Spatial distribution of water quality in the Amazonian region: implications for drinking water treatment procedures

Julio Cesar Wasserman, Viviane Maia Damaceno, Gilson Brito Alves Lima and Maria Angélica Wasserman

ABSTRACT

Riparian communities in the Amazon suffer from water-borne diseases due to the lack of adequate water treatment capabilities. Therefore, small local water treatment plants are necessary, but the selection of treatment procedures depends largely on the physico-chemical characteristics of the water. The aim of the present research was to evaluate the physico-chemical characteristics of the water in the Amazon River and its tributaries, in order to determine customized processes for water treatment. Data from 54 fluviometric monitoring stations were organized and used to construct distribution maps. The parameters such as pH, electrical conductivity, and the concentration of suspended matter, turbidity and flow rates were evaluated. Results showed that pH was very acidic (4–5) in the northwestern portion of the region while conductivity was quite low in the entire Amazonian region ($<140\ \mu S\ cm^{-1}$). Both parameters were strongly influenced by geological settings and sources of organic matter. Suspended matter and turbidity were affected by weathering processes. It was concluded that considering the acidity of the waters, mechanical procedures like filtration or slow settling should be applied to remove suspended matter rather than chemical procedures. For disinfection, instead of chemicals, solar energy should be applied.

Key words | distribution maps, electrical conductivity, pH, riparian communities, suspended matter, water physico-chemistry

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INTRODUCTION

In spite of the astronomical amount of water in the Amazon River, riparian communities do not have ready access to potable water because of the complete absence of sanitation infrastructure along the river (Binsztok *et al.* 2009). These communities consist mainly of dispersed agglomerations of about 120 inhabitants each (Sousa 2009), located in remote areas with few financial or technological resources. Water treatment systems and pipelines, and even connection to electricity networks, are simply not possible in such regions. Potable water and electricity must therefore be produced locally within the community. Electricity is, in fact, produced with small gasoline generators, but water is seldom treated, and people drink raw water directly from the river. These unsanitary practices result, as might be expected, in poor health outcomes within these rural communities.

Regardless of the fact that individual riparian communities are small human groups, together these rural groups, who depend on the Amazon River watershed, add up to more than four million people (IBGE 2010).

In a recent paper, Gama *et al.* (2018) carried out a health survey in 24 riparian communities of the Solimões Basin, with an average population of 168 inhabitants (ranging

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from 75 to 422), located at an average of 57 km from any urban center. In their study, they found that 77.4% of the population complained of health problems, but because health facilities were distant, only 25.2% ever visited a medical provider. The authors also established that the human development index was very low (0.587), comparable to countries like Zambia, Equatorial Guinea and Ghana. The authors showed that water is obtained from rivers, lakes, groundwater and sometimes directly collected from rainwater, and is treated by only 72.2% of the population (simply by the application of sodium hypochlorite). Also, there was no indication of the presence of sewage treatment systems, engendering a high incidence of severe diarrheic diseases.

Considering the unsanitary state of riparian communities in the Amazon region, the development of small water treatment plants with simple technologies and low maintenance requirements is highly advisable. Many purification techniques exist, but the most widespread is the application of aluminum sulfate for flocculation/coagulation and disinfection with chlorine. However, the choice of water purification procedures should consider the chemistry of the available raw water, because the expected chemical reactions may not work in some situations. For instance, in the Western Amazon, black rivers present acidic waters (Horbe & Santos 2009), and treatment with aluminum sulfate may promote aluminum dissolution instead of flocculation of particles. In these waters, which are rich with humic substances (Ertel *et al.* 1986; Oliveira *et al.* 2007), the disinfection agent chlorine may react with the organic matter and form trihalomethanes (THMs) as by-products (Pifer & Fairey 2014). The main issue for populations drinking aluminum-rich water is the proven risk of cognitive decline (Yang *et al.* 2017). Besides, THM (acetone)-rich waters have been shown to be correlated with bladder cancer (Nieuwenhuijsen *et al.* 2009).

Other aspects that should be considered when choosing cleaning and disinfecting techniques to produce potable water in riparian communities are the availability of drinking-grade reagents and the capability of the community to continually carry out the necessary maintenance of the system. For instance, contaminated reagents may pollute the water, exposing communities to unacceptable doses. Giroussi *et al.* (1996) showed that commercial aluminum sulfate may be contaminated with Cd (22 $\mu g\, g^{-1}$) and Hg (1.0 $\mu g\, g^{-1}$). Wasserman *et al.* (2018) showed that water treatment plant sludge piles may be severely contaminated with mercury from the chemicals used for disinfection.

In a recent study, Pandit & Kumar (2015) reviewed a number of water treatment procedures that could be used in remote communities, including solar disinfection, filtration, hybrid filtration, treatment of harvested rainwater, herbal water disinfection and the application of innovative water treatment devices like plant xylem as filters, terafilters and hand pumps. All these techniques may be adequate for developing countries, but the type of water where they are to be applied must be taken into consideration to identify the most healthful procedures for that particular situation.

The identification of types of water in the Amazon is the first step in the development of a regional policy for safer water treatment procedures. The aim of the present work was to construct distribution maps of the water quality in the Amazon region, in order to support the planning of customized processes for water treatment.

