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Influence of seasonality on the physical-chemical properties of water for human consumption by residents of floating villages in the interior of the Amazon

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ABSTRACT

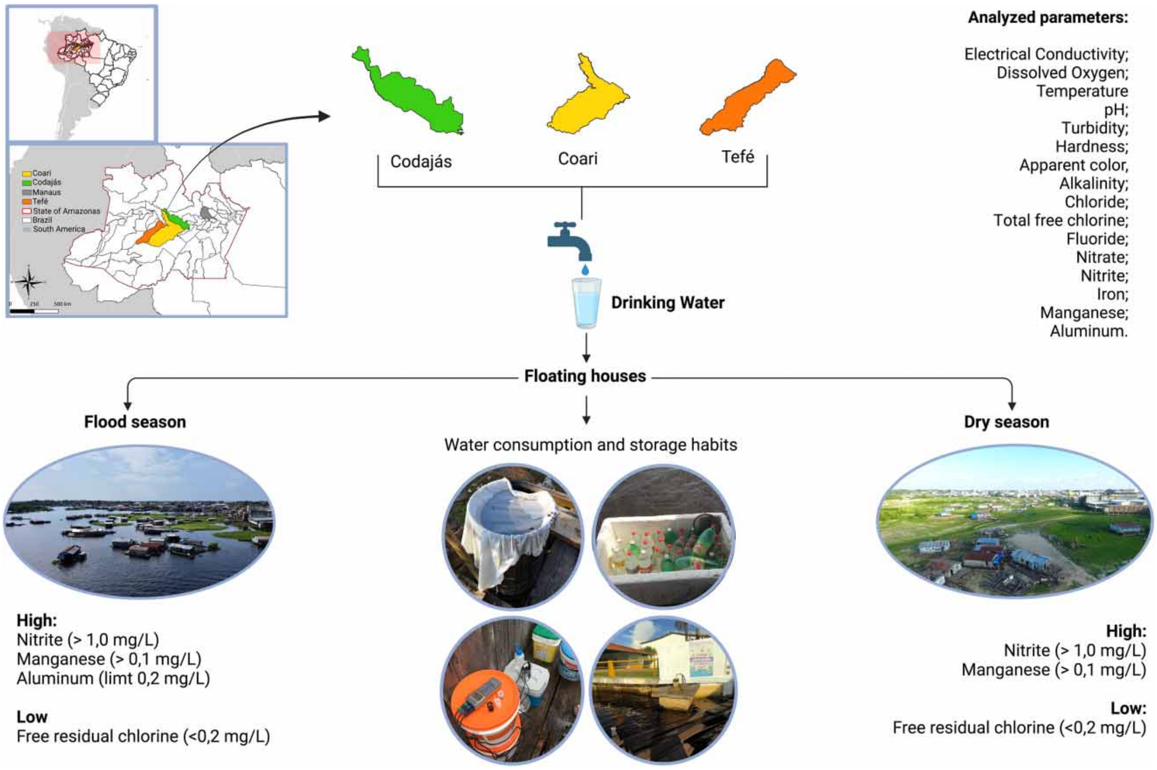
The aim of this study was to evaluate the physicochemical properties of the water consumed by residents of floating houses and the influence of the hydrological cycles of flood and drought on these parameters. The sample consisted of 44 floating domestic units per hydrological cycle, located on the edges of the cities of Codajás, Coari and Tefé. Sociodemographic data and data related to water consumption and storage habits were collected using a semi-structured questionnaire. Water samples were collected and analyzed in accordance with the Standard Methods for the Examination of Water and Wastewater. Data were analyzed in the dry and flood hydrological phases and compared to the maximum values allowed by Ordinance GM/MS No. 888/2021. The results showed that the nitrite, manganese and free residual chlorine parameters were not in accordance with the legislation. Manganese ($p = .035$) and aluminum ($p < .001$) showed significant differences between the hydrological phases. The considerable increase in aluminum content during the flood period, even though it was within the limits of the ordinance, was also highlighted. Accordingly, even with periodic control by the supply companies, it is important to monitor the water at the point of consumption of the population.

