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ORIGINAL ARTICLE

Water chemistry of rivers and streams from the Jaú and Uatumã basins in central Brazilian Amazon

Eduardo Antonio Ríos-Villamizar[1,2,3,6] · Aline Lopes[1] · Maria do Socorro Rocha da Silva[1] · Nilyan Adria Santarém dos Santos[1] · Regison Oliveira[1,2,3] · Robson M. Calazães[1] · Maria Teresa Fernandez Piedade[1] · Jochen Schöngart[1,3] · Bruce R. Forsberg[1,3] · Florian Wittmann[4] · Wolfgang J. Junk[1,3,5]

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Abstract
This work reports on the concentration of dissolved ions and identifies water chemistry patterns by the analysis of 79 water samples from rivers and streams in the Jaú and Uatumã basins, Negro and Solimões/Amazon rivers in the Brazilian Amazon central part. This dataset was analyzed by means of a principal component analysis (PCA) followed by a one-way analysis of similarities (ANOSIM) and a Neighbor Joining Cluster analysis of the samples, explaining 50.8% of the limnological data variation, which was strongly influenced by electrical conductivity, alkalinity, Fe_{total}, P_{total}, NH_4, $Fe_{dissolved}$, SiO_2 and pH. This analysis showed the formation of five groups such as: 1) Solimões-Amazon River; 2) Jaú basin streams; 3) Padre stream; 4) Jaú and Carabinani rivers (Jaú basin); and 5) Uatumã basin streams, Uatumã and Abacate rivers, and Negro River. These waters showed typical Amazonian characteristics, with the exception of the Jaú River and the Padre stream. The hydrochemical parameters of the former did not correspond to the typical values of Amazonian blackwater rivers. The mean concentrations of color, COD, chloride, NH_4 and dissolved iron of the latter are unusually high if compared with other rivers and streams on the Uatumã basin. However, the K and silica concentrations were exceptionally lower than those of other Uatumã basin streams. The evaluated samples from the Jaú and Uatumã basins could fit within the current classification as Intermediate Type A. Furthermore, the Jaú River, during low water period, could fit within the Intermediate Type B category according to its geochemical features. This chemical characterization is extremely important when it comes to water Brazilian legislation and its adjustments for inclusion of the Amazon region waters. Hence, this paper may contribute to understanding such water chemical patterns, and to water resources management and conservation of these Amazon aquatic ecosystems.

Keywords Amazonian region · Hydrogeochemistry · Limnology · Solimões/Amazonas River basin · Negro River basin

✉ Eduardo Antonio Ríos-Villamizar
eduardorios17@hotmail.com

1 Instituto Nacional de Pesquisas da Amazônia (MAUA/RHANIA, CPCRH - CODAM/INPA), Av. André Araújo 2936, Petrópolis, Caixa Postal 478, Manaus, Amazonas CEP: 69067-375, Brazil

2 National Institute of Amazonian Research – INPA/MCTIC, Programa de Grande Escala da Biosfera– Atmosfera na Amazônia – LBA, Coordenação de Pesquisas Hidrológicas – CPH, Grupo de Hidrobiogeoquímica, Av. André Araújo, 2936 - Petrópolis - Campus II, Manaus, Amazonas CEP 69067-375, Brazil

3 ational Institute of Amazonian Research – INPA/MCTIC, Programa de Pós-Graduação em Clima e Ambiente - PPG-CLIAMB, Av. André Araújo, 2936 - Petrópolis - Campus I, Manaus, Amazonas CEP 69067-375, Brazil

4 Department of Floodplain Ecology, Institute of Geography and Geoecology, Karlsruhe Institute for Technology, Karlsruhe, Germany

5 Instituto Nacional de Ciência E Tecnologia Em Áreas Úmidas (INCT-INAU-UFMT), Cuiabá, Mato Grosso, Brazil

6 Universidade do Estado do Amazonas – CESTB/UEA, Av. da Amizade 74 - Centro, Tabatinga, Amazonas CEP 69640-000, Brazil

Introduction

The Amazon, the world's largest river in terms of watershed, discharge and number of tributaries, receives the name of Solimões, from the Peruvian border to the mouth of the Rio Negro, and from there to the Atlantic Ocean it is called the Amazon. Among the hundreds of tributaries of the Amazon, Rio Negro is considered the most important, because of its discharge (Küchler et al. 2000). Water chemistry provides important parameters for quantifying biogeochemical cycles and determines management options in river systems and wetlands. The first scientific classification of Amazonian rivers was elaborated by Sioli (1956) who used water color, transparency, pH and electrical conductivity to explain limnological characteristics of the large Amazonian rivers and correlated these characteristics to the geological properties of the river catchments, a landscape ecology approach. Whitewater rivers, such as the Solimões/Amazon River main course (Fig. 1), are turbid with water transparency that varies between 20 and 60 cm, and have their origins in the Andes, from which they transport large amounts of nutrient-rich sediments. Their waters have near-neutral pH and relatively high concentrations of dissolved solids indicated by the electric conductivity that varies between 30 and 140 µS cm^{-1}. Blackwater rivers, such as the Negro River, drain the Precambrian Guiana shield, which is characterized by large areas of white sands (podzols). Their water transparency is about 60–120 cm, with low quantities of suspended matter but with high amounts of humic and fulvic acids that give the water a brownish-reddish color. The pH values of such rivers are in the range of 4–5 and their electrical conductivity is low (< 20 µS cm^{-1}) (Ríos-Villamizar et al. 2013, 2014, 2020a, b, c).

Following the previously published literature, a review of the physicochemical and chemical conditions of the major Amazonian rivers and streams was recently published by Ríos-Villamizar et al. (2013, 2020a; b, c). According to this research, most chemical studies on Amazonian rivers were restricted to the main stems of some high order (9–11th) rivers (e.g., the Solimões/Amazon, Negro, and Madeira). Studies on low order blackwater rivers and their drainage basins such as the Jaú (Belger and Forsberg 2006; Bisinoti et al. 2007; Schneider et al. 2009) and Uatumã (Walker et al.

