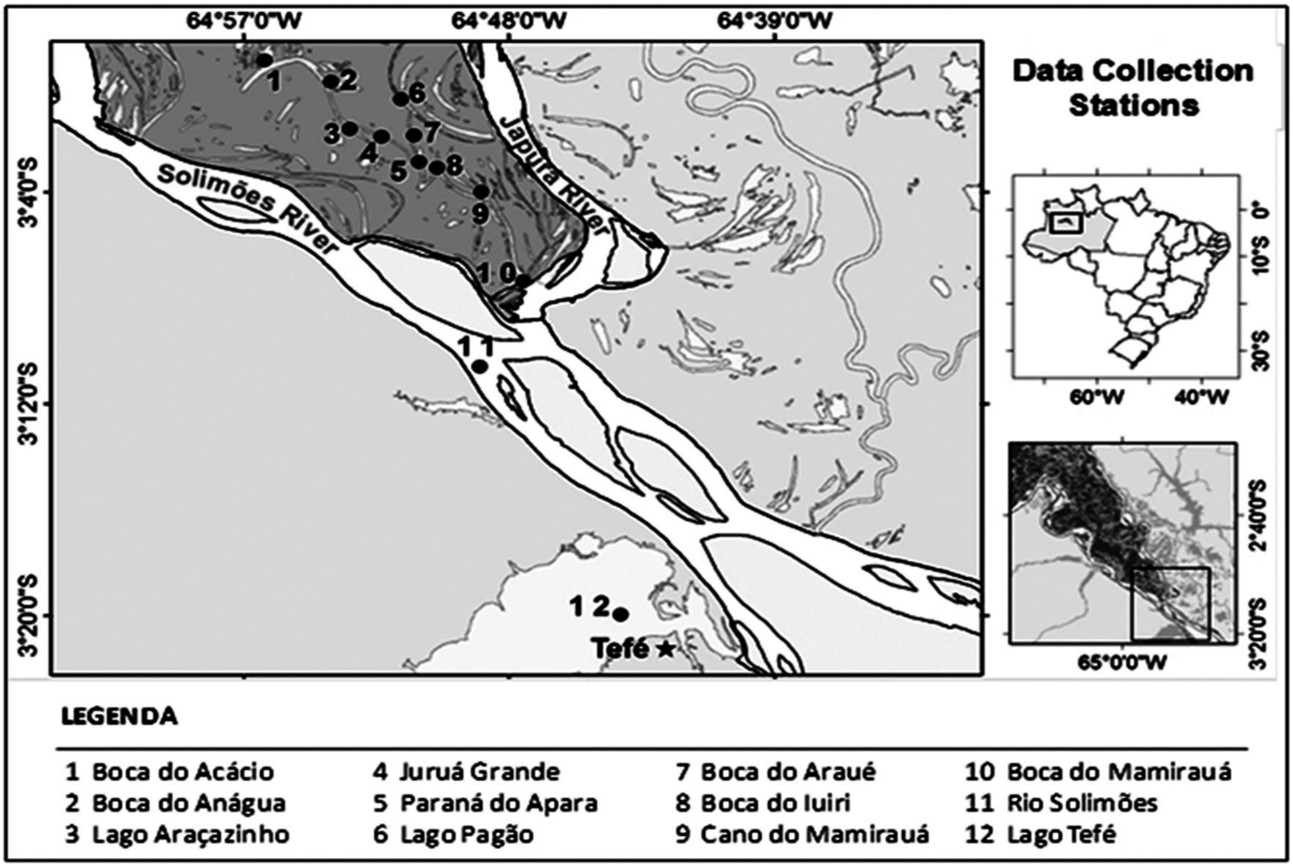

Figure 1 – Location of collection stations.

The probe's pH sensors proved to be more sensitive to conditions in the field and often had functional problems during the study period. For this reason, the number of pH readings was greatly affected. Similar problems occurred with the sensors for the dissolved oxygen parameters, especially during peak high water periods in the areas outside the MSDR, which also produced a reduced number of measurements for these variables in the river collection stations. Such problems impeded some of these variables from being evaluated and understood in detail for some depths at some fixed collection stations or during some periods of the hydrological cycle.

Data Analysis

The collection points were classified into different categories based on their environmental and geomorphological characteristics and the general typology of their waters (Sioli, 1984): white water canal (WWC), white water river (WWR), white water lake (WWL) and black water river mouth (BRM), according to their location (Table 1).

Table 1 – Categories of water bodies include in this study.

WWC (White Water Canal)	WWL (White Water Lake)	WWR (White Water River)	BRM (Black Water River Mouth)
Boca do Araué	Lago Acácio		
Boca do Mamirauá	Ressaca do Anágua		
Mamirauá Canal	Lake Araçazinho	Rio Solimôes	Lago Tefé
Paraná do Apara	Lake Juruá Grande		
Ressaca do Iuiri	Lake Pagão		

The data series from this monthly monitoring was analyzed by means of descriptive statistics, grouping statistics, and analysis of principal components. For the cluster analysis type grouping (method of simple connection, using Euclidian distances as a measure of similarity) (EVERITT et al, 2011), the following variables were used: transparency, temperature, and electrical conductivity, in an attempt to avoid the simultaneous use of parameters which would present co-linearity in the study area, as was demonstrated by Affonso et al. (2011). The objective of the cluster analysis was to verify the similarity between the water bodies which were studied, and to evaluate the evolution of this grouping throughout the hydrological cycle. The data were standardized to avoid influences from the measuring units in the grouping results, as recommended by Frei (2006).