Key words: Amazonian ecosystem, drinking water, floating houses, manganese, nitrites, public health

HIGHLIGHTS

- The water source was predominantly Amazonian tube wells.
- Most residents do not pre-treat water before consumption.
- High concentrations of nitrite and manganese were identified in the drinking water.
- The contamination by Mn and Al showed a significant difference between the hydrological phases.
- Residents of floating houses do not have good drinking water consumption and storage practices.

GRAPHICAL ABSTRACT



INTRODUCTION

Access to clean water and sanitation is a fundamental condition for the survival of humanity, as well as for its economic and social development. However, even though the importance of quality water consumption is recognized, there are irregularities in the public water supply, which compromise the safe use of this resource in several Brazilian regions (Giatti 2007; Medeiros *et al.* 2016).

Global data reveal that approximately two billion people lack access to safe drinking water in their homes, and 3.6 billion do not have access to safely managed sanitation. Of these, 494 million people perform their basic hygiene needs outdoors, mainly in rural areas, where 8 out of 10 individuals do not have access to basic sanitation services (World Health Organization 2021).

As a result, 2.3 billion people are in need of basic hygiene services. Considering a total of 193 countries, in 28 of them, 1 in 4 people do not have facilities to wash their hands at home, and in rural settings, 1 in 3 people do not have access to water and soap for hand hygiene (World Health Organization 2021).

In the Amazon, the floating villages, clusters of floating houses that float on the banks of the Amazonian cities, are characterized by being similar to the houses built on land, but located on the water, which makes it possible to move to other places, offering the dynamism needed to adapt to the specific rhythm of the Amazonian rivers.

Floating houses are built and maintained with wood, which allows them to float and support the floor and other structures. In general, the interior of floating houses has up to four rooms and can have up to two floors, divided into a bedroom, living room and kitchen. The bathroom is usually built outside the floating house and there is no toilet; only a rectangular space on the floor, where residents relieve themselves directly into the river, without any treatment (Tiago 2014).

Water scarcity is a widely discussed and studied topic. However, living in an environment rich in water, where this water is not suitable for consumption, involves a particular problem.

Among the worrying factors related to the consumption of unsuitable water, several health problems related to chemical compounds found in samples of human-consumption water stand out. Currently, large amounts of chemical compounds produced and used industrially, from agriculture and urban runoff, have been accidentally or deliberately introduced into water bodies, altering their quality and making the water harmful to human health (Zini & Gutterres 2021).

Toxic chemical compounds present in water can be classified as inorganic toxins (heavy metals, fertilizers and radioactive compounds) and organic toxins (pesticides, herbicides and chemicals used in the synthesis of pharmaceuticals, paints and personal care products). When consumed, they can accumulate in different organs of the body and can cause acute or chronic toxicity (Sarkar *et al.* 2022).

The consumption of toxic chemical compounds can generate diverse bodily repercussions that affect the circulatory system (red blood cell rupture, low hemoglobin production and high blood pressure), respiratory system (lung and laryngeal cancer, nasal irritation and nasal ulcers), liver (hepatotoxicity and hepatomegaly), central nervous system (neurological disorders, cognitive impairment, neural tissue damage and psychosis), gastrointestinal system (vomiting and nausea, constipation, loss of appetite, stomatitis and gingivitis), renal system (nephrotoxicity and renal dysfunction) and skeletal system (bone cell damage and arthritis) (Sarkar *et al.* 2022).

Many factors can influence the physicochemical characteristics of water, such as geological structures, weathering, rainfall rates, river flow and anthropic factors (domestic sewage) (Aguilar Piratoba *et al.* 2017; Wasserman *et al.* 2019). In environments such as the Amazon, the hydrological cycles and climatic changes can have an impact on the water quality. Heavy rainfall and floods can cause turbidity, compromising the efficiency of water treatment, and can also mobilize and transport pathogens. This can lead to overload or damage to the infrastructure, which further compromises the efficiency of water treatment. In addition, floods can overwhelm containment systems and cause untreated wastewater to be discharged, damaging the water supply and sanitation infrastructure or forcing people to use inadequate sanitation facilities (Semenza 2020).

Risks that can affect the physicochemical properties of the water include droughts, which cause low availability of water and increase the lack of hygiene and the distance to search for alternative sources; cross connections with sewer lines; accumulation of human and animal excrement; domestic water containers as a source of vector reproduction; and risks related to a rise in temperature, which increases the replication and transmission of opportunistic pathogens (Semenza 2020).