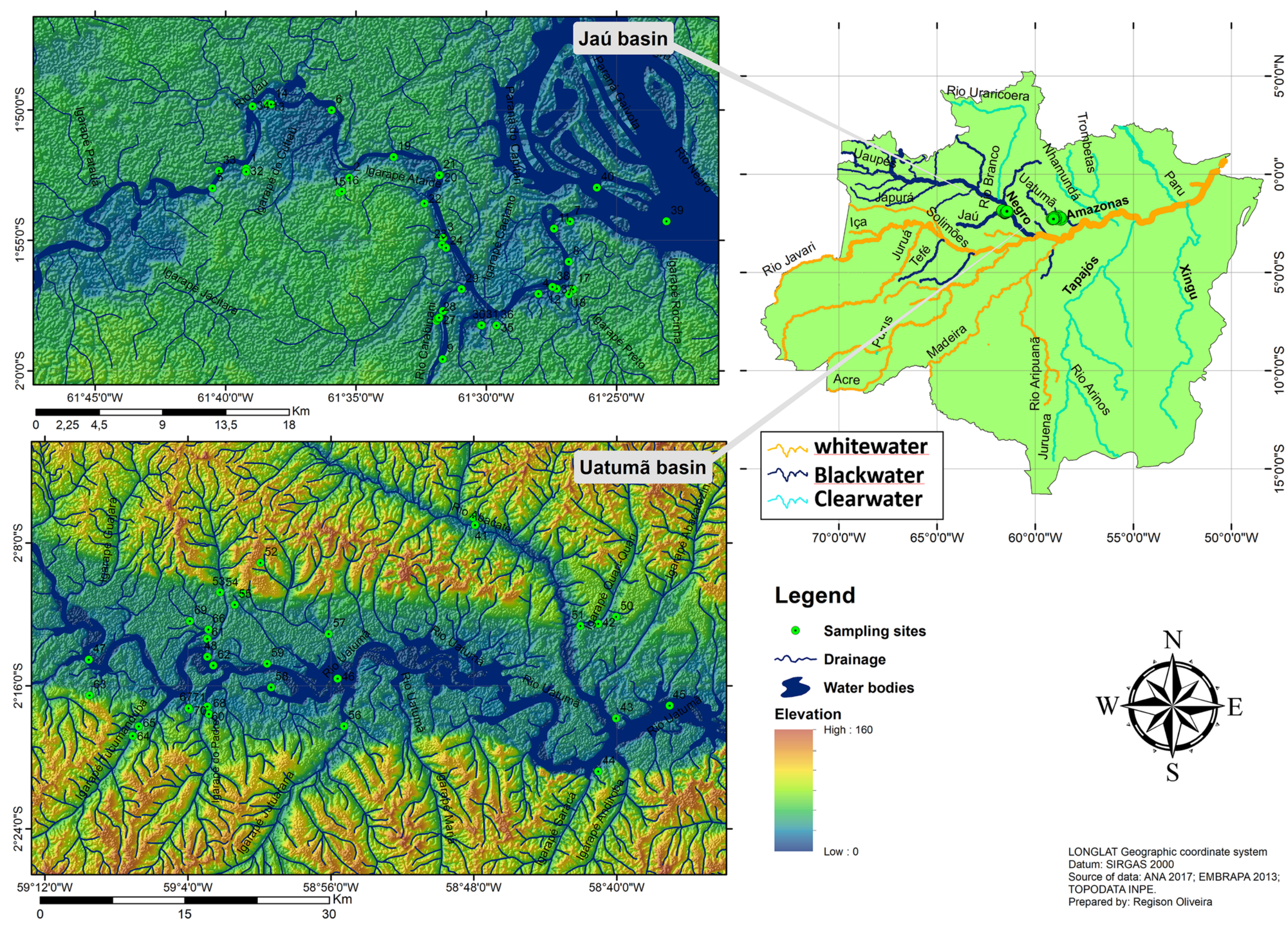

Fig. 1 Study area map showing the elevation background

1999; Dosseto et al. 2006; Kemenes et al. 2007; Horbe and Oliveira, 2008; Kehrig et al. 2009; Silva et al. 2013) have been rare and generally limited to a small number of chemical compounds (Küchler et al. 2000). In this context, this study presents a unique record of water quality indicator parameters in 2 environmental protection areas, which is very scarce for the Amazon's rivers and streams, and aims to contribute to the chemical characterization and diagnose water chemistry patterns of the major elements concentrations, pointing at the water samples classification of rivers and streams from the Jaú and Uatumã basins.

Materials and methods

Study area characterization

Jaú river

The Jaú River is a slow meandering river which drains 10,000 km^2 of largely undisturbed lowland tropical forest and merges with the Negro main channel about 300 km above its mouth (Figs. 1 and 2). The intermediate sized tributaries (4–7th order) of the Jaú are flooded on an annual cycle due to backwater effects from the main channel flood pulse. The frequency of flooding of the smaller tributaries (1–3rd order) tends to be much higher and unpredictable, depending more on local storm events than on main channel hydrology (Forsberg et al. 2001; Junk et al. 2011, 2014, 2015). The Jaú drains highly weathered, predominantly tertiary soils, of fluvio-lacustrine origin and is consequently very low in dissolved conductivity (10–30 μS cm^{-1}) and nutrients. The relatively high concentrations of dissolved organic carbon (10–20 mg L^{-1}) in the system are derived from extensive areas of hydromorphic soils (both oxisols and podsols) and seasonally inundated swamps found in the interfluvial headwater regions of the basin (Forsberg et al. 2001).

Uatumã River

Immediately downstream from the Balbina dam, the Uatumã River passes through a narrow valley in the Precambrian