Analysis of the principal components was conducted in order to understand the relative importance of the water quality parameters which were studied in the groupings that were obtained. In order to do this, the data were standardized and analyzed without previous differentiation into groups. The following variables were used: transparency, temperature, electrical conductivity, dissolved oxygen, and pH.

RESULTS AND DISCUSSION

Tables 2 and 5 are the synthesis of results of physical and chemical values measured in the four categories of bodies of water which were measured, at different depths, during periods of rising water, high water, dropping water and draught, respectively.

In general, the temperature and electrical conductivity show the highest values during the droughtperiod. On the other hand, the oxygen concentration, transparency, and pH are higher during the flood period.

As can be seen in the Tables, and as described in the section discussing data acquisition (Methodology), the number of pH and oxygen measurements was reduced in some fixed stations for some periods of the hydrological cycle. Although this small number of pH measurements impedes a complete analysis of the spatial-temporal variation of all the variables under study, a general and comprehensive picture of the variation of the parameters registered throughout this study can be obtained.

Table 2 - Physical and chemical variables for water during the rising water period.

FLOOD		Temperature (°C)		pH		Conductivity (μS.cm^{-1})		DO (mg.L^{-1})		OS (%)		Transparency (m)	
Water body category	**Depth. (m)**	Average	N	Average	N	Average	N	Average	N	Average	N	Average	N
WWC	0.5	29.7 ± 1.3	126	6.8 ± 0.3	86	123.0 ± 61.3	126	0.6 ± 1.2	45	29.1 ± 38.2	102	0.7 ± 0.4	125
	1	29.2 ± 1.2	126	6.8 ± 0.3	86	119.1 ± 56.5	126	0.5 ± 0.9	45	27.2 ± 37.1	103		
	2	28.9 ± 0.9	123	6.8 ± 0.3	83	117.9 ± 55.7	123	0.4 ± 0.7	45	25.2 ± 36.2	100		
	3.5	28.7 ± 1.0	122	6.8 ± 0.3	87	117.2 ± 54.0	122	0.5 ± 0.7	44	25.8 ± 36.4	99		
WWL	0.5	29.3 ± 1.5	132	6.7 ± 0.3	91	117.7 ± 58.7	132	0.4 ± 0.6	63	23.6 ± 36.6	126	0.8 ± 0.5	129
	1	28.8 ± 1.1	122	6.7 ± 0.3	82	114.5 ± 58.2	123	0.4 ± 0.5	61	23.4 ± 36.4	115		
	2	28.4 ± 0.9	111	6.7 ± 0.3	72	106.9 ± 40.1	111	0.3 ± 0.4	60	20.3 ± 34.5	105		
	3.5	28.1 ± 0.9	95	6.7 ± 0.2	65	102.2 ± 31.9	95	0.3 ± 0.2	56	15.9 ± 29.7	91		
WWR	0.5	28.5 ± 0.7	26	7.0 ± 0.3	18	111.1 ± 11.8	26	0.5 ± 1.0	16	30.1 ± 37.7	25	0.1 ± 0.04	25
	1	28.5 ± 0.7	26	7.0 ± 0.2	18	111.0 ± 11.7	26	0.5 ± 1.0	16	30.3 ± 37.8	25		
	2	28.5 ± 0.7	26	7.0 ± 0.2	18	110.9 ± 11.8	26	0.5 ± 1.0	16	30.6 ± 38.1	25		
	3.5	28.5 ± 0.7	26	7.0 ± 0.2	19	110.9 ± 11.8	26	0.5 ± 0.9	16	31.2 ± 38.4	25		
BRM	0.5	29.7 ± 1.1	25	6.3 ± 0.9	17	16.5 ± 21.0	24	0.7 ± 1.8	16	32.4 ± 40.3	25	1.3 ± 0.5	21
	1	29.4 ± 0.7	25	6.3 ± 0.9	17	16.4 ± 20.8	24	0.6 ± 1.8	16	31.9 ± 39.5	25		
	2	29.2 ± 0.6	25	6.4 ± 0.8	17	16.5 ± 20.8	24	0.6 ± 1.7	16	32.5 ± 39.7	25		
	3.5	29.1 ± 0.6	25	6.5 ± 0.7	18	16.5 ± 20.4	24	0.6 ± 1.6	16	32.6 ± 39.7	25		

Legend: WWC: white water canal; WWL: white water lake; WWR: white water river; BRM: black water river mouth; DO: dissolved oxygen; OS: oxygen saturation

Table 3 – Physical and chemical variables for water during the high water period.

