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To cite this article: Eduardo A Ríos-Villamizar *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **427** 012003

2019 The 2nd International Symposium on Water Pollution and Treatment IOP Publishing
IOP Conf. Series: Earth and Environmental Science **427** (2020) 012003 doi:10.1088/1755-1315/427/1/012003

# Physicochemical features of Amazonian water typologies for water resources management

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**Abstract**. Today, an increasing amount of hydrochemical data indicate that the chemical composition of Amazonian rivers varies much more than the traditional classification indicates. In this first comprehensive review of Amazonian river chemistry, we synthesized critical information from 400 scientific publications and distinguish the types: white, black, clear, intermediate type A and type B. We show the distribution of such rivers across the Amazon basin and the limitations of such approach. These insights into Amazonian river classification provide a new understanding of their baseline limnological conditions. They have implications for sustainable management of Amazonian freshwater systems.

## 1. Introduction

Physico-chemistry of water provides important parameters for quantifying biogeochemical cycles and establishing management options. The first scientific classification of Amazonian water bodies was elaborated in the 1950s by Sioli, 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 still used today. Whitewater rivers (such as the Amazon, Juruá and Madeira) are turbid 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 electrical conductivity that varies between 40–140 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 waters show low quantities of suspended matter but high amounts of humic 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 <20 µS $cm^{-1}$. Clearwater rivers (such as the Tapajós and Xingu rivers) have their upper catchments in the Cerrado region of the Central Brazilian archaic shield. The transparency of their greenish waters is above 1.5 m, with low amounts of sediments and dissolved solids, electrical conductivity that is in the range of 10-20 µS $cm^{-1}$, and pH that varies between 6 and 7 in large rivers.

The aim of this study is to (1) establish a comprehensive data base about hydrochemistry of Amazonian rivers [1], (2) analyze the data under Sioli's classification criteria, (3) provide new insights into the limnological classification of Amazonian rivers, and (4) subsidy sustainable management actions on Amazonian water resources.

## 2. Material and Methods

From literature (400 publications from the last 70 years) we collected the data available on hydrochemistry of Amazonian rivers, and water samples were collected in the course of four field surveys (Jutaí, Tefé, Juruá and Tapajós rivers). The transparency, electrical conductivity and pH were measured in the field, and in the laboratory were obtained the values of the major chemical ions. We used the hydrochemical data of 371 rivers and streams for our meta-analysis (Figure 1). To better differentiate the water types we established 5 categories: White water, black water, clear water, intermediate type A, and intermediate type B.