METHODOLOGY

Study area

The Amazon hosts the largest tropical rain forest in the world, comprising many countries in South America (including Peru, Colombia, Ecuador, Venezuela, French Guiana, Guyana, Suriname, Bolivia and Brazil), and thanks to its photosynthetic capacity of CO_2 transformation into O_2; this forest is commonly referred to as the lungs of the planet Earth. Although the destruction of the rainforest is critical for plantation owners and cattle ranchers, the decline of the environmental conditions affects traditional communities (Indians included), whose survival is based on their access to natural resources. These populations tend to live close to the rivers where transportation is easier, and water is largely available. Most of them have migrated from northeast Brazil and from the south, searching for new opportunities and inexpensive land, where they intended to develop small-scale agriculture and cattle ranches.

Although the climate of the Amazon is recognized as humid tropical, considering the extension of the region, there is broad variability. Using Koppen's classification, the following types of climates can be found in the region:

Af (humid tropical or equatorial), Am (monsoon) and Aw (tropical, with a dry season in the winter). The average rainfall in the Amazon is 2,300 mm year^{-1}, ranging from 1,700 to 3,500 mm year^{-1}.

In order to understand the water quality distribution in the Amazon Basin, it is important to analyze the regional geology. A more detailed description of the regional geology and morphostructure of the Amazon was proposed by Stallard & Edmond (1983), who identified the main geological features: Andean Shield (divided into Western Cordillera, Subandean Trough, Intercordilleran Zone and Eastern Cordillera), Amazon Trough, Guiana Shield and Brazilian Shield. Although the Andean Shield was not included in the present research, Merschel *et al.* (2017) underlined its importance in establishing the dissolved and particulate mineral composition of the downstream waters. On the other hand, these authors state that Brazilian and Guiana Shield rivers yield organic-rich waters.

Most of the Andean geology is dominated by Cenozoic and Mesozoic volcanic rock. Extensive areas also present Mesozoic and Paleozoic sediments, whose composition is dominated by oxidized shales, sandstones, carbonates and evaporites. In the lower Paleozoic sediments, dark shales, sandstones and carbonates are abundant. The Guiana Shield was shown to have an older geology, composed mainly of Precambrian granitic rocks. After Stallard & Edmond (1983), Precambrian metamorphic rocks associated with Precambrian intrusive rocks have been largely identified in the Brazilian and Guiana Shields. In the axis of the Basin, the Amazonian Trough is mainly composed of late Tertiary and Quaternary lacustrine or marine deposits, where less intense weathering is associated with the development of 'thick and indurated soils.' In this region, Stallard & Edmond (1987) observed that the mineral composition of the water is controlled by geochemical processes in the Andes. In a later work, Gaillardet *et al.* (1997) applied elements' relationships to show that white water rivers (Madeira and Solimões) are loaded with sediments from the Andes and also from the recycling of sediments from weathered soils.

Database

Considering that in the Andean region the networks for measuring water quality and flow rates are uneven, the study region was limited to the Brazilian Amazon Basin (Figure 1(a)). The data from the network of water quality fluviometric stations are available in the 'Hydroweb,' a site from the Brazilian Waters Agency that gathers the results from monitoring programs over the entire country (http://www.snirh.gov.br/hidroweb/). In the study region, we were able to find 54 fluviometric stations where measurements of water quality were carried out (Figure 1(b)). These stations had different sampling periods, from 1975 up to 2008. The number of sampling years ranged from 4.3 to 32.8 years (average 21.2 years). The number of measurements per station (all parameters confounded) was calculated in average as 404.7 (SD = 198.3).

The measured parameters were water volumetric flow rate (m^3 s^{-1}), pH, conductivity (μSiemens cm^{-1} at 20 °C), concentration of suspended matter (mg L^{-1}) and turbidity (FTUs – Formazin Turbidity Units). Considering that in the Amazon, a large seasonal variability affects the water quality (Oliveira *et al.* 2007), the data were separated into wet and dry periods. Based exclusively on rainfall, Neill *et al.* (2001) defined the wet period as November to May and the dry period as June to October.

Contour map preparation

Average values (for wet and dry seasons) were calculated for each station in the software Surfer® version 11 (Golden Software, Inc.), and interpolations were carried out with the kriging method. The volumetric flow rates of the rivers were presented in monthly averages for two stations (Manacapuru and Óbidos) that received most of the inputs of the Amazonas basin (Figure 1(b)). In Manacapuru, the measurements begun in 1976 and ran until October 2007 while in Óbidos the measurements began in 1975 and ran until 2000.

RESULTS AND DISCUSSION

Variation in flow rates

Monthly average volumetric flow rates for the stations Manacapuru and Óbidos are presented in the graphs of Figure 2.

In Figure 2, it can be seen that the flow rates are extremely elevated (which is normal for the largest river in the