Therefore, the aim of this study was to determine the physical-chemical indicators of water quality consumed by residents of floating houses in the interior of the Amazon during periods of drought and flooding and to compare the results obtained with the reference values of Ordinance GM/MS No. 888, of May 4, 2021.

METHODS

Study area and sampling

The study was carried out in the municipalities of Codajás, Coari and Tefé, located in the Amazon River Basin, in the middle Solimões region, in the state of Amazonas, Brazil.

The sample size was defined considering the guidelines of the National Guideline for the Sampling Plan for Environmental Health Surveillance, which pertains to the quality of water intended for human consumption. These guidelines are based on indicators established in the literature that are important for the quality control of such water, including turbidity, free residual chlorine and the presence of total coliforms/*Escherichia coli* (Brasil 2016). Accordingly, 44 households were selected (11 from Codajás; 17 from Coari and 16 samples from Tefé), which were visited on two occasions (dry and flood seasons).

Collection and analysis

The collection of data and water samples was carried out at two moments, following the hydrological cycle of the Amazonian rivers, over a period of 12 months. In the 'dry' period, the collection occurred in September and October 2021 and, in the 'flood' period, between May and June 2022. Sociodemographic information on the inhabitants, consumption habits and water storage data were collected from the residents of floating residences, using a data collection instrument. Water samples were collected following the recommendations of the 23rd edition of the Standard Methods for the Examination of Water and Wastewater (American Public Health Association *et al.* 2017):

Collection of samples from water storage containers (PET bottle, gallons or other storage containers)

The entire content of the bottle was homogenized, inverting it five times. Then, the opening, still closed, was disinfected with the aid of a 70% alcohol sprayer and paper towel. Next, the container was uncapped and the initial volume of approximately 100 mL was discarded, followed by collection in a sterile collection bag with a capacity of 532 mL (NASCO).

The electrical conductivity (EC), dissolved oxygen (DO), temperature and pH parameters were measured at the time of collection, with the aid of a portable multiparameter meter AK88/AKSO® (accuracy of pH ±0.1; conductivity ±0.1 μS/cm; DO ±0.1% and temperature ±0.5). For this, a water sample was transferred to a 500 mL Becker flask, previously washed with distilled water and with the sample itself, into which the probes were immersed. Then, the readings were allowed to stabilize and the data were recorded. All analyses were performed in triplicate.

After collection, all samples were sealed, stored and transported under refrigeration at a temperature below 6 °C to the Institute of Health and Biotechnology of the Federal University of Amazonas (ISB/UFAM), where they were processed and analyzed within 24 h.

All procedures performed to determine the water quality indicators followed the guidelines of Ordinance GM/MS No. 888, of 4 May 2021, and the most recent international norms of the Standard Methods for the Examination of Water and Wastewater (American Public Health Association *et al.* 2017).

For turbidity analysis, a Marconi turbidimeter, model MA TB100®, was used, employing the nephelometric method. For the hardness, apparent color, alkalinity, chloride, total free chlorine, fluoride, nitrate, nitrite, iron, manganese and aluminum analyses, a Hanna® multiparameter photometer, model HI83399 (resolution 0.001Abs; precision ±0.003Abs; light emitting diode; silicon photocell light detector; with 24.6 mm diameter round cuvettes) was used. Analyses were performed according to the manufacturer's guidelines for each parameter.

The results found were compared with the potability standards described in Ordinance GM/MS No. 888, of 4 May 2021. The interaction between the hydrological phase (dry and flood) and the municipality was verified by two-factor analysis of variance (ANOVA) using the linear mixed effects model and Wald's chi-square test. The significance level considered was $\alpha = .05$.

The investigation was approved by the Research Ethics Committee (REP) of the Federal University of Amazonas (UFAM) under authorization number 4.752.891 (CAAE:45655721.8.0000.5020).

RESULTS

A total of 84 samples from 44 floating houses were analyzed. During the second collection campaign, there was a loss of four (9%) sample units in relation to the first collection campaign. Residents interviewed were mostly farmers (40.9%), with incomplete primary education (56.8%), considered themselves mixed race (38.6%) or black (29.5%), and were in the age group between 39 and 59 years (50.0%). Most floating houses had a fixed location (79.5%), that is, the floating house did not change location regardless of the season, and 47.7% had between four and seven residents per household.