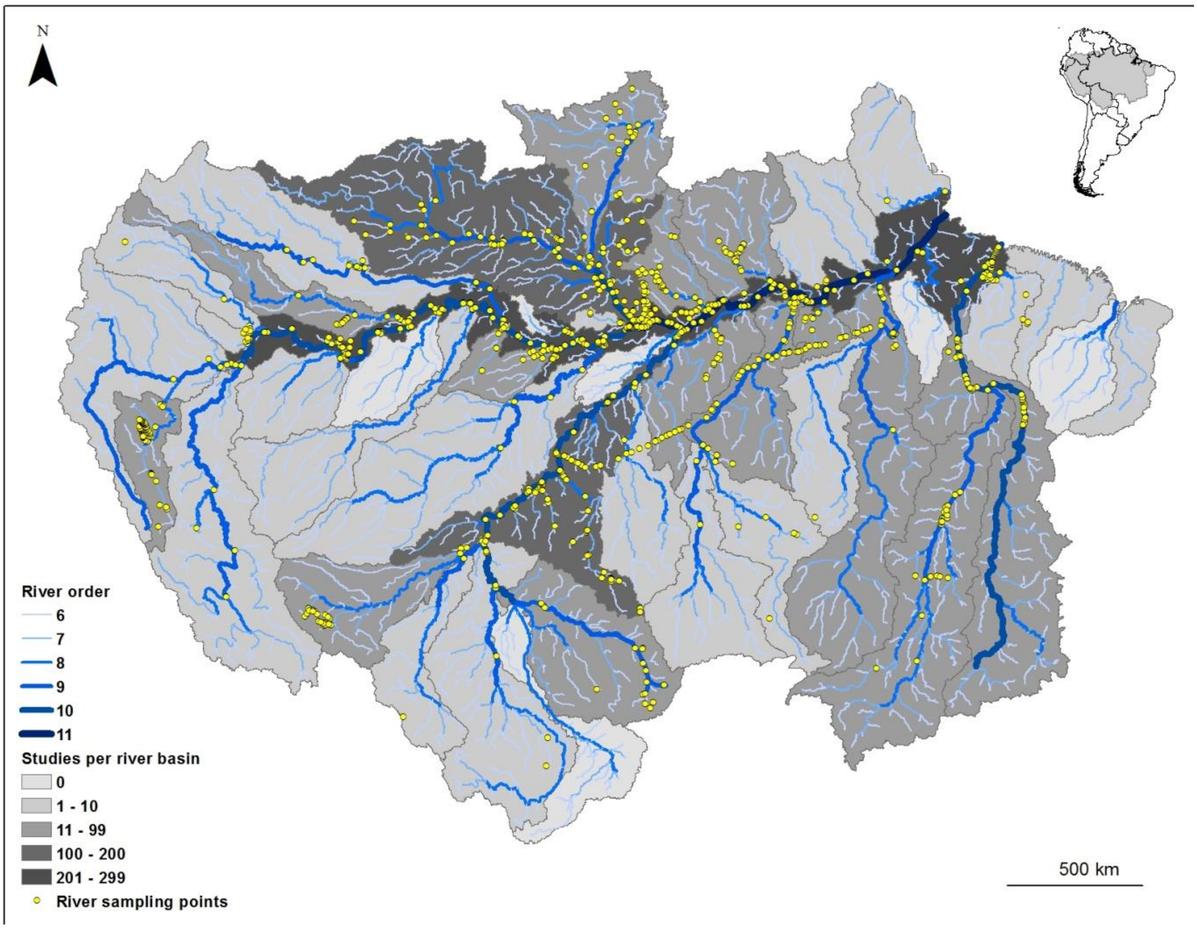

**Figure 1**. Water physicochemistry sampling sites in the Amazon Basin. Dots show the locations of samples identified in the literature review used in this paper. Also shown are the amount of samples per river basin and river order. The vast majority of studies (count = 209) were carried out along the main stem of the Solimões/Amazon rivers. Other highly sampled rivers include the Negro, Madeira,

Huallaga, and Tocantins. The vast majority of rivers has fewer than 25 samples or remains unrepresented in the literature. River basins (shown is level 3) and river order are from [2].

## 3. Results and Discussion

The major element geochemistry of the Amazon Basin rivers and the relationships between hydrochemistry and geology/soil geochemistry have been extensively documented [3]. Rivers that drain siliceous rock types are relatively high in silica and low in total cations. Those that drain carbonates are relatively high in alkalinity and possess intermediate levels of total cations, while those that drain evaporites are rich in sulphate and chloride and are highest in total cations, which is consistent with the weathering trends for minerals in tropical environments [4]. Hence, it is possible to classify the chemical composition of rivers according to the geochemistry and mineralogy of the soils through which they flow. In contrast to the classical Amazonian black waters which show pH-values below 5.0 and electrical conductivity below 25 μS $cm^{-1}$, the typical Amazonian white waters are characterized as carbonate waters [3], indicating richness in carbonates and calcium, pH above 6.5 and electrical conductivity above 40 μS $cm^{-1}$. On the other hand, Sioli's observations of clear waters were based at the lower Tapajós and Arapiuns [5]. Both rivers show typical high transparency because they are Ria lakes without major current, where sediments brought in by the rivers became quickly deposited. They do not represent the physicochemical conditions of the channels of these rivers, but those of Ria-lakes, which have been built in the large mouth bays of the black and clearwater tributaries of the Amazon River by the damming back of the river water because of the raise in sea-level after the last glacial period. Transparency of the Tapajós-water increases from 85 cm at Itaituba on Transamazon Highway to 245 cm at Santarém, 280 km far. The other parameters do not show major changes. We may assume that sediment load of the Tapajós has increased since Sioli's time because of increased erosion as a result of increased land use. But this certainly will happen in the future in other transparent rivers and streams, pointing out the limited value of transparency for river classification. Furthermore, annual data sets show for some rivers considerable seasonal fluctuations in physico-chemical parameters, which makes difficult to relate these characteristics to a specific water type, as shown for the Branco river [6].