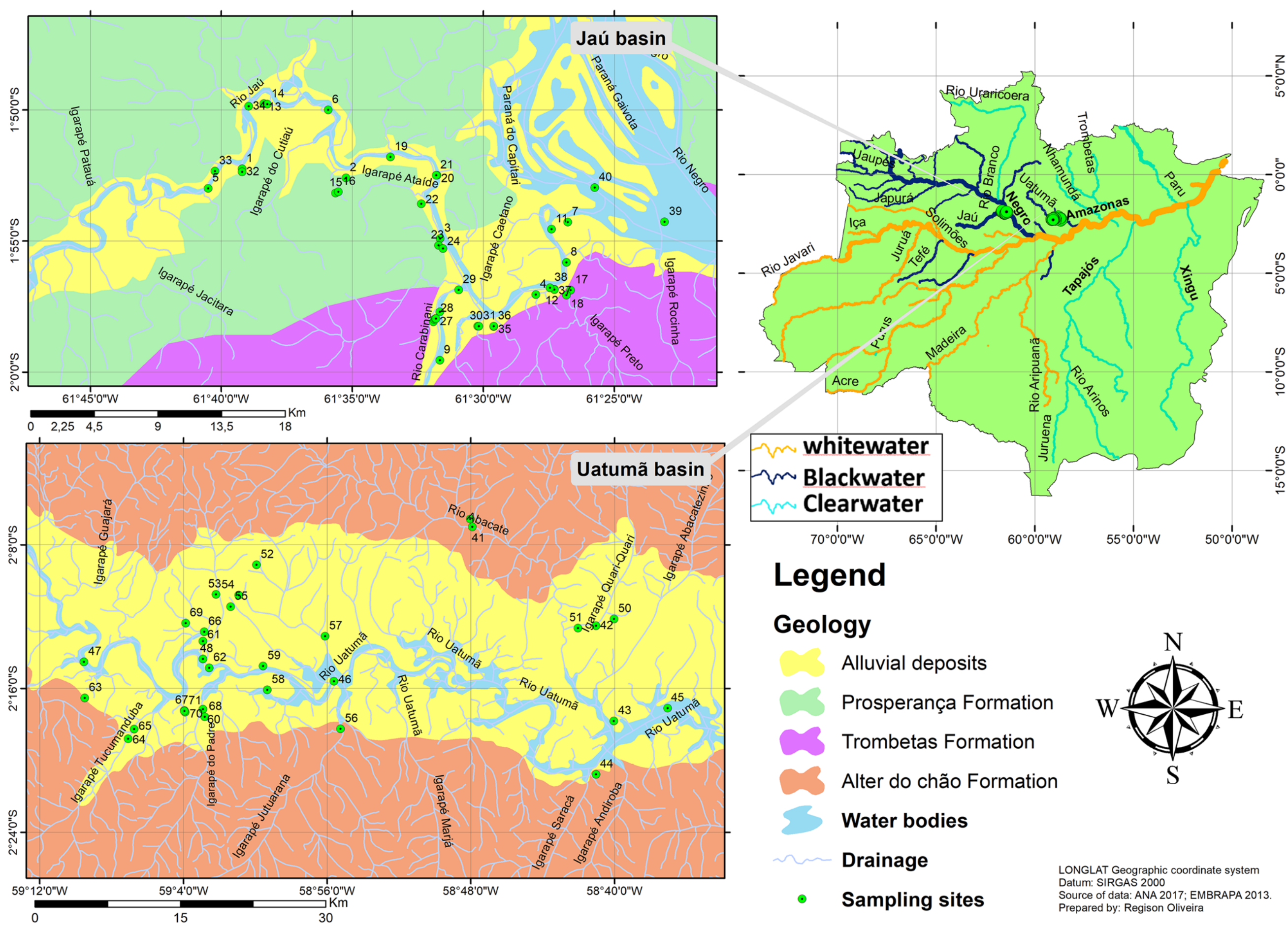

Fig. 2 Study area map showing the geology background

Guyana Shield (Figs. 1, 2). The lower stretch of the river flows through the central Amazon sedimentary basin, characterized by flat topography with extensive alluvial floodplains, where tertiary fluvial sediments, argilites and arenites predominate (Walker et al. 1999; Kasper et al. 2014). The floodplain of the Uatumã is much broader in this reach (1 – 6 km) and is inundated by a strong seasonal flood pulse (depth: 1 – 9 m), with high water levels occurring from April to June. The flood dynamic in this region is a backwater effect linked to the annual flood pulse of the Amazon River main channel (Kasper et al. 2014). The rocks types in this region are usually poor in cations, and weathering of the sedimentary rocks gives rise to clay and sandy soils. Podzolization processes, moreover, result in acid blackwaters which are rich in dissolved humic substances. Parts of the north-eastern Uatumã River basin, however, drain areas on marine, sedimentary rocks which are rich in cations and anions (Walker et al. 1999; Dosseto et al. 2006). The area consists of different forested ecosystems (Targhetta et al. 2015).

Field sampling and data analysis

We collected 31 water samples in the Uatumã (26–29 August 2015) and 40 water samples in the Jaú (29 October to 4 November 2015) basins. In order to enable comparisons with the major Amazonian water typologies, this dataset was complemented with literature results from Negro (3 samples) and Solimões/Amazon (5 samples) rivers, totalizing 79 samples (Figs. 1–2 and Supplementary Material, Appendix S1). Water pH and temperature (°C), electrical conductivity (μS cm^{-1}) and dissolved oxygen (mg O_2 L^{-1}) were measured in the field (on site) with standard portable devices (WTW, models 315i, Germany). The measuring range, resolution and accuracy for each parameter are presented in the Supplementary Material, Appendix S2. The Secchi depth water transparency (m) was also measured in the field.

Water samples were collected in the middle of the river and stream channels using 1 L acid-washed polyethylene bottles, which were rinsed with the water being collected and the samples were manually collected beneath the surface and kept cool (ice box) until the time of the analysis. Water samples were vacuum-filtered through Whatman GF/F glass-fiber filters (0.45 μm) within the next three days after the collection. The chemical analyses were performed in the laboratory of environmental chemistry of INPA.

The watercolor was determined in filtered samples by spectrophotometry (450 nm) using a Femto 700 Plus equipment and a standard solution of platinum-cobalt. The turbidity was determined by turbidimetry using an Alfakit turbidimeter (Supplementary Material, Appendix S2) and the values were expressed in Nephelometric Turbidity Units (NTU). The total suspended solids (TSS) were determined by gravimetry method using the dry weight of the material, retained in a 0.45 μm glass fiber filter, from a known volume of sample.

Dissolved silica (SiO_2) was determined by molybdosilicate method. NO_3^-, NO_2^-, PO_4^{3-}, Cl^-, NH_4^+, dissolved and total iron (Fe^{+2} and Fe^{+3}) were determined by spectrophotometry using the Flow Injection Analysis (FIA) techniques and a Shimadzu UV-1800 device. Chemical oxygen demand (COD) was determined by titrimetry using potassium permanganate as an oxidizing agent. Ca^{2+}, Mg^{2+}, Na^+ and K^+ by atomic absorption – Perkin Elmer model 1100B. The alkalinity (HCO_3^-) was determined by neutralization reaction for samples with pH > 4.3 with 0.02 N sulfuric acid solution (H_2SO_4) by titration using a digital potentiometer. The dissolved iron (Fe^{+2}) was determined by phenantrolin method in which the ferrous ions react with the phenanthroline resulting in the formation of a brown complex with optical absorption in 512 nm. The limits of detection (LOD) expressed in μg L^{-1} for the different parameters are as follow: NO_3^- (10), NO_2^- (5), PO_4^{3-} (10), Cl^- (100), alkalinity (10), NH_4^+ (100), Fe^{+2} (5), Fe^{+3} (5), Ca^{2+} (20), Mg^{2+} (20), Na^+ (100), K^+ (5), SiO_2 (100), COD (1000), and TSS (100). All the analyses were carried out by standard methods (APHA 2005, 2012).