Most residents collected their drinking water from tubular wells (75.0% – dry; 72.7% – flood) and stored it in PET bottles (59.1% in both hydrological phases) (Table 1).

Table 1 | Water consumption and storage habits of floating houses residents

		Drought		**Flood**	
Variables		***n***	**%**	***n***	**%**
Drinking water source	Tubular wells	33	75.0	32	72.7
	Public water supply	10	22.7	8	18.2
	Rainwater	1	2.3	2	4.5
	River	0	0.0	2	4.5
Drinking water storage	PET bottles	26	59.1	26	59.1
	Buckets	14	31.8	14	31.8
	Others	4	9.1	4	9.1
Pretreatment of drinking water decantation	None	28	63.6	28	63.6
	Hypochlorite	14	31.8	14	31.8
	Filter	1	2.3	1	2.3
	Decantation	1	2.3	1	2.3
Source of water for cooking	Tubular wells	32	72.7	31	70.5
	Public water supply	10	22.7	8	18.2
	River	2	4.5	5	11.4

Coari, Amazonas, Brazil, 2022.

The EC showed a mean value of 62.25 μS/cm (min. 11.90 μS/cm–max. 165.20 μS/cm) in the dry season and 72.68 μS/cm (min. 6.53 μS/cm–max. 199.57 μS/cm) in the flood season. The pH ranged from 5.2 to 8.2 (mean = 6.69) in the dry season and from 4.9 to 8.8 (mean = 7.35) in the flood season. The temperature showed mean values of 28.28 °C in the dry season and 24.28 °C in the flood season; the maximum temperature was 38.00 °C in the dry season and the minimum 10.57 °C in the flood season. Considering DO, higher values were observed in the flood season, with a mean of 6.45 mg/L, while in the dry season, the mean was 4.93 mg/L. When comparing the results of the *in situ* analyses with the maximum permitted values (MPV) according to Ordinance GM/MS No. 888, of May 4, 2021, the mean pH and temperature values were in compliance.

Table 2 demonstrates that all parameters analyzed *in situ* showed a significant interaction effect ($p < .050$) between the hydrological phase and municipality variables, demonstrating that these parameters behave differently in each city analyzed in relation to the dry and flood hydrological phases.

Table 2 | Results of *in situ* analyses of water for human consumption distributed by municipality and hydrological phase

			***P*-value**		
Variables/(MPV)	**Drought Mean (SD)**	**Flood Mean (SD)**	**Hydrological cycle**	**City**	**Interaction**
Electrical conductivity μS/cm[a] (MPV: n/a)			0.291	0.797	< **0.001**
Coari	63.83 (27.57)	64.55 (31.89)			
Codajás	87.99 (22.76)	55.68 (32.00)			
Tefé	42.89 (25.53)	94.13 (57.34)			
pH[a] (MPV: 6.0–9.0)			< **0.001**	0.121	< **0.001**
Coari	6.52 (0.91)	7.95 (0.62)			
Codajás	6.90 (0.39)	7.07 (0.39)			
Tefé	6.73 (0.85)	6.88 (0.87)			
Temperature[a] (MPV: 35 °C)			< **0.001**	**0.033**	**0.028**
Coari	27.59 (2.34)	25.51 (3.77)			
Codajás	32.42 (4.44)	24.16 (3.47)			
Tefé	26.17 (5.04)	23.00 (7.36)			
[b]Dissolved Oxygen mg/L (MPV: n/a)			< **0.001**	< **0.001**	< **0.001**
Coari	4.69 (0.93)	7.39 (1.21)			
Codajás	4.81 (0.92)	4.47 (0.70)			
Tefé	5.27 (0.59)	6.80 (0.87)			

Coari, Amazonas, Brazil, 2022.

[a] ANOVA – linear mixed model. Type III Wald chi-square tests.

[b] ANOVA – generalized linear mixed model. Type III Wald chi-square tests. n/a, not applicable.

The parameters that represent significant values in the statistical tests are in bold.

Free residual chlorine was used as an indicator parameter for the by-products from the water disinfection processes that pose a health risk. The mean value found was 0.016 mg/L in the dry season and 0.270 mg/L in the flood season.