A multivariate analysis from a matrix containing 17 parameters indicated that the first two principal components account for over 65% of the variability in the data set (Figure 2). According to the first component, the more important variables are the major anions, major cations, $HCO_3$, Ca, and electrical conductivity. Accounting to the second component in terms of importance are the eq% Ca, eq% $HCO_3$, and eq% $SO_4$. All the loading values are above 0.1 or below -0.1. The plots of the major cations and anions also reveal the separation of the water typologies (Figure 3).

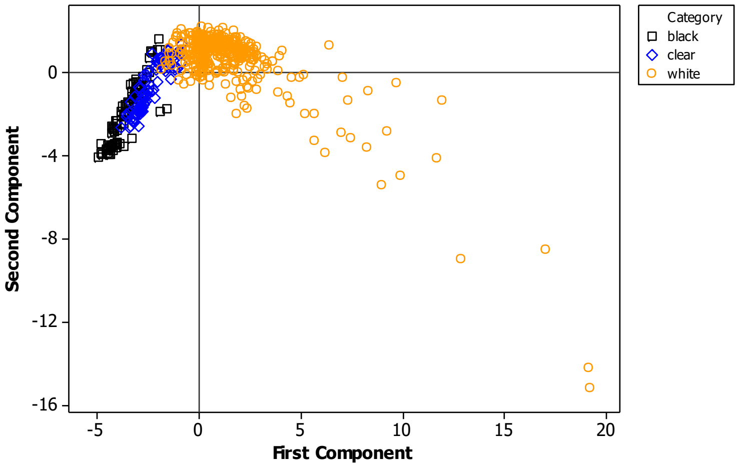

**Figure 2.** PCA score plot for the first (47.3% of the variance) and second (18.2%) component.

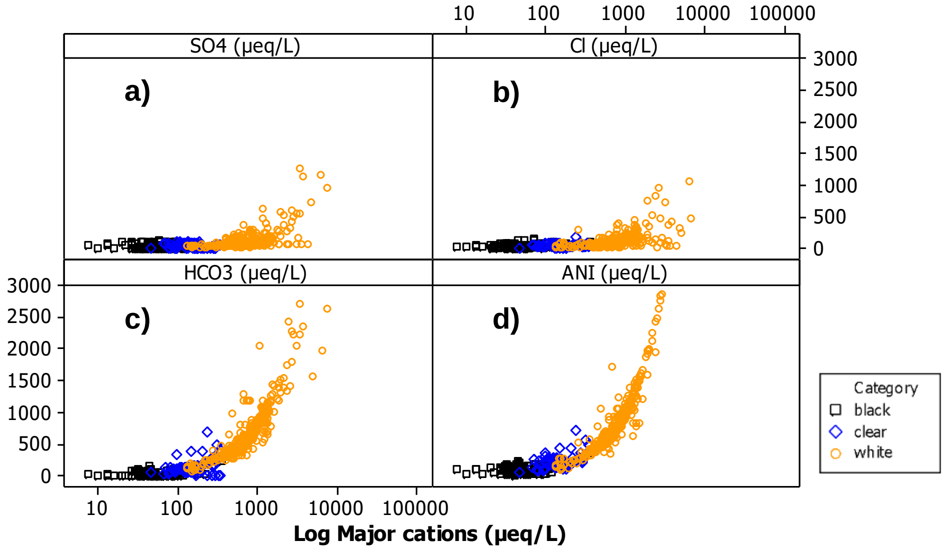

**Figure 3.** Relationship between the content of $SO_4^{2-}$ (a), $Cl^-$ (b), $HCO_3^-$ (c), major anions – ANI (d) and Major cations of Amazonian rivers and streams. Major anions correspond to the sum of total concentrations of $HCO_3^-$, $SO_4^{2-}$, and $Cl^-$. Major cations correspond to the sum of total concentrations of $Ca^{2+}$, $Mg^{2+}$, $Na^+$, and $K^+$. After [4].