PEAK FLOOD		Temperature (°C)		pH		Conductivity (μS.cm^{-1})		DO (mg.L^{-1})		OS (%)		Transparency (m)	
Water body category	**Depth. (m)**	Average	N	Average	N	Average	N	Average	N	Average	N	Average	N
WWC	0.5	27.1 ± 0.5	50	6.9 ± 0.6	20	87.7 ± 14.8	50	0.6 ± 0.7	27	7.0 ± 8.3	38	1.2 ± 0.4	49
	1	27.1 ± 0.5	50	6.9 ± 0.6	20	87.8 ± 14.9	50	0.6 ± 0.7	27	6.5 ± 7.4	38		
	2	27.1 ± 0.5	50	6.9 ± 0.6	20	87.9 ± 15.0	50	0.6 ± 0.6	27	6.3 ± 6.9	38		
	3.5	27.1 ± 0.5	50	6.9 ± 0.5	24	87.7 ± 15.3	50	0.6 ± 0.6	27	6.4 ± 6.5	38		
WWL	0.5	27.3 ± 0.6	54	6.9 ± 0.6	20	81.7 ± 17.4	54	0.6 ± 0.7	36	6.0 ± 7.7	50	1.6 ± 1.6	53
	1	27.1 ± 0.6	54	6.9 ± 0.6	20	81.5 ± 17.4	54	0.5 ± 0.6	36	5.3 ± 6.2	50		
	2	27.1 ± 0.5	54	6.9 ± 0.6	20	81.5 ± 17.5	54	0.5 ± 0.5	36	5.0 ± 5.5	50		
	3.5	27.1 ± 0.5	54	6.8 ± 0.5	24	81.7 ± 17.3	54	0.5 ± 0.4	36	5.0 ± 4.9	50		
WWR	0.5	27.7 ± 0.6	9	7.2 ± 0.5	2	90.5 ± 9.2	9	1.1 ± 1.7	8	13.6 ± 20.5	9	0.2 ± 0.03	8
	1	27.6 ± 0.6	9	7.1 ± 0.5	2	90.5 ± 9.2	9	1.1 ± 1.7	8	13.2 ± 19.8	9		
	2	27.6 ± 0.6	9	7.1 ± 0.5	2	90.5 ± 9.2	9	1.1 ± 1.6	8	13.0 ± 19.7	9		
	3.5	27.7 ± 0.7	9	7.1 ± 0.5	2	90.4 ± 9.5	9	1.1 ± 1.6	8	12.9 ± 19.5	9		
BRM	0.5	29.2 ± 1.2	8	7.8 ± 1.6	2	10.0 ± 1.4	8	1.9 ± 2.9	7	22.7 ± 34.4	8	1.9 ± 0.3	9
	1	28.9 ± 1.0	8	7.5 ± 1.6	2	10.3 ± 1.4	8	1.9 ± 2.9	7	22.6 ± 34.2	8		
	2	28.5 ± 0.7	8	7.3 ± 1.6	2	10.2 ± 1.9	8	1.8 ± 2.7	7	21.6 ± 33.4	8		
	3.5	28.4 ± 0.7	8	7.0 ± 1.5	2	10.0 ± 1.8	8	1.7 ± 2.6	7	19.5 ± 30.9	8		

Legend: WWC: white water canal; WWL: white water lake; WWR: white water river; BRM: black water river mouth; DO: dissolved oxygen; OS: oxygen saturatio

Table 4 – Physical and chemical variables of water during the dropping water period.

DRAINING		Temperature (°C)		pH		Conductivity (μS.cm-1)		DO (mg.L-1)		OS (%)		Transparency (m)	
Water body category	**Depth (m)**	Average	N	Average	N	Average	N	Average	N	Average	N	Average	N
WWC	0.5	28.1 ± 1.6	68	6.8 ± 0.6	37	87.5 ± 24.5	67	0.5 ± 0.6	26	10.7 ± 17.9	46	1.1 ± 0.6	63
	1	27.9 ± 1.4	64	6.6 ± 0.2	33	87.7 ± 23.2	63	0.5 ± 0.6	23	10.3± 18.0	44		
	2	27.7 ± 1.2	62	6.6 ± 0.2	33	87.5 ± 24.5	61	0.5 ± 0.6	24	9.7 ± 17.6	43		
	3.5	27.5 ± 1.0	61	6.3 ± 1.0	38	89.1 ± 26.0	60	0.4 ± 0.5	24	9.5 ± 18.1	42		
WWL	0.5	28.5 ± 2.1	65	6.7 ± 0.4	34	94.5 ± 50.9	65	0.5 ± 0.6	34	13.7 ± 22.9	61	1.1 ± 0.7	62
	1	27.8 ± 1.4	57	6.6 ± 0.2	31	88.5 ± 42.6	57	0.4 ± 0.6	30	13.0 ± 23.9	53		
	2	27.3 ± 1.1	52	6.6 ± 0.2	29	84.8 ± 27.2	52	0.4 ± 0.5	28	12.9 ± 24.8	48		
	3.5	27.1 ± 1.1	45	6.4 ± 0.7	30	85.2 ± 23.4	45	0.4 ± 0.4	25	14.3 ± 26.3	42		
WWR	0.5	28.3 ± 1.0	13	7.1 ± 0.6	7	99.8 ± 26.3	13	1.0 ± 2.0	7	20.6 ± 28.7	10	0.2 ± 0.04	12
	1	28.3 ± 1.0	13	7.1 ± 0.6	7	94.3 ± 33.8	13	1.0 ± 1.9	7	20.3 ± 28.2	10		
	2	28.3 ± 1.0	13	7.0 ± 0.7	7	99.4 ± 26.8	13	1.0 ± 1.9	7	20.6 ± 29.1	10		
	3.5	28.3 ± 1.0	13	6.7 ± 1.2	8	107.5 ± 26.2	13	1.0 ± 1.9	7	20.8 ± 29.5	10		
BRM	0.5	29.3 ± 1.1	13	6.5 ± 1.1	7	13.9 ± 2.7	11	0.8 ± 1.5	8	22.2 ± 32.0	11	1.9 ±0.9	12
	1	29.2 ± 1.1	13	6.4 ± 1.0	7	13.4 ± 2.5	11	0.7 ± 1.2	8	20.3 ± 29.7	11		
	2	29.0 ± 0.9	13	6.3 ± 0.9	7	13.3 ± 2.4	11	0.7 ± 1.1	8	19.2 ± 28.2	11		
	3.5	28.9 ± 0.9	13	6.1 ± 0.9	8	13.3 ± 2.7	11	0.6 ± 1.0	8	18.7 ± 27.9	11		

Legend: WWC: white water canal; WWL: white water lake; WWR: white water river; BRM: black water river mouth; DO: dissolved oxygen; OS: oxygen saturation

Table 5 – Physical and chemical variables for water during the draugth period.