Data normality was tested using the Shapiro Wilk test. As the data did not present a normal distribution, Spearman's Correlation test was used to exclude the highly correlated variables ($r > 0.70$), reducing from 21 to 16 variables (Supplementary Material, Appendix S3). After the PCA analysis, Bartlett's sphericity test (Bartlett 1951) was used to tests the null hypothesis that the points are sampled from a spherical distribution. If so, PCA will not be able to provide a useful reduction of dimensionality. The p value from this test should ideally be less than 0.05. The PCA was based on a correlation matrix because the data does not have the same unit of measure. The dissimilarities were calculated based in the Euclidean distance. The one-way ANOSIM was performed to test the groups formed by PCA ordination, which can be associated to different water types (Ríos-Villamizar et al. 2020a; Ferreira et al. 2021). Additionally, Neighbor joining Cluster analysis of the samples was used to confirm the formation of the groups defined by PCA (Supplementary Material, Appendix S3). Neighbor joining clustering (Saitou and Nei 1987) is an alternative method for hierarchical cluster analysis. In contrast with UPGMA, two branches from the same internal node do not need to have equal branch lengths. A phylogram (unrooted dendrogram with proportional branch lengths) is given. These analyses were conducted using the PAST 4.05 program (Hammer et al. 2001; free software).

Results

Water chemistry

For the Jaú basin rivers were obtained the following mean values of the parameters such as electrical conductivity

(33.67 ± 15.96 μS cm^{-1}), color (83.78 ± 11.59 mg Pt L^{-1}), COD (35.6 ± 5.11 mg L^{-1}), chloride (3.65 ± 1.552 mg L^{-1}), NH_4 (0.184 ± 0.046 mg L^{-1}) and dissolved iron (0.159 ± 0.009 mg L^{-1}). For the Jaú basin streams: 11.22 ± 3.549 μS cm^{-1}, 81.59 ± 39.16 mg Pt L^{-1}, 37.6 ± 12.8 mg L^{-1}, 1.012 ± 0.488 mg L^{-1}, 0.243 ± 0.332 mg L^{-1} and 0.162 ± 0.020 mg L^{-1}, respectively; for the Negro River: 8.801 ± 3.009 μS cm^{-1}, 201.6 ± 84.81 mg Pt L^{-1}, 49.4 ± 2.27 mg L^{-1}, 1.175 ± 0.676 mg L^{-1}, 0.239 ± 0.123 mg L^{-1} and 0.213 ± 0.059 mg L^{-1}; for the Uatumã basin rivers: 10.29 ± 5.02 μS cm^{-1}, 45.65 ± 37.09 mg Pt L^{-1}, 27.3 ± 15 mg L^{-1}, 1.476 ± 1.785 mg L^{-1}, 0.188 ± 0.104 mg L^{-1} and 0.113 ± 0.038 mg L^{-1}; for the Uatumã basin streams: 9.668 ± 4.664 μS cm^{-1}, 36.21 ± 59.15 mg Pt L^{-1}, 32.9 ± 21.1 mg L^{-1}, 0.962 ± 0.636 mg L^{-1}, 0.159 ± 0.189 mg L^{-1} and 0.163 ± 0.053 mg L^{-1}; for do Padre stream, in the Uatumã basin: 61.98 ± 2.103 μS cm^{-1}, 934.5 ± 8.145 mg Pt L^{-1}, 233 ± 74.6 mg L^{-1}, 5.363 ± 0.228 mg L^{-1}, 3.49 ± 0.149 mg L^{-1} and 0.64 ± 0.042 mg L^{-1}; and finally, for the Solimões/Amazon River: 65.21 ± 8.535 μS cm^{-1}, 48.94 ± 9.115 mg Pt L^{-1}, 20.2 ± 5.03 mg L^{-1}, 3.037 ± 0.353 mg L^{-1}, 0.111 ± 0.089 mg L^{-1} and 0.088 ± 0.012 mg L^{-1}, respectively. The mean, maximum and minimum values of the remaining parameters as well as the individuals results for each sample are shown in the Supplementary Material, Appendix S1.

In addition, the mean percentage of ionic imbalances was 67.4 ± 15.6% and the range 19.7–93.04%. In the analyzed water samples there was a predominance of anions over cations (%Total Anions = 83.7 ± 7.8 ranging 59.9–96.5%). This lack of ion balance could be associated with acidic and low ionic concentrations waters, but also waters which were alkaline and contained soluble silica generally showed an excess of negative charges (anionic dominance) (Johnson et al. 1979; Stallard and Edmond 1983; Horbe et al. 2005).

Grouping of samples

The Bartlett test of sphericity indicates that with a given significance level < 0.0001, the assumption of sphericity is tenable. Hence, it makes sense to apply the PCA. The first two principal components from PCA ordination explained 50.8% of the variation of limnological data. The variables that most contributed to formation of the first principal component were electrical conductivity, alkalinity, Fe_{total} and P_{total}. The formation of the second principal component was strongly influenced by NH_4 and $Fe_{dissolved}$, negatively, and SiO_2 and pH positively (Table 1). The PCA ordination showed the formation of five groups of samples such as: (1) Solimões-Amazonas River; (2) Jaú basin streams; (3) Padre stream; (4) Jaú and Carabinani rivers (Jaú basin); and (5) Uatumã basin streams, Uatumã and Abacate rivers, and Negro River (Fig. 3). The ANOSIM ($r = 0.61$, $p < 0.0001$) and Neighbor joining Cluster analyses of the samples confirmed the formation of these groups (Fig. 4 and Supplementary Material, Appendix S3).

Discussion

Hydrogeochemical patterns

Regional geochemical characteristics can explain the spatial variability of dissolved chemical species (Stallard and Edmond 1983). The mean conductivity on Jaú basin rivers (33.67 μS cm^{-1}) (Fig. 5a) does not correspond to the typical values observed in blackwater rivers such as the Rio Negro (8.8 μS cm^{-1}), and also the alkalinity (9.03 mg L^{-1}) is aproximately five times higher than the Rio Negro (1.8 mg L^{-1}), corresponding with a diference of about 1.31 pH units (Supplementary Material, Appendix S1). The mean sodium and silica concentrations on Jaú basin rivers were almost 4.7 and 3.06 times higher than the Rio Negro. The waterfall and rocky rapids that occur relatively close to the surficial contacts between sedimentary deposits are commonly encountered in the Jaú River (Forsberg et al. 2000). In the paper about classification of the major habitats of Amazonian black water river floodplains, Junk et al. (2015) postulate that some of the right-bank tributaries of the Negro River,

Table 1 Correlation coefficients among the limnological variables with the two first principal components of the PCA. *Percentage explained for each axis

	Axis 1	Axis 2
Parameters	28.245*	22.557*
Electrical conductivity	0.853	– 0.053
Alkalinity	0.842	0.288
Fe_{total}	0.753	– 0.037
P_{total}	0.666	– 0.196
Na	0.624	0.541
N_{total}	0.620	– 0.396
Turbidity	0.617	0.375
PO_4^3	0.541	– 0.298
NO_3	0.505	– 0.115
NH_4	0.398	– 0.825
pH	0.330	0.703
$Fe_{dissolved}$	0.229	– 0.818
K	0.178	0.300
Oxygen saturation	0.081	0.538
Temperature	0.045	0.404
SiO_2	0.041	0.632