Electrical conductivity indicates the amount of anions and cations in the water. Mineral-rich waters with pH values about 7 (i.e., of Andean origin and from stripes of carboniferous sediments in the lower Amazon) have relatively high electrical conductivity, while waters from other areas show low to very low values. In very acidic waters, the electrical conductivity is slightly increased by the high concentration of $H^+$ ions. The total amount and the relative proportions (eq%) of the major elements (e.g., $Ca^{2+}$, $Na^+$, and $HCO_3^-$) provide additional information about the geology. Rivers draining catchments rich in carbonates contain much more calcium and magnesium in the form of carbonates and bicarbonates than rivers draining central Amazonian tertiary sediments and the archaic shields of the Guianas and Central Brazil. In these waters, the total concentration of electrolytes is lower, and sodium and potassium (in the form of chlorides and sulfates) occur in similar or even larger quantities than the alkali-earth metals [3].

Unlike the clear differences in chemical composition between the whitewater rivers draining the Andes mountains and those blackwater rivers draining the Central Amazonian lowlands, clearwater rivers and streams in the Shield areas are much more variable. The overall chemistry of these rivers and streams suggests an intermediate composition. The clear dominance of calcium suggests that the solute-rich waters of the whitewater rivers such as the Solimões/Amazon could be classified as carbonate waters, and are indicative of the carbonate source (mostly limestones) in the Andes mountains. The solute-deficient waters of the blackwater rivers such as the Rio Negro are characterized by a completely different proportion of major elements. These waters show an extremely high Si to cation ratio which is indicative of the podsols in the Central Amazon, and a greater proportion of K to those of the alkaline-earth metals (Ca and Mg), suggesting an alkali dominance [3-4, 7].

We separated the typical whitewater, blackwater, and clearwater rivers, according to the criteria given by Sioli, slightly modified by us, and added 2 other intermediate categories. Of the 371 rivers and streams analyzed, 193 could be addressed to Sioli’s categories: 105 whitewater rivers, 76 blackwater rivers and 12 clearwater rivers. They can be clearly separated with respect to the major physico-chemical parameters. The remaining 178 rivers and streams (47.9% of the total number analyzed) do not fit into the 3 categories of Sioli. They occupy an intermediate position between the classical water types: Intermediate Type A (131) that includes clear waters draining a mixture of different geological formations in the Guiana and Central Brazilian shields, and the Intermediate Type B (47) that includes waters draining sediments of Andean origin on paleo-várzeas (Figure 4).

Paleo-várzeas occupy large areas along whitewater rivers in Central Amazonia and consist of sediments of Andean origin that were deposited during former interglacial periods and that are impoverished in nutrients (i.e., of lower nutrient status than those of várzeas). Ecological characteristics and vegetation species compositions are intermediate between whitewater and blackwater floodplains. Blackwater river floodplains on alluvial paleo-várzea substrates are found all over the differentiated quaternary formations occurring in equatorial and western Amazonia. River waters of these areas have intermediate levels of suspended solids, which originate from anciently deposited and newly eroded sediments of Andean origin. Depending on the age of the ancient várzea river terraces within the catchment (e.g., Pleistocene, Holocene), water and soil nutrient levels may be intermediate. Free-floating plants are rare and semi-aquatic macrophytes may occur but mostly show lower coverage and reduced biomass in comparison with whitewater rivers. The flora of these flooded forests shares many components with the várzea, but species richness is substantially lower [8].