DRAUGTH		**Temperature (°C)**		**pH**		**Conductivity (μS.cm^{-1})**		**DO (mg.L^{-1})**		**OS (%)**		**Transparency (m)**	
Water body category	**Depth (m)**	Average	**N**	Average	**N**	Average	**N**	Average	**N**	Average	**N**	Average	**N**
WWC	0.5	31.3 ± 1.2	64	6.8 ± 1.0	38	200.6 ± 80.3	58	0.2 ± 0.1	18	41.5 ± 44.6	48	0.6 ± 0.4	67
	1	30.8 ± 1.0	58	6.7 ± 0.9	33	198.3 ± 79.6	54	0.2 ± 0.1	18	29.5 ± 35.9	42		
	2	30.5 ± 0.8	55	6.7 ± 0.9	32	198.0 ± 78.3	52	0.2 ± 0.1	18	24.5 ± 33.3	39		
	3.5	29.9 ± 0.9	48	6.5 ± 0.9	29	204.7 ± 80.5	45	0.2 ± 0.05	18	22.2 ± 33.5	35		
WWL	0.5	30.8 ± 2.1	62	6.4 ± 1.1	31	182.1 ± 95.9	57	0.2 ± 0.1	29	28.4 ± 37.4	58	0.4 ± 0.3	63
	1	30.2 ± 1.0	25	6.6 ± 0.9	10	174.5 ± 74.0	24	0.2 ± 0.05	12	20.5 ± 28.9	21		
	2	29.9 ± 0.9	13	*	*	159.0 ± 57.7	13	0.2 ± 0.1	7	11.1 ± 16.7	9		
	3.5	28.9 ± 1.4	6	*	*	138.4 ± 21.6	6	0.2 ± 0.02	4	15.5 ± 19.6	6		
WWR	0.5	30.1 ± 0.5	14	7.0 ± 0.9	8	127.3 ± 39.9	12	0.2 ± 0.1	7	33.0 ± 37.2	13	0.2 ± 0.1	13
	1	30.1 ± 0.5	14	7.0 ± 0.9	8	126.0 ± 40.2	12	0.2 ± 0.1	7	33.0 ± 37.3	13		
	2	30.1 ± 0.5	14	7.0 ± 0.9	8	126.9 ± 40.2	12	0.2 ± 0.1	7	33.0 ± 37.4	13		
	3.5	30.1 ± 0.5	14	6.9 ± 1.0	8	126.4 ± 40.0	12	0.3 ± 0.1	7	33.5 ± 38.0	13		
BRM	0.5	30.2 ± 2.3	13	6.8 ± 0.4	6	21.7 ± 5.5	11	0.2 ± 0.1	7	32.1 ± 40.0	12	0.5 ± 0.3	12
	1	30.3 ± 1.8	13	6.6 ± 0.7	7	21.8 ± 5.5	11	0.2 ± 0.1	7	32.1 ± 40.2	12		
	2	30.2 ± 1.4	12	6.5 ± 0.7	7	21.6 ± 5.8	10	0.2 ± 0.1	6	34.7 ± 41.0	11		
	3.5	29.9 ± 1.5	11	6.7 ± 0.8	7	20.9 ± 5.6	9	0.3 ± 0.1	5	38.2 ± 42.0	10		

Legend: WWC: white water canal; WWL: white water lake; WWR: white water river; BRM: black water river mouth; DO: dissolved oxygen; OS: oxygen saturation. Note: *these collection stations did not reach the depths of 2.0 and 3.5 m.

Water temperature was close to 27°C during the high water period, and 30°C in the drougth period. There was variation in this parameter according to the measuring depth (from 0.5 to 3.5 meters) throughout the year, with the exception of the high water period, when the temperature was the same at the sampled depths. In the WWR, temperature stratification was not observed until a depth of 3.5 m, unlike the other categories of water bodies, in which stratification was identified. The strong current observed in the Solimões River probably causes large vertical movement and mixing of the water, impeding any type of stratification by temperature as well as by oxygen content variables (Affonso et al., 2010).

Electrical conductivity, as shown in Figure 2, was similar in the classes of water bodies that were made up of fixed stations located in white water (WWC, WWL, and WWR). This was the parameter that presented the most accentuated difference between white water and black water stations. While the waters in WWC, WWL, and WWR had electrical conductivity varying from 87 to 204 μS.cm^{-1}, BRM (black water river mouth) had values varying from 10 to 21 μS.cm^{-1}. The results obtained are compatible with those for white water presented by Santos and Ribeiro (1988), 91 μS.cm^{-1} for the Solimões River in front of Tefé City, and by Queiroz et al (2009), with an average of 99 μS.cm^{-1} in the Solimões River (upstream from Manaus) during the drougth season. The results for black water were also compatible with those presented by Kuchler et al. (2000), 8.8 to 28.6 μS.cm^{-1}, in the Rio Negro hydrological basin (black water), and Darwich et al. (2005), which showed values of 3.7 to 10.8 μS.cm^{-1} in studies of black water igarapés influenced by that same river.

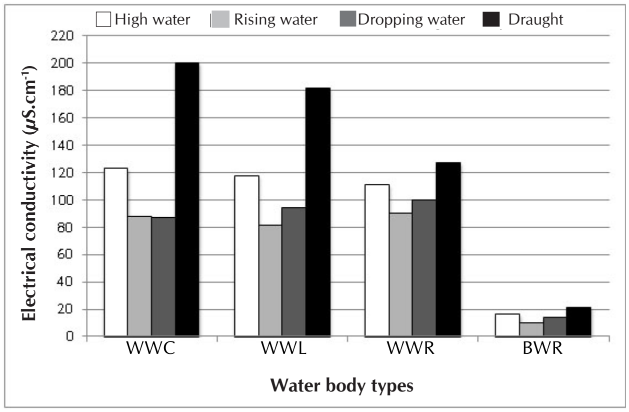

Figure 2 – Electrical conductivity (μS.cm^{-1}) of water bodies in different periods of the hydrological cycle.