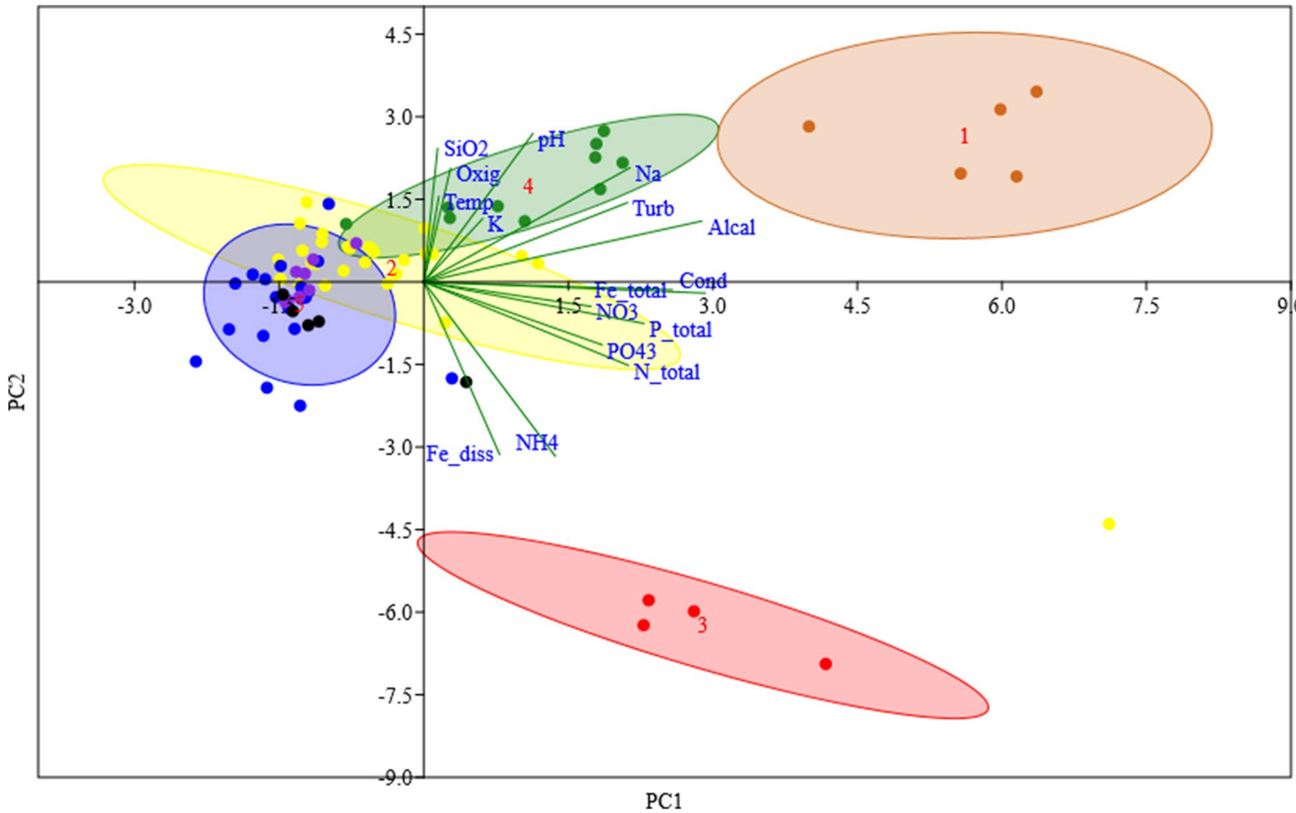

Fig. 3 Principal Components Analysis (PCA) synthesizing the data of the limnological variables sampled at the Jaú and Uatumã basins. (1) Brown color – Solimões/Amazonas River; (2) Yellow color – Jaú basin streams; (3) Red color – Padre stream (Uatumã basin); (4) Green color – Jaú and Carabinani rivers (Jaú basin); (5) Blue color – Uatumã basin streams, Purple color – Uatumã and Abacate rivers (Uatumã basin), and Black color – Negro River. The Negro and Solimões/Amazonas rivers data are from Sioli and Klinge (1961, 1962), Oltman (1968), Gibbs (1972), Leenheer and Santos (1980), Stallard and Edmond (1983), Junk and Howard-Williams (1984), Santos and Ribeiro (1988), Furch and Junk (1997), Gaillardet et al. (1997), Küchler et al. (2000), Aucour et al. (2003), Seyler and Boaventura (2003), Dosseto et al. (2006), Richey et al. (2008), Sousa (2008), Silva et al. (2013), and Ríos-Villamizar (unpublished data)

such as the Cuyuni and Unini rivers, drain recent várzea and paleo-várzea of the Japurá River, a left-bank tributary of the Solimões/Amazon River. The hydrochemical data of the Jaú River, during low water period, are similar to those of the Cuyuni and Unini rivers, suggesting also erosion of paleo-várzea sediments (Supplementary Material, Appendix S1).

The mean values of electrical conductivity and pH of the Jaú River were 42.4 ± 8.6 µS cm^{-1} and 5.8 ± 0.44, respectively. The literature values were 3.5 times lower for conductivity (12.03 ± 0.21 µS cm^{-1}) and presented more acidic pH (4.8 ± 0.39). This relatively high values of conductivity are probably related to the extremely low water period the Jaú basin was getting through at the time of samples collection, as well as the influence of recent várzea and paleo-várzea sediments erosion of the Japurá River, as it was described above. On the other hand, the mean values of electrical conductivity and pH of the Uatumã River (7.83 ± 0.25 µS cm^{-1} and 5.34 ± 0.93, respectively) were more similar to the literature data for conductivity (13.3 ± 4.75 µS cm^{-1}) and pH (5.8 ± 0.67) values.

According to the silica values, the Jaú River basin water bodies, which drain the Prosperança and Trombetas Formations sediments, are clearly separated from their Uatumã River basin counterparts, which drain the Alter do Chão Formation sediments (Figs. 2 and 6). In the Jaú River basin was observed an average SiO_2 value of 6.68 ± 1.49 mg L^{-1}. Nearly similar values were observed at the Coari basin by Horbe and Santos (2009). On the other hand, the Uatumã River basin showed an average SiO_2 of 2.38 ± 0.57 mg L^{-1}. Ferreira et al. (2021) found analogous mean values of SiO_2 concentrations (2.4 ± 0.5 mg L^{-1}) in preserved streams of protected areas in the Adolpho Ducke Forest Reserve, which are part of the Tarumã-Açu basin, on the outskirts of Manaus, Amazon Basin, Brazil. Horbe et al. (2005) also reported similar SiO_2 concentrations in other central Amazonian streams. The relatively low values of this anion, which is considered a geogenic component (Ferreira et al. 2021), on Uatumã River basin are probably indicating the influence of silicate weathering and more dilution of its waters due to the geological features in this area (Horbe and Oliveira 2008).