These paleo-várzeas floodplains cover an area of at least 125,000 km$^2$ and occur along small to intermediate rivers that pass through more or less leached paleo-sediments originating from the Andes. Information on water and soil chemistry in these areas is scarce. In addition to occurring along rivers such as the Coarí, Jutaí, and Tefé, these floodplains occur in the central and western parts of the Amazon basin along the numerous lakes (e.g., Ria-lakes) that have formed in the submerged lower valleys of minor tributaries of the Amazon River as well as some of its major whitewater tributaries such as the Purús, Madeira and Japurá rivers. However, these areas are not yet mapped. Flood amplitudes are highest near the confluence with the whitewater rivers but decline rapidly upstream. These areas may be temporarily influenced by “true” whitewaters during the highest water periods, but they are flooded by blackwaters during years with low flood levels. Tree species compositions are closer to the várzea than to the igapó and productivity is intermediate [8].

The impacts of hydropower infrastructure will vary according to the water type and sediment load of a given river. The whitewater Andean tributaries are of particular concern. The complex hydrology of the Amazon and its tributaries will also likely be greatly affected as dams break the connectivity between Andean headwaters and lowland rainforests, blocking the passage of rich sediments and disrupting the seasonal floods that fertilize one of the most productive ecosystems on earth [9].

The vast size of the Amazon basin, the interlocking relationships between uplands and wetlands, and the flow of water through wetlands from the Andes to the Atlantic strongly suggest that, to be effective, development planning must be based on scientific analysis and synthesis of information at scales large enough to capture and understand these ecological complexities and how they interact with social and economic factors. Such planning should move beyond a project-by-project approach to account for cumulative impacts of all planned projects on ecosystem connectivity and function across the Amazon basin.

The classification of Amazonian waters is extremely important from the point of view of the legislation on water quality standards and the management of water resources. Although 3 types of water have been defined, there is a gradient of the types of waters considering electrical conductivity, transparency, pH, content of humic material, major anions, major cations, and the relationships between alkali and alkaline-earth metals and major anions. In this sense, this work helps to clarify the idea of the existence of a gradient of water types. This idea is also important not only to be able to scale future impacts, but for biodiversity studies, in order to better establish whether there is a relationship between the type of water and the biodiversity observed. A water classification system, based on a comprehensive water chemistry dataset, is critical information for understanding baseline conditions in major Amazonian rivers and their related freshwater resources, for evaluating actual or potential impacts of development projects, and for planning management and conservation priorities in this region.

Approximately 30% of the Amazon Basin is covered by different wetland types. A classification system of Amazonian lowland wetlands already uses hydrochemical parameters for the differentiation between the large nutrient-rich whitewater and nutrient-poor blackwater rivers floodplains [8]. These water types represent the upper and the lower end of the fertility gradient. Low fertility of blackwater river floodplains show low resilience against disturbance, and strong limitations for human use, in contrast to their nutrient-rich whitewater counterparts. The overlaps in the hydrochemical categories indicate, probably, the existence of many transitional hydrochemical stages and/or the change in water quality between rainy and dry seasons for lower order tributaries. These transitional/intermediate categories have not yet been considered in the general Amazonian wetland classification system. They require additional research efforts for vegetation inventories, soil and water quality characterization to allow a specific macrohabitat classification and, on this basis, corresponding sustainable management recommendations can be formulated.