Figure 3 shows the water transparency results during the four periods of the hydrological cycle. The results are similar between stations located in white water canals and lakes. The WWR had approximately 1.2 m transparency in all periods, which is compatible with the "muddy" characteristic that is used to describe this type of water (MAYORGA et al., 2002). Again, the turbulence provided by the Solimões River's strong current was probably responsible for maintaining the large quantity of sediment in suspension, stopping it from decanting and keeping transparency very low, as had already been detected by other authors (HENDERSON, 1999). The black water river mouth category (BRM) showed the highest transparency values during all periods of the hydrological cycle, with the exception of the drougth period, when proximity to the Solimões River probably allowed more sediment to enter the river mouth.

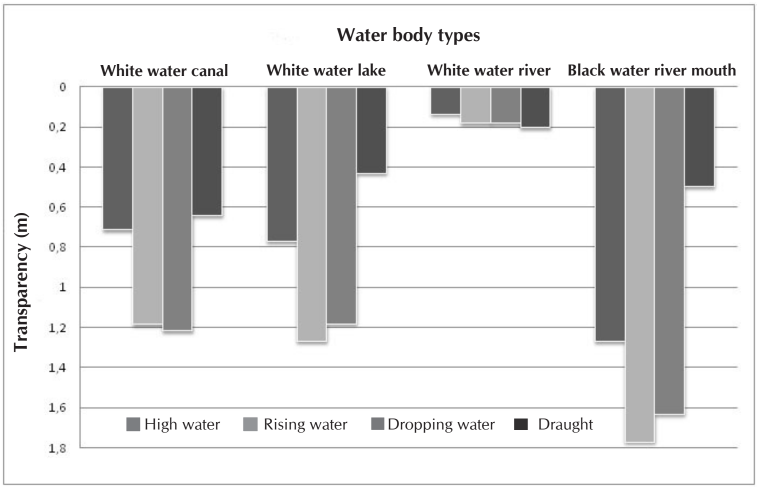

Figure 3 - Transparency (Secchi disk, in meters) of water bodies during different periods of the hydrological cycle.

This correlation (pH - conductivity) cannot be confirmed with the data obtained in this study for the BRM (the black water Tefé River's mouth), where conductivity is low but pH is close to neutral (6.1-7.8), different from the more acidic values which are common in black water. Wismar et al. (1981) obtained a pH measurement of 5.75 for the Tefé River, and Santos and Ribeiro (1988) obtained 6.12. Among the possible causes for this variation in pH is the influence of Tefé City on the water quality with the release of flood water, household sewage, and solid waste into the body of water. Furthermore, the proximity of this fixed collection station to the Solimões River also seems to be important.

The results of the pH measurements are represented in Figure 4. WWR had neutral pH results, varying from 7.0 to 7.2 during all the periods at a depth of 0.5m. It was not possible to identify pH stratification patterns in the water bodies to a depth of 3.5 m. There was not sufficient sampling for this parameter during the collection period (2004-2011) to adequately represent the pH of the water bodies for the high water phase stage.

According to Furch (1984), the pH values for Amazonian waters are strongly connected to the presence of electrolytes, which makes low connectivity normally be connected to low pH. For this reason, black waters with low conductivity normally present more acidic pH readings (4.5-5.1) in comparison with high-conductivity white waters (pH 6.5-6.9). In this study, the white waters presented a pH close to neutral, and high conductivity, agreeing with Furch's conclusions (1984).

Other aspects to be considered in interpreting the pH values obtained in this study are the influence of pluviometric precipitation (GIBBS, 1970) and the morphology of the mouth of the Tefé River. The areas adjacent to the river mouth and the lower course of the Tefé River are flooded, forming an "RIA" lake (IRION, 1984), possibly influencing the characteristics of the water due to processes of sedimentation, contribution from tributaries, and the proximity to the Solimões River. It is suggested that more profound studies of the pH of natural waters in this region be conducted, increasing the sampling of black waters in the Tefé River, including its tributaries and points more distant from the falls and the Tefé city.