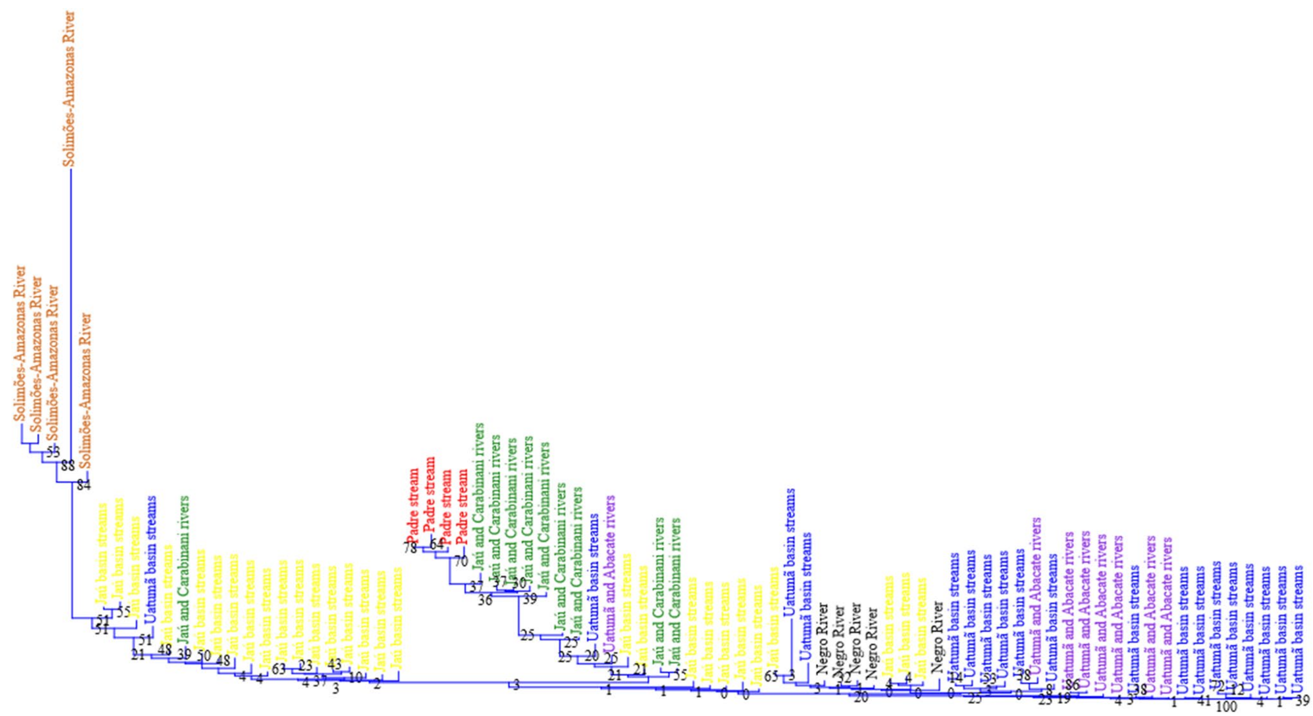

Fig. 4 Neighbor joining cluster analysis of the water samples from the Jaú and Uatumã basins

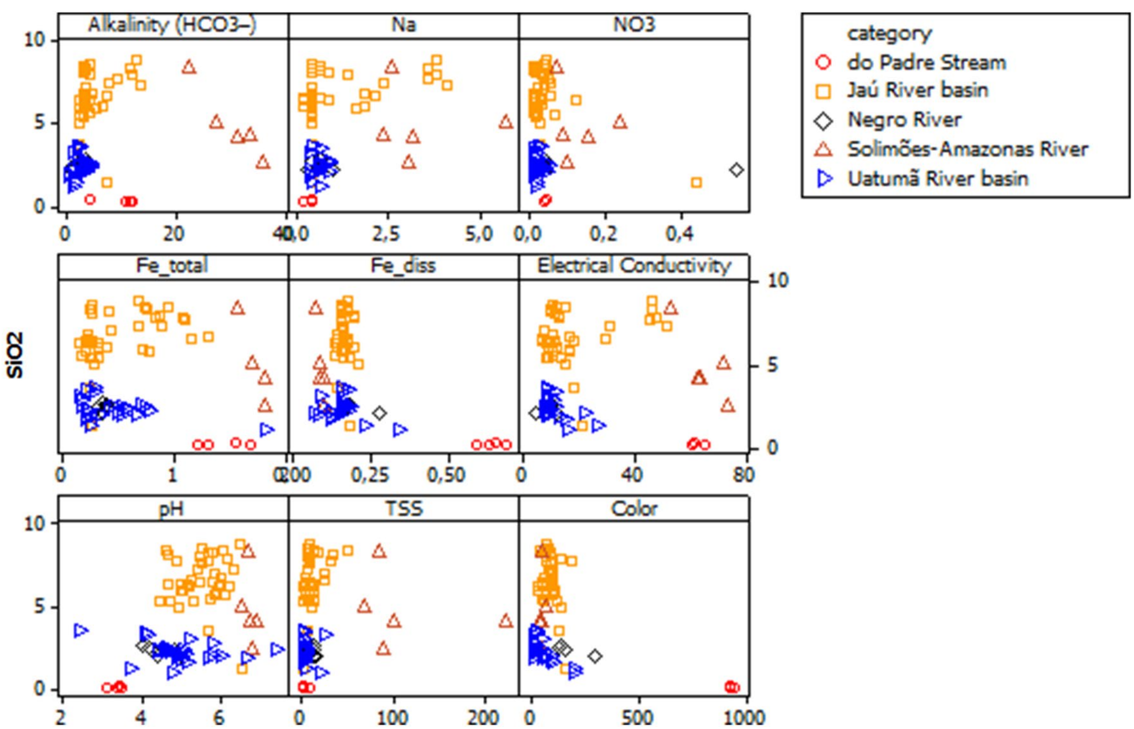

Fig. 5 Relations of silica and other hydrochemical parameters from the Jaú and Uatumã basins. EC = electrical conductivity (μS cm^{-1}), the other parameters are expressed in mg $L.^{-1}$