Regarding the inorganic chemical substances that pose a health risk, nitrite presented a mean of 1.91 mg/L (dry) and 4.73 mg/L (flood), both above the limits established by the ordinance. Fluoride showed mean values within the MPV: 0.49 mg/L in the dry season and 0.27 mg/L in the flood season. When analyzing the influence of the hydrological phases on the aforementioned parameters, it was observed that the free residual chlorine parameter did not present a significant interaction effect ($p = .144$). There were no significant differences between the means in the dry and flood periods ($p = .124$) or among the municipalities ($p = .117$). The same occurred with nitrite: there was no significant interaction effect ($p = .346$), with no difference between means in different hydrological phases ($p = .086$) or among municipalities ($p = .495$) (Table 3).

Of the organoleptic parameters investigated, the apparent color showed values above that allowed by the ordinance in the samples from Codajás, in both the dry season (17.7 mgPt-Co/L) and flood season (45.3 mgPt-Co/L). Manganese presented a mean above the MPV in all analyzed cities and in both seasons (dry: 0.45 mg/L) (flood: 0.40 mg/L).

Table 3 | Results of analyses of inorganic chemical substances and disinfection by-products that pose health risks from water samples for human consumption distributed by the municipality and hydrological phase

Variables/(MPV)	Drought Mean (SD)	Flood Mean (SD)	*P*-value[a] Hydrological cycle	City	Interaction
Free residual chlorine (MPV: 0.2–5.0 mg/L)			0.124	0.117	0.144
Coari	0.00 (0.01)	0.00 (0.00)			
Codajás	0.02 (0.05)	0.10 (0.26)			
Tefé	0.03 (0.07)	0.72 (1.81)			
Fluoride (MPV: 1.5 mg/L)			$<$ **0.001**	$<$ **0.001**	$<$ **0.001**
Coari	0.39 (0.34)	0.43 (0.36)			
Codajás	1.22 (0.76)	0.15 (0.28)			
Tefé	0.09 (0.26)	0.18 (0.26)			
Nitrate (MPV: 10 mg/L)			$<$ **0.001**	$<$ **0.001**	$<$ **0.001**
Coari	8.09 (4.99)	0.21 (0.27)			
Codajás	0.26 (0.42)	0.74 (1.03)			
Tefé	0.59 (0.96)	1.51 (1.62)			
Nitrite (MPV: 1 mg/L)			0.086	0.495	0.346
Coari	1.82 (2.18)	7.06 (14.87)			
Codajás	1.18 (2.82)	4.10 (6.30)			
Tefé	2.50 (2.22)	2.50 (2.03)			

Coari, Amazonas, Brazil, 2022.

[a] ANOVA – linear mixed model. Type III Wald chi-square tests.

The parameters that represent significant values in the statistical tests are in bold.

By analyzing the main effects independently of the others, it was possible to observe that the apparent color ($p = .008$), alkalinity ($p < .001$) and iron ($p < .001$) parameters showed significant differences between the means when comparing the municipalities. The manganese ($p = .035$) and aluminum ($p < .001$) parameters showed significant differences when comparing the hydrological phases. Turbidity presented significant differences between the means when comparing the hydrological phases ($p < .001$) and the municipalities ($p = .012$). The same occurred with chloride for the hydrological phases ($p < .001$) and municipalities ($p < .001$). The total hardness parameter showed a significant interaction effect ($p = .002$), demonstrating that the parameters behaved differently in the municipalities analyzed (Table 4).

DISCUSSION

One of the Sustainable Development Goals of the United Nations is to ensure the availability and sustainable management of water and sanitation for all (Goal 6) (Organização Pan-Americana da Saúde 2019).

However, despite the Brazilian Amazonian states holding approximately 80% of the water available in the country, this region has difficulties in providing drinking water for its population (Vasconcelos *et al.* 2016; Wasserman *et al.* 2019). This challenge in water collection is due to the distribution points (tubular wells) usually being located on the edges of cities and having limited working hours. Furthermore, the transportation to the distribution point is done by river and is dependent on factors such as climate and availability of fuel for the movement, making the practice of storing water very common among residents. Accordingly, the containers used for storage or inadequate handling and cleaning can impact water quality, causing contamination of the drinking water or changing its properties (Chalchisa *et al.* 2017).