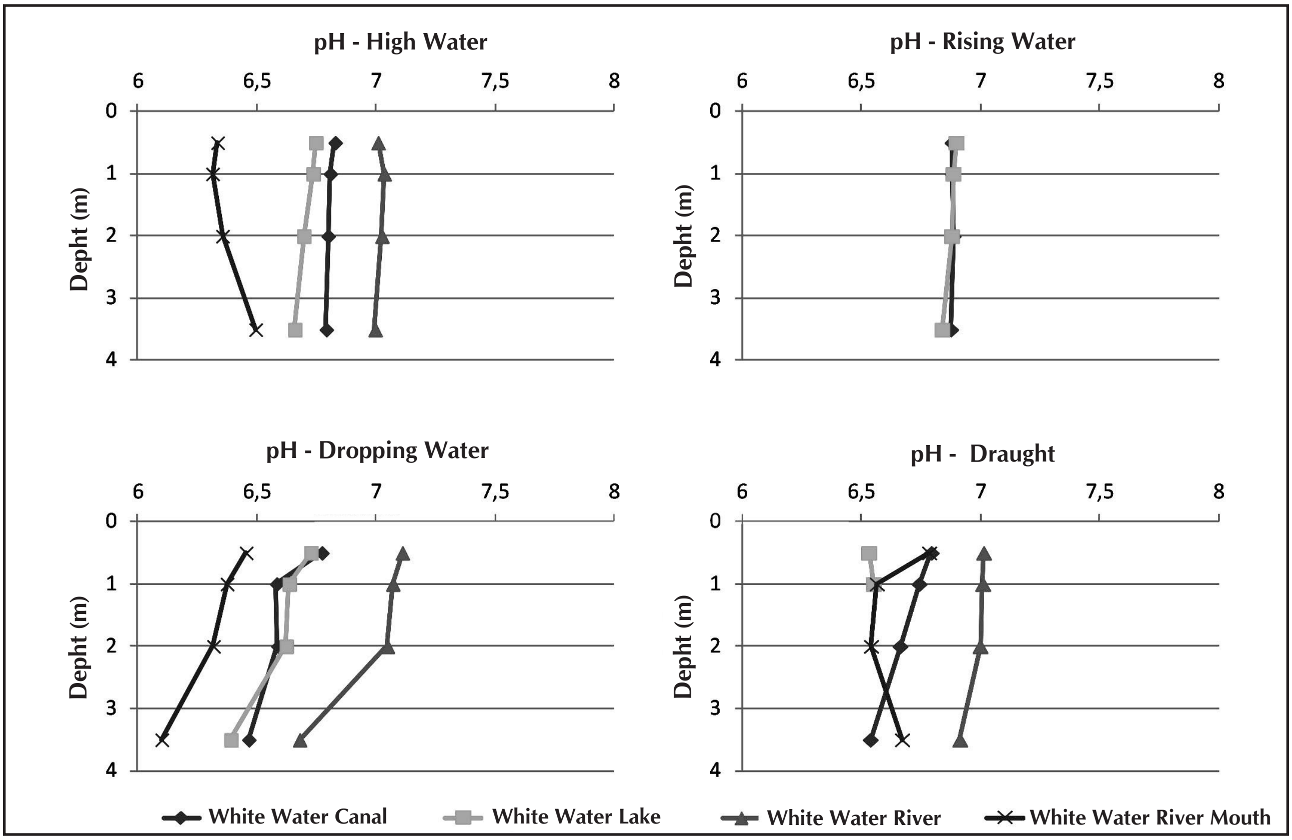

Figure 4 – pH measurements of water bodies during different periods of the hydrological cycle, by depth (m).

The concentrations of dissolved oxygen (DO) at different depths are shown in Figure 5. The lower concentrations occur during the drougth period in all types of water bodies monitored, with mean values of less than 0.5 mg.L^{-1}. At the same time, oxygen saturation is greater during this period than any other (41.5 to 28.8% at 0.5 m depth), probably due to the elevated water temperature (greater than 30°C) during this period of the hydrological cycle. A reduction of DO is observed with increased depth, which occurs principally to a depth of one meter below the surface.

In general, the availability of the oxygen dissolved in white water lakes and canals is low during all hydrological periods, due to its consumption in the decomposition of organic matter (FURCH et al., 1997), and due to the low primary productivity of waters that have a high quantity of dissolved solids, and low transparency, which reduces the width of the photic zone and the photosynthetic activity of phytoplankton, among other factors (HENDERSON, 1999). It is also relevant to consider the large variation which was observed in the measurements for oxygen concentration (high standard deviation and high variation) in the same collection location. This fact could be due to elements such as the presence and predominant type of aquatic vegetation (SANCHEZ-BOTERO et al., 2001), seasonal variation, and nictemeral variation (APRILE et al., 2009).

Cluster analysis

Figures 6 and 7 show the similarity dendrograms for the physical and chemical properties of the water bodies which were monitored, for draught and high water periods, using Euclidian distance. As the figures demonstrate, the water bodies studies are grouped differently in these two extremes of the hydrological cycle.

During the high water stage, Lake Tefé and the Solimões River diverge from the other water bodies to form distinct branches with a Euclidian distance (e.d.) of 0.4 and 0.64, respectively. For the same period, nine white water lakes and canals made a homogenous group with high similarity (e.d. = 0.14). Only Lake Araçazinho has greater similarity with relation to the other white water lakes and canals (e.d. = 0.38), forming an exclusive group, probably due to its closer proximity to the Japurá River, and capture of its flood waters during the high water period. The increase in the similarity of the water bodies due to flooding also was indicated in other studies, such as Thomaz et al. (2007), for locations in the interior of the Amazon River flood plain.