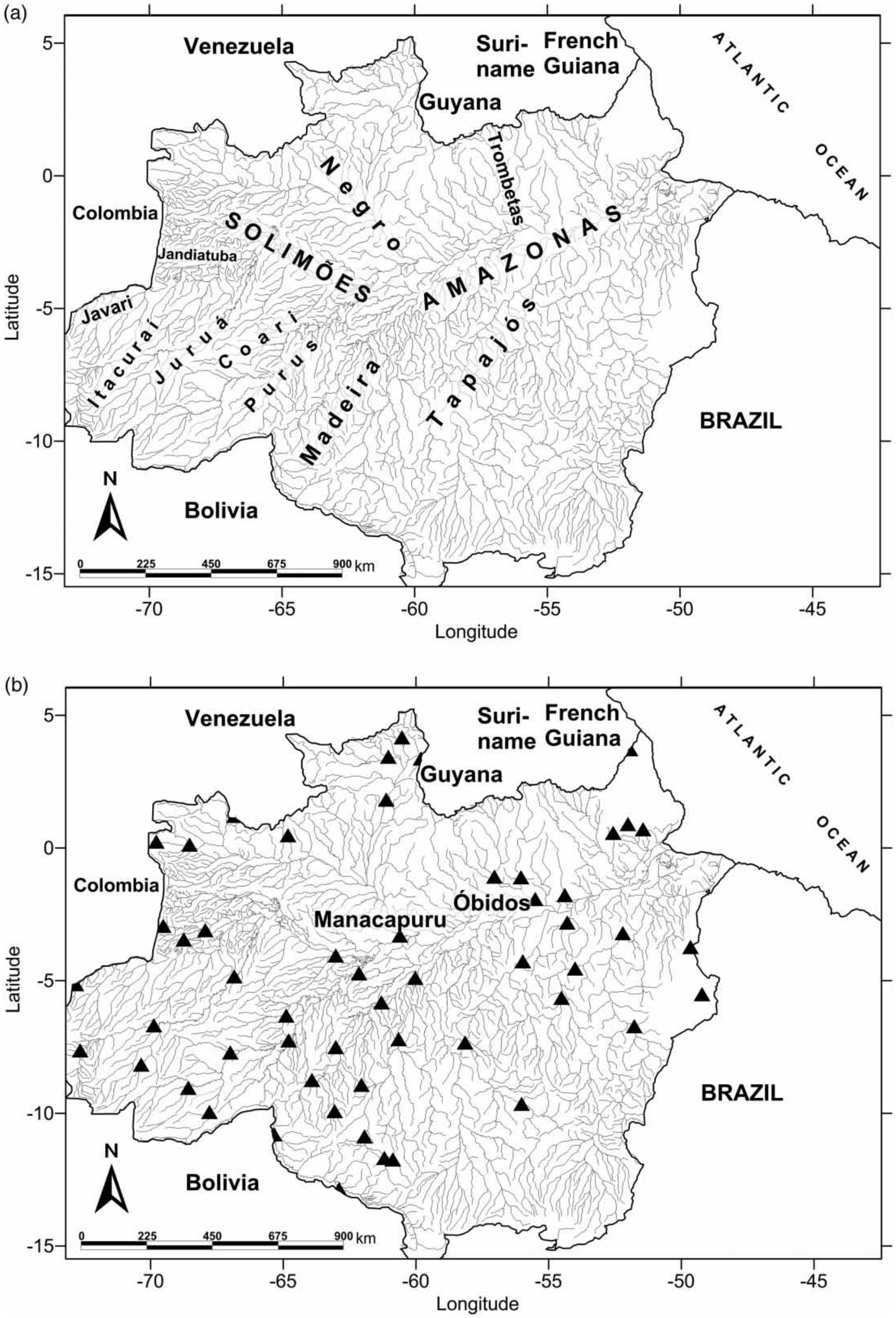

Figure 1 | (a) Map showing the Brazilian Amazon Basin with its main rivers. (b) Location of the 54 water quality monitoring stations in the Brazilian Amazon, whose data were used in the present research.

world). Considering that the average overall flow of the Amazon reaches 206,000 $m^3 s^{-1}$ (FAO 2016), the values presented in the graph are not so elevated, largely because the overall flow is measured in the Atlantic Ocean output of the river, whereas both stations are located well upstream. From Figure 2, it is also evident that there is not much

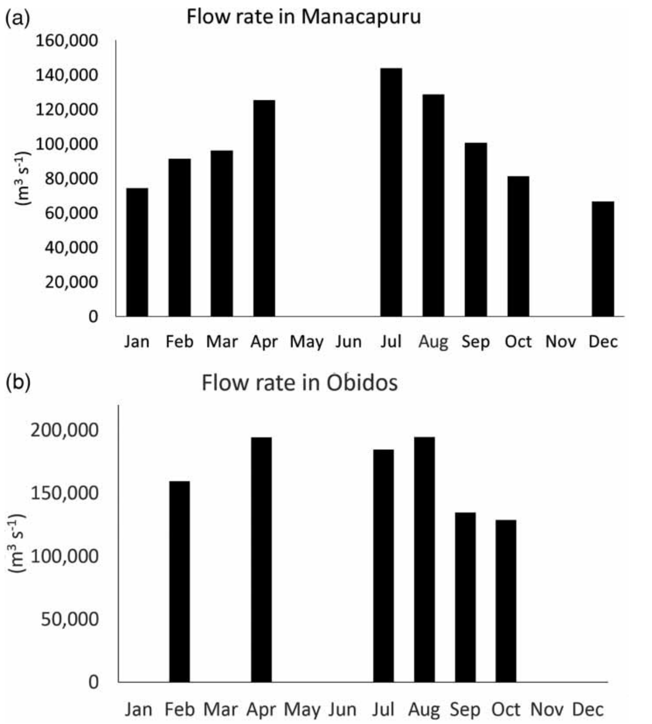

Figure 2 | Average monthly volumetric flow rates (in $m^3 s^{-1}$) in (a) Manacapuru and (b) Óbidos.

variation in the flow rates, and although in some months there were no measurements, it can be observed that there is a phase shift between the wet and dry seasons (based on rainfall) and the higher and lower flows, because the basin is so large that it takes several weeks after major rainfall events for an increased flow rate to be detectable farther downstream. Therefore, in Manacapuru, although the wet season ends in May, the highest flow rate is observed in July. Conversely, although the dry season ends in October, the January flow rate is still low.

Distribution of the water quality parameters

The contour maps showing the distribution of water quality parameters are presented in Figures 3–6. The left-hand maps represent the wet season, and the right-hand maps represent the dry season.