Most floating houses have electricity and refrigerators; however, the water storage containers are stored at room temperature. This can influence variables such as the loss of function of the disinfectant agents eventually used, the development of taste or odor, an increase in pH and the accumulation of iron and manganese (Slavik *et al.* 2020).

The majority (63.9%) of the residents of the floating houses visited did not use any form of water treatment prior to consumption and, when they did, hypochlorite was the most common agent (31.8%), which is also an aspect portrayed in previous studies analyzing rural communities in the Amazon (Silva *et al.* 2014; Gama *et al.* 2018). Chlorine residue was identified in seven samples (50%), of which only three were within acceptable legal standards.

Table 4 | Results of the organoleptic parameters of drinking water samples for human consumption distributed by municipality and hydrological phase

			***P*-value**		
Variables/(MPV)	**Drought Mean (SD)**	**Flood Mean (SD)**	**Hydrological cycle**	**City**	**Interaction**
Turbidity (MPV: 5 μT)[a]			< **0.001**	**0.012**	0.386
Coari	0.68 (0.99)	1.18 (0.48)			
Codajás	2.03 (1.98)	4.04 (5.31)			
Tefé	0.53 (0.55)	1.35 (1.12)			
Hardness, total (MPV: 500 mg/L)[a]			< **0.001**	< **0.001**	**0.002**
Coari	43.71 (7.35)	29.13 (8.86)			
Codajás	57.18 (8.41)	41.80 (15.77)			
Tefé	38.44 (8.92)	35.86 (5.95)			
Apparent color (MPV: 15 mgPt-Co/L)[b]			0.611	**0.008**	0.145
Coari	4.24 (13.68)	1.31 (4.51)			
Codajás	17.73 (21.44)	45.30 (85.03)			
Tefé	4.19 (8.07)	13.64 (35.77)			
Alkalinity (mg/L)[b] (MPV: n/a)			0.991	< **0.001**	0.175
Coari	1.16 (2.63)	0.06 (0.25)			
Codajás	33.00 (10.83)	11.60 (10.46)			
Tefé	0.00 (0.00)	4.29 (5.31)			
Chloride (MPV: 250 mg/L)[a]			< **0.001**	< **0.001**	0.723
Coari	10.75 (2.75)	17.46 (2.39)			
Codajás	4.01 (2.24)	10.67 (7.12)			
Tefé	4.44 (4.17)	9.80 (7.49)			
Iron (MPV: 0.3 mg/L)[a]			0.106	< **0.001**	0.060
Coari	0.01 (0.02)	0.00 (0.00)			
Codajás	0.09 (0.12)	0.23 (0.34)			
Tefé	0.00 (0.01)	0.00 (0.00)			
Manganese (MPV: 0.1 mg/L)[a]			**0.035**	0.253	0.710
Coari	0.46 (0.08)	0.43 (0.11)			
Codajás	0.44 (0.07)	0.36 (0.22)			
Tefé	0.44 (0.07)	0.39 (0.06)			
Aluminum (MPV: 0.2 mg/L)[a]			< **0.001**	0.079	0.079
Coari	0.00 (0.00)	0.18 (0.02)			
Codajás	0.00 (0.00)	0.18 (0.02)			
Tefé	0.00 (0.00)	0.17 (0.02)			

Coari, Amazonas, Brazil, 2022.

[a] ANOVA – linear mixed model. Type III Wald chi-square tests.

[b] ANOVA – Generalized Linear Mixed Model. Type III Wald chi-square tests.

The parameters that represent significant values in the statistical tests are in bold.

Chlorine is among the most used chemical products for water treatment worldwide, not only because of its low cost but also because of its active residual effect, ensuring disinfectant action even after application in the distribution system or storage location (Vargas *et al.* 2021). After application, it reacts with various substances present in water, mainly through the oxidation of organic and inorganic matter, therefore causing a decrease in its concentration and, consequently, reducing its biocidal effect (Li 2021).

The parameters analyzed *in situ* were not influenced by the seasonality of the Amazonian rivers, presenting similar behavior in the dry and flood periods. Regarding the pH, the comparison between the two periods shows a difference of approximately half a measurement unit, being more acidic in the dry period in relation to the flood season, however, remaining very close to neutral. Similar results were found in other studies developed with water samples from tube wells (Aguilar Piratoba *et al.* 2017; Clebsch 2018; Cardoso 2019).