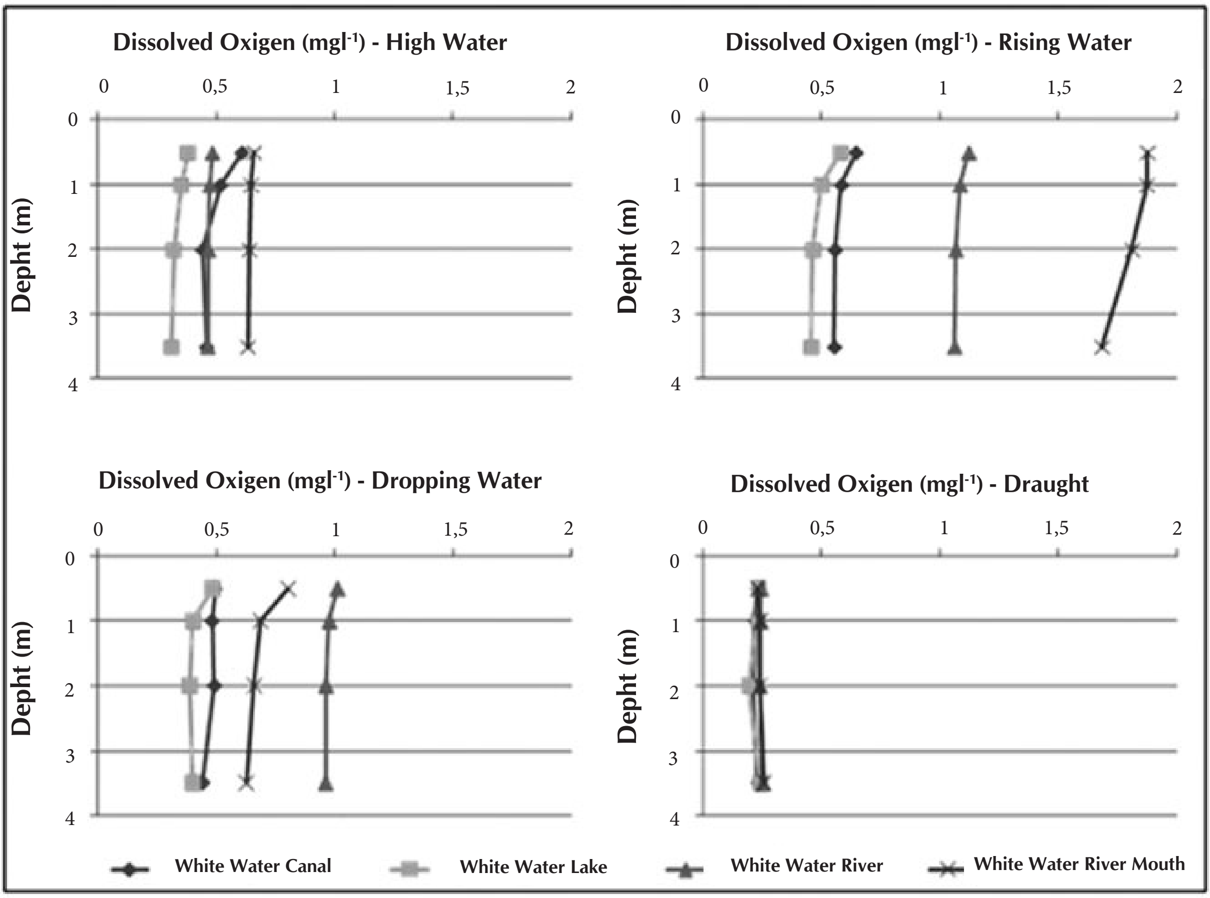

Figure 5 – Measurements of dissolved oxygen ($mg.L^{-1}$) for water bodies in different periods of the hydrological cycle, by depth (m).

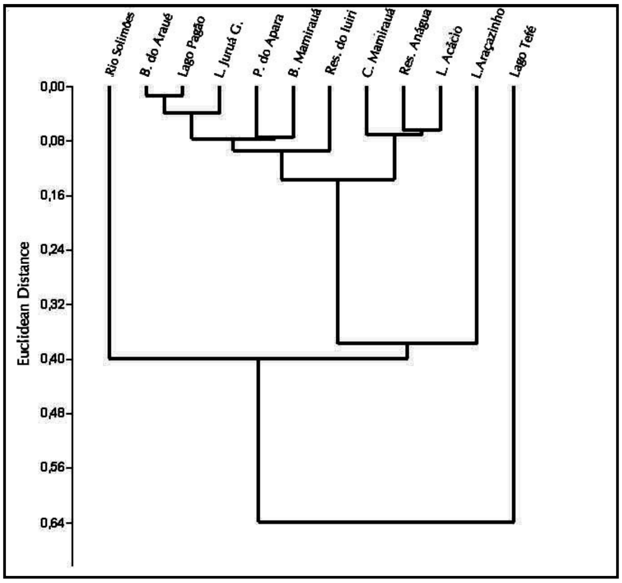

Figure 6 – Similarity dendrogram with grouping of the monitored collection stations, for the high water period.

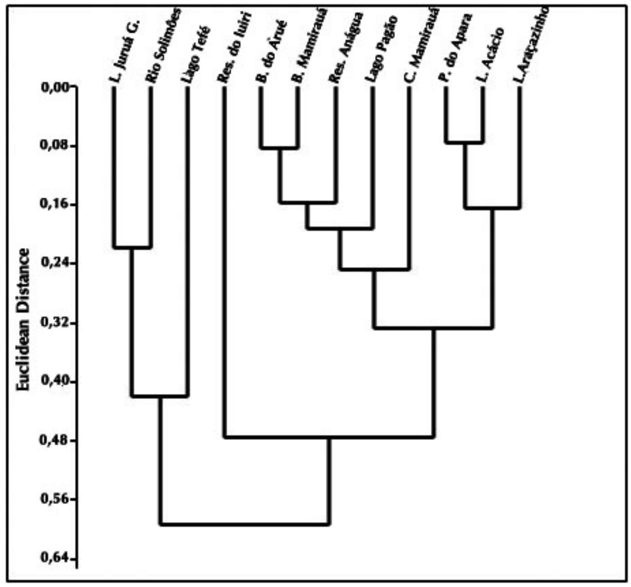

Figure 7 – Grouping dendrogram for collection stations in the drougth period.