The pH of the water in the Amazon environment has been discussed by a number of authors (e.g. Horbe *et al.* 2013) who have identified several factors that affect this parameter. On the one hand, the weathering patterns in some geological structures – mainly those associated with the Andean Shield – cause a higher consumption of CO_2, reducing the amount of carbonic acid in the water and increasing the concentration of dissolved electrolytes (Gaillardet *et al.* 1997; Merschel *et al.* 2017). This water is more alkaline and richer in suspended matter, and it flows into the Madeira and Solimões rivers. On the other hand, waters leaching older lithologies, composed of more weathered terrains (Brazilian and Guiana Shields), yield less mineralized waters with more organic matter (Gerard *et al.* 2003). Examples of these water patterns can be identified in the Negro River.

The above proposed model can be identified in both maps of Figure 3, where more alkaline waters appear in the southwestern portion of the Amazon, draining from the Andean Shield. Significantly more acidic waters are observed in the northern portion – the result of the draining of extremely weathered soils with large amounts of organic matter (humic substances) gives the waters a black color. In the east, the intermediate acidic waters of the axis of the Amazon River indicate that they come from various sources, including the Solimões River, the Madeira River (both less acidic) and the Negro River (acidic). Waters draining through the Brazilian and Guiana Shields are rather acidic, because soils in these regions are intensively weathered and rich in organic matter (Stallard & Edmond 1987).

A comparison between the two periods shows a difference of a half pH unit, more acid in dry conditions, indicating that less rainfall implies reduction of the amount of electrolytes in the Amazon waters. Ríos-Villamizar *et al.* (2013) observed that waters with lower conductivity drain more weathered areas and tend to display lower pH, which is also controlled by organic matter content. Hence, it can be expected that in the Amazon as a whole, periods of lower flow show lower conductivity and lower pH. This is corroborated by the water electrical conductivity data presented below.

pH is a relevant parameter in drinking water treatment systems, because chemical reactions are intensively affected by this parameter. For instance, highly acidic waters cannot be treated with the traditional coagulation/flocculation procedures, applying alum. On the other hand, during disinfection, chlorine may react with acid organic-rich waters, forming trihalomethanes (Pifer & Fairey 2014).

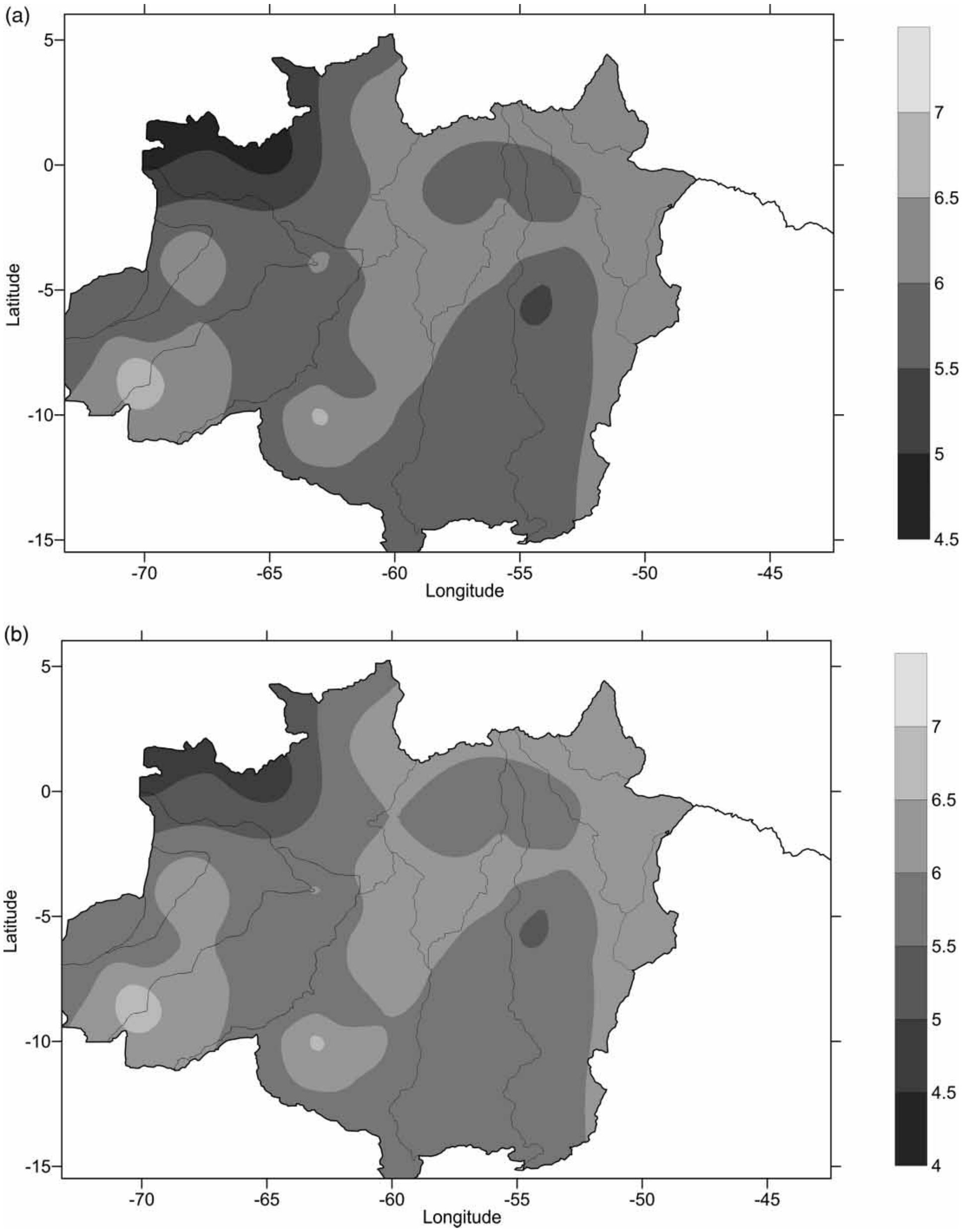

Figure 3 | pH in the wet season (a) and in the dry season (b).