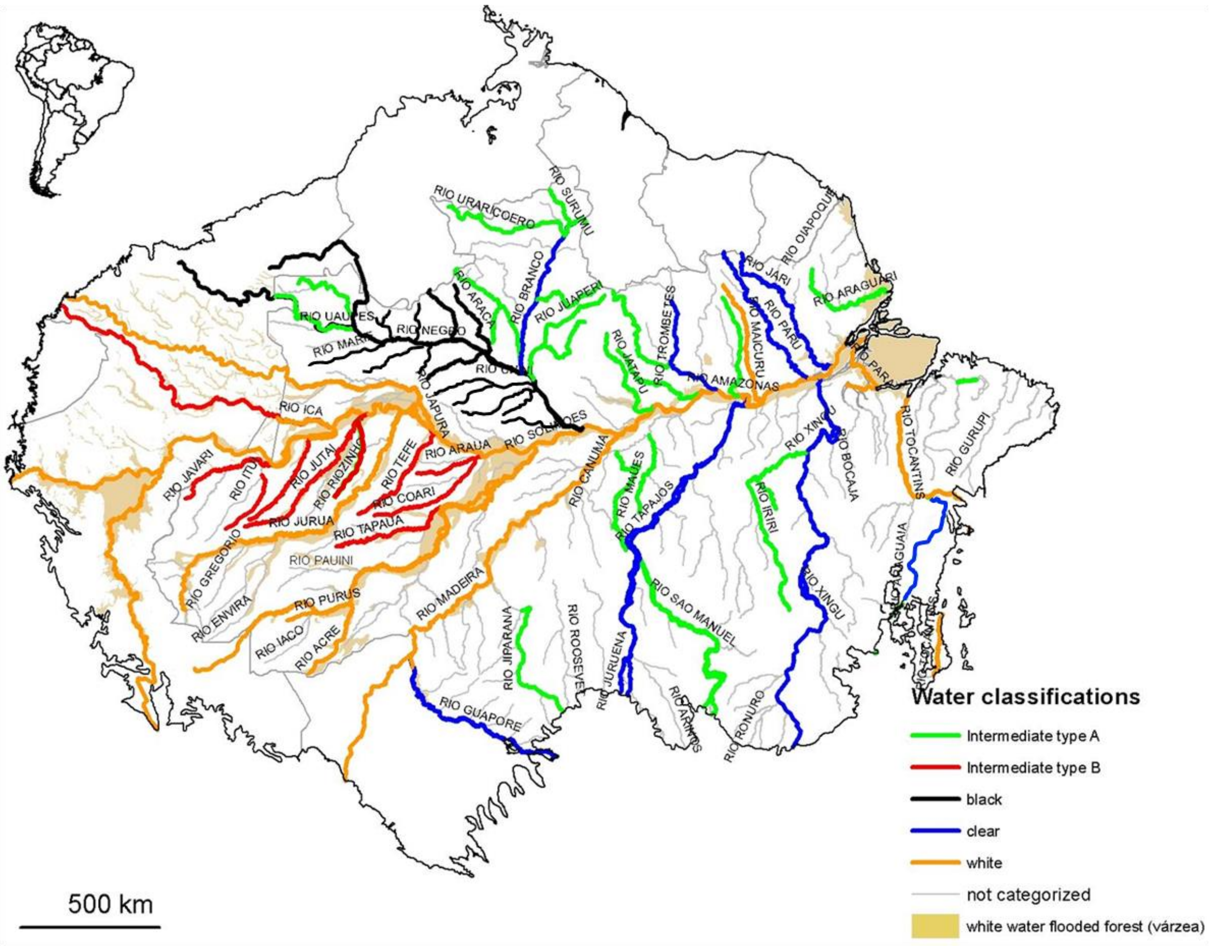

**Figure 4.** Classification of major Amazonian rivers.

## 4. Conclusions

A classification system is necessary for the discussion of ecological ecosystem peculiarities such as species diversity and distribution, biomass, primary and secondary production and decomposition, and management options in the water and associated wetlands. Despite some adjustments by including the amount and relationship between alkali and alkali-earth metals and carbonates into Sioli's general classification, his approach continues to be valid for ecological and management purposes in rivers and wetlands systems as well as for offering arguments for management actions on water resources. Several examples from studies on rivers around the globe have revealed the negative and cumulative impacts of hydroelectric power plants on the hydrological and hydrochemical conditions of rivers with potential implications for fishing and fisheries, and other ecosystem processes. The impacts of hydropower infrastructure will vary according to the water type, nutrient and sediment load of the rivers. Damming whitewater Andean tributaries, which feed lowland Amazonian ecosystems and associated vegetation, could have dramatic negative impacts on flood regime and physicochemical conditions downstream.