During the drougth period, with reduced input of water from the tributaries and exchange of water among the water bodies, the similarity between them was lesser. The dendrogram in Figure 7 shows the formation of more divergent clusters (greater e.d.), as well as the fact that the Solimões River and Lake Tefé are still diverging from the water bodies in the MSDR. This divergence is even greater than 0.4 e.d. But there was an important differentiation for Lake Juruá Grande, the characteristics of which were similar to the conditions of the Solimões River (0.2 e.d.). Lakes and canals in the MSDR which were very similar during the high water phase (0.02 to 0.12 e.d.), were much less similar during the drougth stage (0.08 to 0.32 e.d.). During the drougth stage, the groups are not the same that formed during the high water period, probably due to their relative isolation and loss of connection between the water bodies.

Principal components analysis

Figure 8 shows the result of the analysis of the principal components (PCA).

The two principal components represent 67% of the variation from the original standardized data. The first principal component (PC1) determined 45% of the variation, and mainly separated the periods of seasonal extremes (drougth and high water). The variable with greater weight for PC1 in the correlation matrix were temperature, with a value of -0.814, electrical conductivity, with a value of -0.714, and transparency, with a value of 0.713.

The second principal component (PC2) determined 22% of the variation, and distinctly separated the four typologies of the water bodies. The main variables in the correlation matrix were pH, with 0.696, and transparency, with a value of -0.525. WWR showed elevated values for PC2 due to its low transparency and high conductivity on the other hand, due to the high transparency and the low conductivity, the black water river mouth category (BRM) presented lower values for PC2.

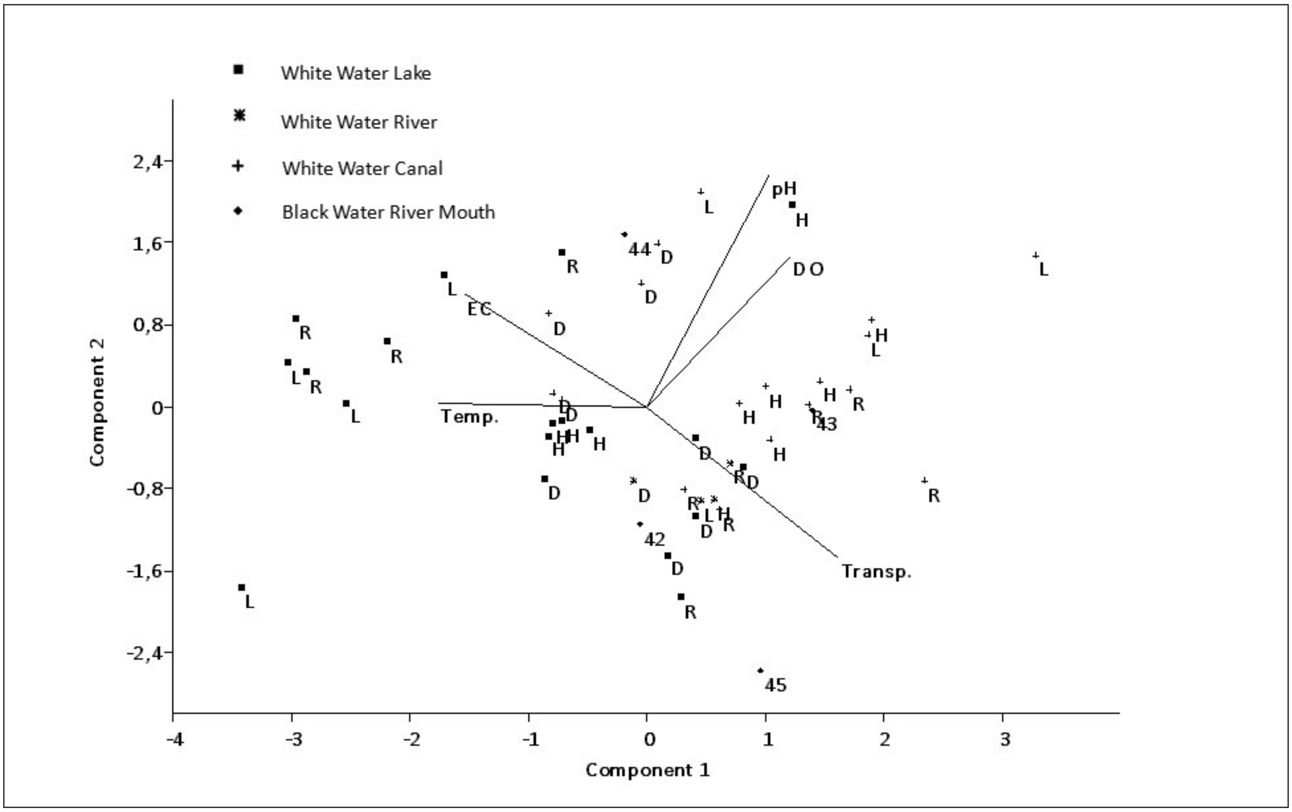

Figure 8 - Analysis of the principal components (APC) of the physical and chemical data for the different water bodies during the following periods:Rising Water (R), High Water (H), Dropping Water (D) and Draught (D).

CONCLUSIONS

The values presented in this study for the physical and chemical variables for bodies of water in the Middle Solimões region resemble the values registered for natural waters in other regions of Amazonia. It was shown that the bodies of water in this region present great similarity among themselves during the high water period, and groupings were obtained in both seasonal extremes. Lakes and canals formed a similar group during the high water period, indicating a high level of homogenization. Electrical conductivity and temperature stood out as important factors for differentiating between periods of the hydrological cycle, while pH and transparency stood out as factors differentiating black water and white water. However, the literature presents a relevant association between pH and electrical conductivity. The variation in water level during the hydrological cycle profoundly influenced the quality of water in the lakes and canals in the RDSM and in the Solimões and Tefé Rivers. The largest variations observed were between the draught and high water periods, with the increase in transparency and dissolved oxygen and reduced conductivity during the high water period.

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