In general, conductivity of the Amazonian rivers, as shown in Figure 4, is quite low, ranging from close to zero to 140 μS cm^{-1}. Differently from pH, conductivity displays a strong seasonal variability that is striking in the northwestern portion of the Amazon Basin. In fact, based on the analysis of pH behavior, it was expected that the presence of electrolytes in the solution would be fairly similar in both seasons and also similar to the distribution during the dry season (Figure 4). A possible explanation for the behavior during the wet season (Figure 4(a)) is that the presence of organic complexes displaying electrolytes in their terminal structure should attribute conductivity to the water. In a study of black-water rivers in the Amazon, Monteiro *et al.* (2014) observed a strong relationship between dissolved organic matter and electrical conductivity, allowing them to propose the use of this parameter

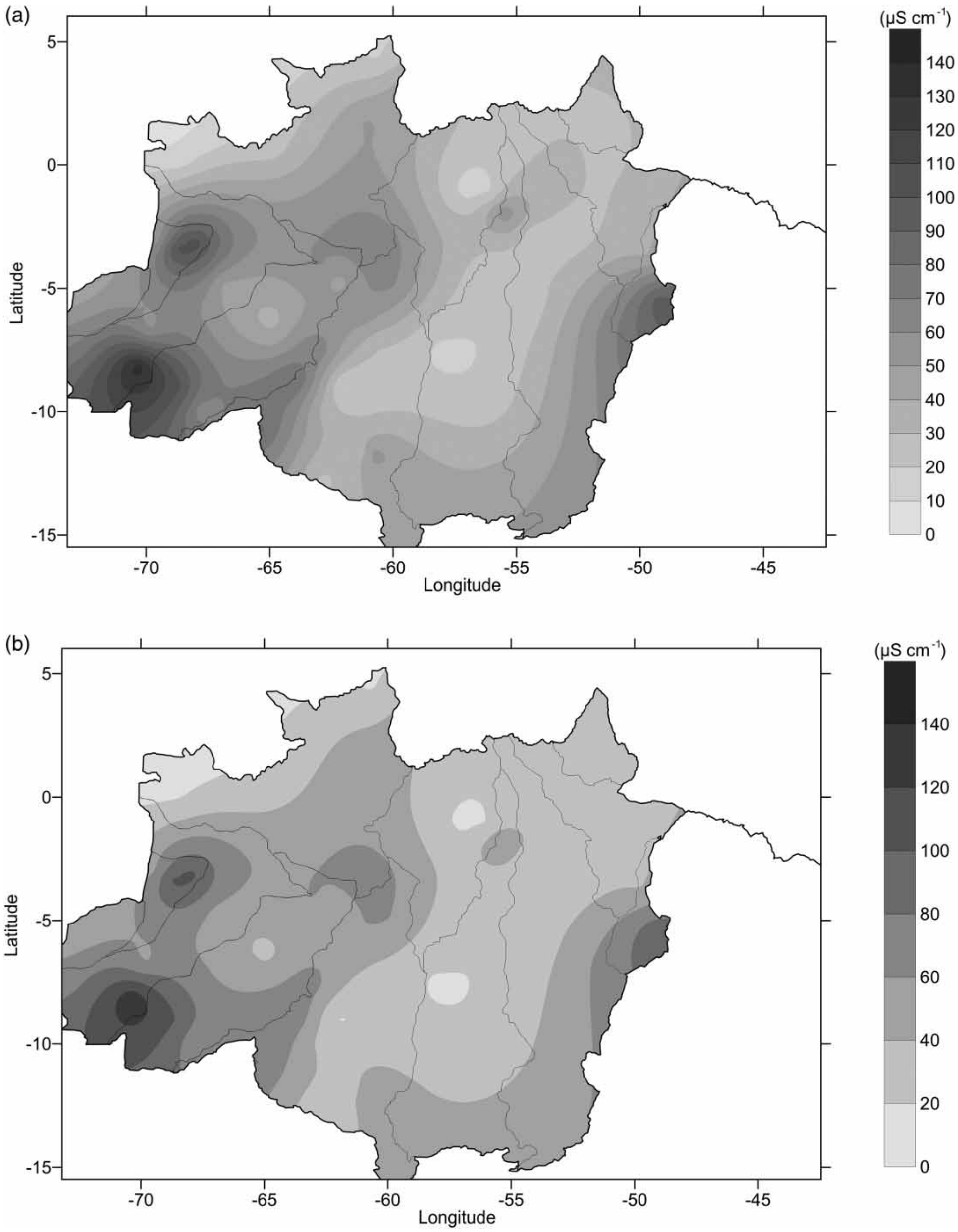

Figure 4 | Conductivity (μS cm^{-1}) in the wet season (a) and in the dry season (b).

as an indicator of the variability of the organic matter in ion-poor rivers (like the Negro River). Higher concentrations of dissolved organic carbon, then, can attribute higher electrical conductivity to water.

Observation of the northwestern portion of the Amazon in Figure 4(b) shows that during the dry season, there must be a reduced input of dissolved organic matter, which should reduce electrical conductivity in the water (Mora *et al.* 2014). Considering that this region does not produce high amounts of ions (as discussed above), the conductivity is low, regardless of the fact that the water is concentrated during the dry season.