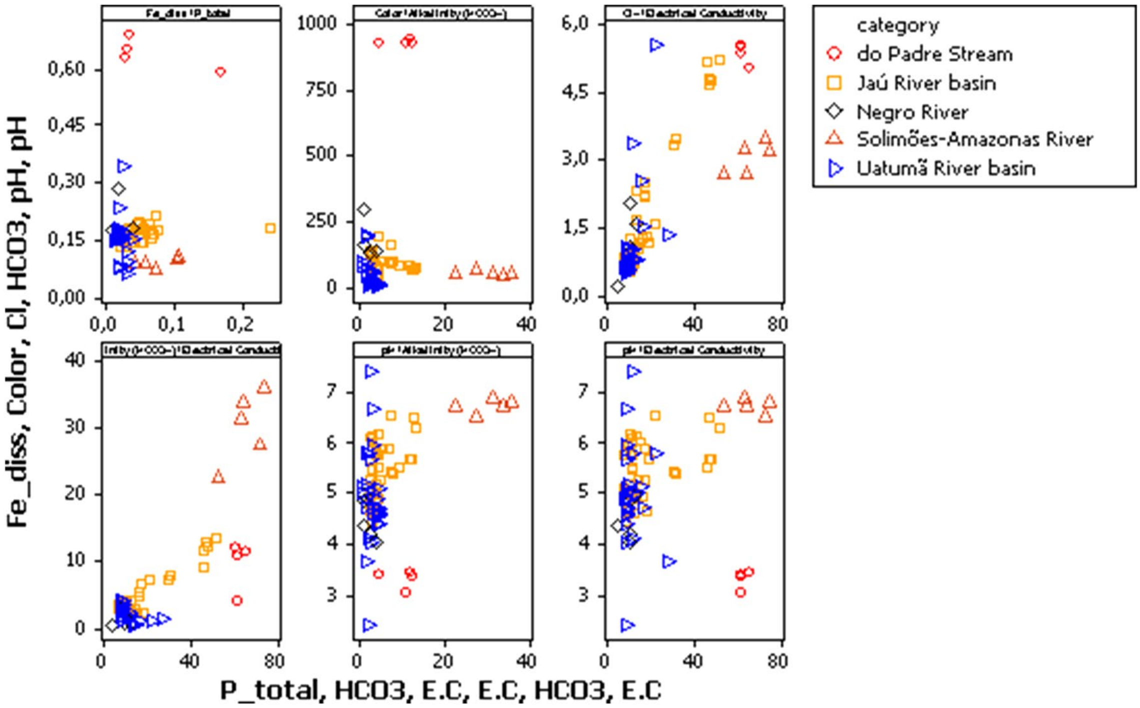

Fig. 6 Relations between different hydrochemical parameters from the Jaú and Uatumã basins. EC = electrical conductivity (µS cm^{-1}), the other parameters are expressed in mg L^{-1}

It seems that there is a trend from the low concentration blackwaters of Uatumã River basin and Negro River to the whitewater of the Solimões/Amazon River that is in agreement with the observations of Horbe and Santos (2009). A classification system of Amazonian lowland wetlands uses hydrochemical parameters for the differentiation between nutrient-rich whitewater and nutrient-poor blackwater rivers floodplains (Junk et al. 2011, 2015). These water types represent the upper and the lower end of the fertility gradient (Ríos-Villamizar et al. 2020a).

Uatumã River basin and Negro River showed similarities of their water chemistry which was indicated by an overlapping between their water chemical parameters, establishing a single group, which could be attributed to the geological and soil features in these areas. The Negro River is considered the classical prototype for blackwater rivers which come from highly leached and weathered tropical environments where most of the soluble elements are quickly removed by high rainfall regimes (Horbe and Santos 2009; Ríos-Villamizar et al. 2020b). In these areas, the predominance of quartz and kaolinite as well as the forest organic matter contribute in a podzolization process producing waters with relatively high SiO_2 contents and low pH (Horbe and Santos 2009). The solute-deficient waters of the Negro River and other blackwater rivers are characterized by a high Si-to-cation ratio which is indicative of the podzols in the Central Amazon, and a greater proportion of K and Na to those of the alkaline-earth metals Ca and Mg, suggesting an alkali dominance (Stallard and Edmond 1983; Konhauser et al. 1994; Furch and Junk 1997; Ríos-Villamizar et al. 2020b). Similar chemically dilute waters were observed on Uatumã River basin in this study.

The most remarkable water quality pattern was shown by the Padre stream (Fig. 5b) on the Uatumã basin, which showed mean values of electrical conductivity (61.98 µS cm^{-1}) analogous to the Solimões/Amazonas River values, but pH values (pH = 3.35) considerably lower than the Solimões/Amazonas River values (electrical conductivity = 65.21 µS cm^{-1}; pH = 6.73) and also lower than the Negro River value (pH = 4.49). For this stream, the mean values of color, COD, chloride, NH_4, and dissolved iron are unusually high if compared with other rivers and streams on the Uatumã basin, the Negro River, and the Solimões/Amazonas River. However, the K and silica concentrations were exceptionally lower (between 8 and 10 times) than other streams on the Uatumã basin, and 17.4 (for K) and 20.1 (for silica) times lower than the Solimões/Amazonas River (Supplementary Material, Appendix S1).

Chloride is commonly attributed to dissolved marine aerosols in the rainwater and evaporative rocks (Gaillardet et al. 1997). This similar behavior between K and silica was previously reported by Stallard and Edmond (1983). This high values of color, COD, NH_4 and dissolved iron are probably an indication of denitrification activity that occurs in an acidic, anaerobic and reductive environment (Luvizotto et al. 2019; Bhattarai et al. 2021).

The Padre stream is significantly different from the natural characteristics of the environment in which it belongs. This is a slightly differentiated or intermediate pattern, where the water body presents mixed characteristics of white water (electrical conductivity) and black water (pH). The low pH and the relatively high electrical conductivity values probably are related to the lack of buffer compounds (Figs. 6, 7) and also to the geology and soil type in the area. Forsberg et al. (2001) already found some streams on the Jaú basin, which showed similar physicochemical characteristics.

Implications for water classification and management

When it comes to classification, water parameters of the Brazilian legislation do not encompass the natural waters of the Amazon. Parameters such as ammonium ion (NH_4^+), watercolor, pH value and/or dissolved oxygen (DO) concentration naturally occur in different patterns in Amazonian waters.

The NH_4^+ did not exceed 3.584 mg L^{-1} in the Padre stream in this study. The NH_4^+ values are strongly related to the water pH and, according to CONAMA Resolution No. 357/2005 (Brasil 2005), which establishes the values for fresh waters in aquatic environments, for pH < 7, concentrations of this ion of 3.7 mg L^{-1} are allowed (class I and II) and 13.3 mg L^{-1} (class III), which do not fit for the Amazon region. The way of relating the ammonium ion to the pH for rivers of acidic waters, where the pH ranges from 3.0 to 5.5, is neither adequate nor justified for the Amazonian river waters with pH values less than 6. For example, regarding the NH_4^+ data, high concentrations would render the environment unsuitable for aquatic biota adapted to low concentrations of this ion in natural waters, and would allow strong contamination by substances containing this ion without violation of the legislation.