The vast size of the Amazon basin and the flow of water through wetlands from the Andes to the Atlantic strongly suggest that, to be effective, development planning must be based on scientific analysis and synthesis of information at scales large enough to capture and understand these ecological complexities and their interactions with social and economic factors. This validated general classification system, based on a comprehensive water chemistry dataset, is critical information for understanding baseline conditions in major Amazonian rivers and their related freshwater resources, for evaluating actual or potential impacts of development projects, and for planning management and conservation priorities in this region.

This paper, based on a review of data in the literature, has highlighted the limitations of existing categorization methods. It suggests new considerations for limnological classification of the Amazon basin to address the gaps in traditional classifications which could be considered for sustainable management of such river ecosystems. The paper also noted that water chemical parameters of larger river basins may change over time indicating the need for classification to be constantly updated.

## Acknowledgements

This work was funded by “CAPES/CNPq-IEL Nacional-Brasil”, Nuclei Excellency Support Projects (PRONEX) “Tipologias Alagáveis (CNPq/FAPEAM)”, INPA/Max-Planck, Ecology, Monitoring and Sustainable Use of Wetlands Group (MAUA/CDAM/PELD/MAUA), Climate and Environment Program at the Brazilian National Institute for Amazonian Research (INPA/UEA), Programa de Apoio à Fixação de Doutores no Amazonas – FIXAM/AM (Edital n. 022/2013, grant number: 062.01319/2014) and Programa de Apoio à Participação em Eventos Científicos e Tecnológicos – PAPE from the Fundação de Amparo à Pesquisa do Estado do Amazonas (FAPEAM/SECTI/AM), and the Instituto Nacional de Ciência e Tecnologia em Áreas Úmidas (INCT-INAU-UFMT). The first author is "Bolsista CAPES/BRASIL". We thank the anonymous reviewers for their valuable comments and suggestions on our manuscript.

## References

[1] Richey J E, Victoria R L, Hedges J I, Dunne T, Martinelli L A, Mertes L and Adams J 2008 *Pre-LBA Carbon in the Amazon River Experiment (CAMREX)*, Data Set Online, Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/904, available at http://daac.ornl.gov

[2] Venticinque E, Forsberg B, Barthem R, Petry P, Hess L, Mercado A, Cañas C, Montoya M, Durigan C and Goulding M 2016 An explicit GIS-based river basin framework for aquatic ecosystem conservation in the Amazon *Earth System Science Data* **8 (2)** 651-661

[3] Furch K and Junk W J 1997 Physicochemical Conditions in the Floodplains *The Central Amazon Floodplain: Ecology of a Pulsing System* ed W J Junk (Berlin Heidelberg: Springer-Verlag) pp 69–108

[4] Stallard R F and Edmond J M 1983 Geochemistry of the Amazon. 2. The influence of geology and weathering environment on the dissolved load *J. Geophys. Res.* **88-C14** 9671-9688

[5] Sioli H 1956 Über Natur und Mensch im brasilianischen Amazonasgebiet *Erdkunde* **10-2** 89–109

[6] Ríos-Villamizar E A, Piedade M T F, Costa J G, Adeney J M and Junk W J 2014 Chemistry of different Amazonian water types for river classification: a preliminary review *WIT Transactions on Ecology and The Environment* **178** 17-28
[7] Konhauser K O, Fyfe W S and Kronberg B I 1994 Multi-element chemistry of some Amazonian waters and soils *Chemical Geology* **111** 155-175
[8] Junk W J, Piedade M T F, Schöngart J, Cohn-Haft M, Adeney J M and Wittmann F A 2011 Classification of Major Naturally-Occurring Amazonian Lowland Wetlands *Wetlands* **31** 623-640
[9] Forsberg B R, Melack J M, Dunne T, Barthem R B, Goulding M, Paiva R C D, Sorribas M V, Silva Jr U L and Weisser S 2017 The potential impact of new Andean dams on Amazon fluvial ecosystems *PLoS ONE* **12 (8)** e0182254