In the southwestern portion of the Amazon, the conductivity seems to respond to a dilution/concentration model: during the wet season, although the intense rains should increase soil and rock leaching, the volume of the water dilutes the electrical conductivity. Conversely, during the dry season, the lower volume of water concentrates ions, yielding higher electrical conductivity. For the rest of the Amazon, a balance between the inputs of organic matter and of ions can explain the electrical conductivity values. Overall, in general, waters in the Amazon present a low electrical conductivity which does not affect potability.

Figures 5 and 6 present distributions of the concentrations of suspended matter and turbidity, as measured by filtration and by turbidimeters calibrated with Formazin, respectively. Although these two parameters give more or less the same information (concentration of solids in suspension), comparing the two is quite difficult, because of the inherent characteristics of each procedure (Nourisson *et al.*

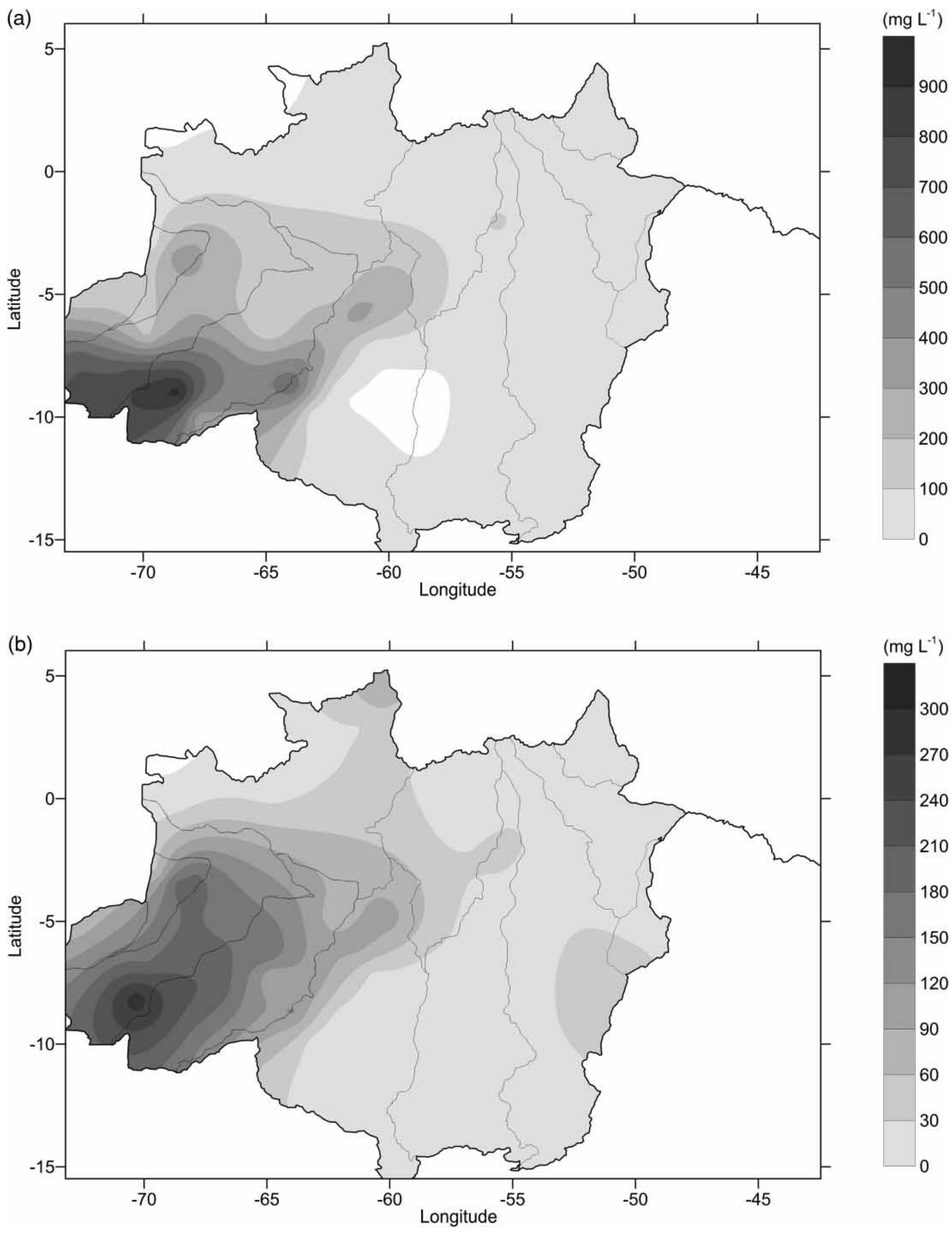

Figure 5 | Concentration of the suspended matter (mg L^{-1}) in the wet season (a) and in the dry season (b).