In many stretches of the Amazon River basin, the DO concentrations can be very low, reaching < 0.01 mg L^{-1} in the Padre stream in this study (29 August 2015). This low DO levels are considered natural and the organisms of these aquatic ecosystems are adapted to this condition (Goulding 1980).

The presence of large amounts of organic matter in the aquatic environment may contribute to decrease the DO concentrations due to the natural organic matter oxidation process, which implies a very strong oxygen consumption dynamic (Kristensen et al. 2008; Silva et al. 2019). Relatively low DO concentrations, in natural environments of the Amazonian region, were also found by Silva et al. (2019) on the Caru (1.47 mg L^{-1}), Solimões (1.41 mg L^{-1}), Ariau (1.21 mg L^{-1}) and Jutai (1.16 mg L^{-1}) rivers.

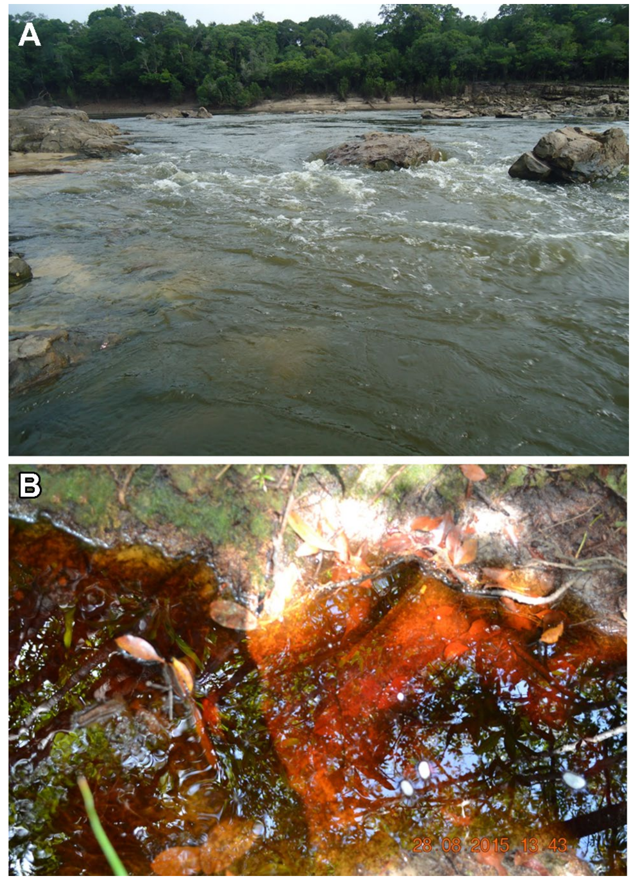

Fig. 7 Jaú River (**a**) and the Padre stream on the Uatumã basin (**b**)

The pH and conductivity are also key parameters for water classification. Amazonian waters draining tertiary sediments and the archaic shields contain few carbonates and bicarbonates, which are common buffers. Therefore, pH values are slightly acidic to acidic. Distilled water saturated by the CO_2 of the air has a pH value of around 5.6. Lower pH values often indicate the presence of humic and fulvic acids, higher values the presence of carbonates (Furch and Junk 1997). Electrical conductivity indicates the amount of electrolytes (anions and cations) in the water. Mineral-rich waters with pH values around 7 (e.g., of Andean origin, from stripes of carboniferous sediments in the lower Amazon, and from near the Atlantic coast) have relatively high electrical conductivity, while waters from other areas show lower values. In very acidic waters (pH about 3–4), the electrical conductivity is slightly increased by the relatively high concentration of hydrogen (H^+) ions (Aufdenkampe et al. 2011; Ríos-Villamizar et al. 2020a, b, c).

Noteworthy is that pH, NH_4^+, watercolor and DO from natural waters are outside of Brazilian standards. This suggests the Brazilian legislation for water quality is not adapted for streams and rivers of Central Amazon (Ferreira et al. 2021). This also suggests that to fit the Amazon's rivers and streams it is necessary to evaluate the regional standards that can be included into the legislation. Due to the diversity of physical and chemical properties of its waters, rivers and streams in the Amazon do not have a uniform pattern, and even with possible classifications of these rivers, more detailed studies are necessary in order to define regional patterns that can contribute to the preservation and sustainable management of rivers and streams in this region (Ríos-Villamizar et al. 2019).

Conclusion

The Jaú River (Jaú basin) and the Padre stream (Uatumã basin) showed remarkable chemical patterns, which probably are atributed to the geological and soil peculiarities of the investigated areas.

Water parameters of the Brazilian legislation should encompass the natural waters of the Amazon. Then the chemical characterization, as it was presented for 2 environmental protection areas in this study, is extremely important since the legislation is based on some parameters that naturally occur in a different way in Amazon waters (e.g., low oxygen levels and/or pH values) as observed in the Padre and Tucumanduba streams in this study.

The evaluated sampling points from the Jaú and Uatumã basins could fit within the classification proposed by Ríos-Villamizar et al. (2013, 2014, 2020a; c) as Intermediate Type A. In addition, the Jaú River, during low water period, could fit within the Intermediate Type B category since its hydrochemical data suggest erosion of the Japurá River's paleo-várzea sediments.

This preliminary characterization will subsidy further studies on these areas and may contribute to the understanding of such water chemical patterns in the Amazon basin, having implications for water resources management and conservation of these Amazon aquatic ecosystems.

The physicochemical and chemical water parameters presented here are key indicators of the chemical and fertility conditions in the studied sites. Forthcoming papers will present soil analysis (chemistry and mineralogy) to better characterize and discuss the inclusion of these areas in the general Amazonian wetland and water classification framework (Ríos-Villamizar et al. 2020a,b,c), and subsequent management options and recommendations may be considered.

Water chemistry is closely related to the geomorphology of hydrographic basins, as demonstrated by the differences between the two studied areas, where the Uatumã basin is among the oldest and most leached regions of the Amazon. Furthermore, these differences can be accentuated in specific periods of the hydrological cycle. This was verified in the Jaú River, where the collections centered in the low water period resulted in very high values, for example, for electrical conductivity, possibly due to the entry of more fertile sediments (e.g., paleo-várzea of the Japurá River) favored by the strong current of the Jaú in this phase. Thus, additional collections in other periods of the hydrological cycle may be important to complement the assessment of this basin. Despite this, the classification of rivers and streams waters of the Jaú and Uatumã basins presented here is a valid contribution to these important areas of environmental protection. It is also a basis for future studies in different seasonal periods, on these and other low-order rivers and streams in the Amazon, and to contribute to the refinement and chemical characterization of these complex Amazonian aquatic landscapes.

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