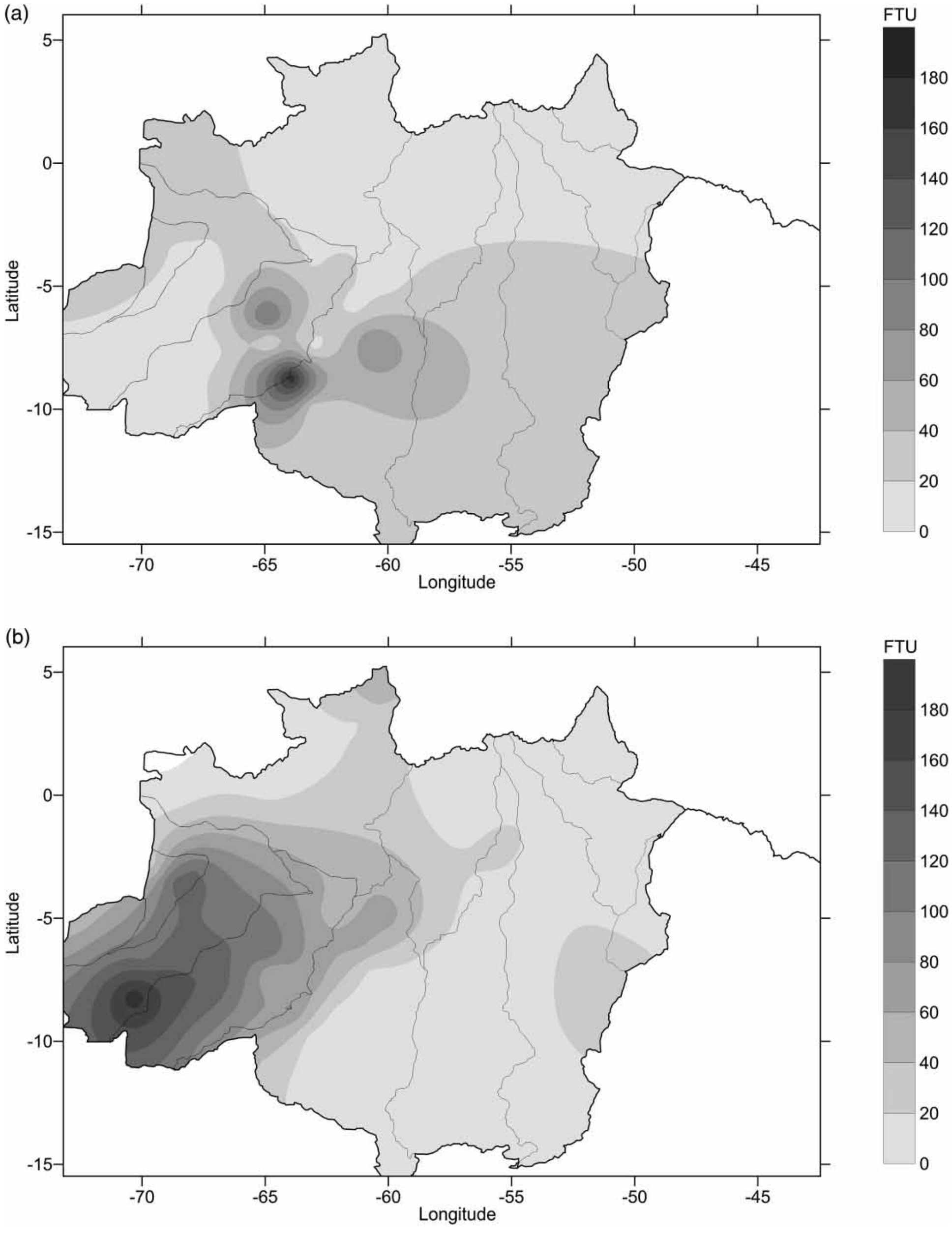

Figure 6 | Turbidity (FTU) in the wet season (a) and in the dry season (b).

2013). While turbidimetry measures the scattering of light in suspended particles, suspended matter filtration is a gravimetric measurement of the materials that are retained in a filter (normally 0.45-μm pore diameter). Many particles that are measured with one method escape from the other. Regardless of these differences, both Figures 5 and 6 show a similar distribution behavior, with significantly higher values in the southwestern portion of the Amazon region. Because primary productivity in Amazonian rivers is low (Pinilla-Agudelo 2009), it can be considered that most suspended particles are detrital, originating from erosion in the Andean Shield (Gaillardet *et al.* 1997). The concentration of suspended particles will determine the type as whitewater (rich in suspended matter), blackwater or clearwater (poor in suspended matter) (Ríos-Villamizar *et al.* 2013). The amount of suspended matter in the rivers has a major bearing on whether the water can be successfully treated for human consumption or not.

Drinking water treatment procedures

Water has been treated for consumption since early primitive societies, and a myriad of procedures have been developed. Since reviewing all drinking water treatment procedures was not the aim of the present study, these procedures are simply summarized in Table 1 (after Di Bernardo *et al.* 2002).

As established in the introduction of the present article, drinking water treatment in the Amazon region presents a series of issues concerning the availability of materials and high-quality reagents, the availability of electrical energy and the type of raw water that is used. Therefore, an effective treatment plant for these riparian communities should be simple and inexpensive, easy to apply by untrained personnel, and should not rely on expensive or complicated reagents.

For most Amazonian waters, pH measurements need to be carried out for the raw water before the application of some coagulation reagents, so the best solutions would be ones that avoid pH-sensitive reagents. Sand filtration, local material filters, long-term settling (Pandit & Kumar 2015) and tangential filtration systems (ones that do not clog over time) should be developed to remove suspended matter. Natural polymers derived from manioc, potato, arrowroot or maize (Di Bernardo *et al.* 2002) can also be applied because of their mechanical effects on the removal of suspended matter and their availability in the region. An extensive discussion on methods for cleaning and disinfecting water in developing countries was recently presented by Pandit & Kumar (2015). In their work, these authors describe (1) solar disinfection, (2) filtration, (3) hybrid filtration (including with terafilters), (4) herbal-based treatments, (5) rainwater harvesting, (6) plant xylem filtration, (7) bio-sand filters and tippy taps, and (8) disinfecting hand pumps.

Because of the large volume of water available in the Amazon, contaminants like trace metals, hydrocarbons and persistent organic pollutants do not constitute a problem for riparian populations. However, in locations where water is obtained from lakes and other lentic environments, algae contaminants like microcystin may be present and can be treated with activated charcoal. Activated charcoal is easily obtained from pyrolysis of natural materials (for example, coconut); however, communities will not be able to determine when the procedure is to be applied, because measuring algae by-products is a complicated procedure. It is therefore advisable that raw water should be obtained from lotic systems.

Considering the concentrations of organic matter in most waters in the Amazonian environment, disinfection with chlorine should be avoided, because it will lead to the formation of trihalomethanes (Pifer & Fairey 2014). The impact of ozonation on the organic-rich waters of the Amazon, mainly the formation of by-products of partial oxidation, is difficult to preview.

A good solution for water disinfection in riparian communities was proposed by Pandit & Kumar (2015): solar disinfection systems. These are easy to set up in areas with a high incidence of solar radiation and can promote the decay of bacteria in periods as short as 2 h (Feitosa *et al.* 2013).

CONCLUSIONS

Although the results of flow rate measurements indicate that there is a phase shift of up to 2 months between maximum/minimum rainfall and maximum/minimum flow, variations in water quality parameters (except for electrical conductivity) between seasons are small.

pH is an important parameter to consider when designing water treatment procedures, and our results indicate that it is controlled by the presence of electrolytes and organic acids in the solution. The presence of mineral electrolytes also controls the electrical conductivity of the solution, but in the wet season, a significant amount of organic matter is leached from the soils and may also affect this parameter.

The main origin of the suspended matter in the Amazonian basin is the Andean Shield, which is subject to intense erosion processes. The Madeira and Solimões rivers, known as the whitewater rivers, present the highest concentrations of suspended matter as well as the highest turbidity. Values of FTUs are not expected to reflect concentrations of particulate matter (by gravimetry), though, because these two parameters are measured

Table 1 | Procedures for the treatment of raw water destined for human consumption (after Di Bernardo *et al.* 2002)

Treatment phase	Physical and chemical processes	Reagents	Advantages for the communities	Disadvantages for the communities
Preparation and polishing	Acidification	Hydrochloric acid Sulfuric acid	Chemistry of the processes are very well known; facilitates the subsequent processes; does not generate by-products	Expensive; risk of contamination with metals and other elements; requires knowledge of chemistry: dosing requires experience
	Alkalization	Hydrated lime Sodium carbonate Sodium hydroxide	Chemistry of the process are very well known; facilitates the subsequent processes; does not generate by-products	Expensive; risk of contamination with metals and other elements; requires knowledge of chemistry: dosing requires experience
Removal of particulate matter	Coagulation	Aluminum sulfate Polyaluminum chloride Ferric chlorine Chlorinated ferrous sulfate Ferric sulfate Tannate	Chemistry of the process are very well known; removes particulate substances efficiently	Expensive; risk of contamination with metals and other elements; generates significant amounts of sludge, contaminated with chemicals. Affected by the presence of organic acids; dosing requires experience; in acidic waters, reagent may dissolve in the produced water
	Mechanical flocculation	Slow shaking – no reagents	Inexpensive; no risk of contamination; application does not require experience	Limited efficiency for removing particles; slow process, requires large installations for even mediocre production
	Chemical flocculation	Natural polymers: manioc, potato, arrowroot, maize Synthetic polymers	With natural polymers, inexpensive; accessible in the region; little risk of contamination	Deterioration of the polymers; generates large amounts of sludge; depending on the polymer, can attribute disagreeable taste to treated water; dosaging requires experience
	Sedimentation/ filtration	Settling Sand filters	Inexpensive; no risk of contamination; application does not require experience	Slow process, requires large installations for even mediocre production; requires periodic maintenance
Removal of contaminants	Adsorption	Activated charcoal Other adsorbents	Little risk of contamination of the produced water	Expensive; application requires experience; generates contaminated effluents
Disinfection	Chorination	Cl_2 (gaseous or liquid) Sodium hypochlorite Calcium hypochlorite Chlorine dioxide	Fast and efficient; application does not require experience	Expensive; formation of THM; possible contamination with various elements
	Ozonation	O_3	Fast and efficient	Expensive; releases O_3 into the atmosphere; attributes disagreeable taste to water; ozonator requires maintenance
	Paracetic acid application	Paracetic acid	Fast and efficient	Expensive; may promote contamination, attributes disagreeable taste to water
	Solar disinfection	Long exposure to sunlight	Inexpensive; efficient; more healthful, with no application of reagents	Slow; requires constant maintenance to avoid algae; frequent replacement of UV-exposed materials

Note: Advantages and disadvantages are based on the characteristics of the riparian communities.

differently. However, the results presented here showed a similar distribution, because suspended matter in these rivers is mainly detrital.

The first point that should be considered when designing water treatment systems for small riparian communities is a preference for low technology and low maintenance. The water characterization presented in this work indicates that treatment systems should avoid reagents that are frequently used for coagulation and flocculation, and slow settling or mechanical filtration systems should be developed. For disinfection, solar systems where UV or solar pasteurization can reduce the life span of bacteria should also be considered.

Although the proposed systems are not new, they need to be adapted to the conditions of the riparian communities of the Amazon. However, it is important to consider that any system that the community is not able to operate and maintain will deteriorate rapidly and will be useless for them in the long term. Detailed socio-cultural studies identifying the acceptability of different procedures for the treatment of water in the Amazon are essential.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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