There was no significant difference in temperature between the hydrological phases, although slightly higher values were found in the dry period. This was expected, since this parameter varies according to the ambient temperature, as well as the way and place in which the water is stored.

EC and DO are not parameters regulated by Ordinance GM/MS No. 888/2021; however, they are useful in helping to describe the characteristics of the samples. The EC reflects the ability of water to conduct electricity and can be used to compare the amount of salts present in the water (cations and anions) (Vasconcelos *et al.* 2019).

Statistical analyses did not show associations between the EC and the hydrological phases; even so, it was possible to observe a mean increase of 10 μS/cm in the flood period. Other authors, when analyzing the EC in different periods, also found similar results, that is, a small increase in the EC in the rainy season (Alencar *et al.* 2019). In general, conductivity does not pose any health risks (Wasserman *et al.* 2019).

DO is a limiting factor for the survival of aerobic organisms, the main sources of oxygen in water are atmospheric air and the process of photosynthesis (Silva *et al.* 2020). In general, water polluted by sewage tends to have low rates, since the process of degradation of organic matter carried out by bacteria makes use of the oxygen present in the water (Simões *et al.* 2020).

Among the inorganic chemical substances that pose health risks, nitrite showed worrying results, with mean values much higher than the maximum value allowed by the ordinance in both hydrological phases. Such results are associated with the high rate of contamination of samples by bacteria.

Nitrification is a process derived from microbial metabolism, in which the free ammonia resulting from the decomposition of chloramine is oxidized into nitrite, mainly by ammonia-oxidizing bacteria and nitrite-oxidizing bacteria (Hossain *et al.* 2021, 2022). Uncontrolled nitrification can cause several problems related to water quality, such as changes in pH, increased microbial activity, formation of biofilms in storage containers, change in taste and odor of water due to the high microbial metabolic rate and more rapid decomposition of residual chlorine (Hossain *et al.* 2021).

The frequent ingestion of nitrite has the potential for serious health problems, including gastric and esophageal cancer, since, when reacting with amines, carcinogenic nitrosamines can be formed (Govindasamy *et al.* 2022; Shi *et al.* 2022).

The other inorganic chemical substances analyzed presented mean values within the MPV and the hydrological phases did not present a significant influence on these parameters.

Of the organoleptic parameters analyzed, only manganese (Mn) showed mean values higher than the MPV in both hydrological phases. The most common forms of manganese intake result from food and water consumption (Yoon *et al.* 2019). Manganese is a chemical element commonly found in the environment, with high concentrations reported in groundwater in several countries (Frisbie *et al.* 2012). Despite being an important element in human development and nutrition, excessive consumption or ingestion of high concentrations can cause various health problems, mainly because it is considered neurotoxic in high concentrations (Kullar *et al.* 2019; Palzes *et al.* 2019; Yoon *et al.* 2019).

The MPV of manganese in drinking water that is considered safe varies according to local legislation or World Health Organization (WHO) recommendations. In countries like Japan, Canada, the United States, the United Kingdom and the European Union, the maximum value considered safe is 0.05 mg/L. The WHO recommends a maximum value of 0.4 mg/L (Frisbie *et al.* 2012; Iyare 2019). In Brazil, the MPV is 0.1 mg/L (Brasil 2021). Initially, the presence of manganese in water was considered only a technical or esthetic problem. However, in recent years, several studies have associated the high consumption of this chemical element with problems in the nervous system, affecting the neurological and neurobehavioral development of children (Neal & Guilarte 2013; Kullar *et al.* 2019; Palzes *et al.* 2019; Schullehner *et al.* 2020).

Manganese is highly persistent in water and, depending on conditions can take over 200 days to degrade. Furthermore, traces of manganese are commonly found in water samples for human consumption from underground sources (Ghosh *et al.* 2020; Rahman *et al.* 2021; Chakraborty *et al.* 2022; Hu *et al.* 2022).

In general, the seasonal variation of manganese levels in drinking water has not been reported in the literature. However, it is worth mentioning that, with the increase in global temperatures, the levels of evapotranspiration and, consequently, the amount of water added to the underground reservoir by vertical percolation of rainwater are also affected. Therefore, during periods of extreme drought, there is a notable reduction in diffuse groundwater recharge. This decrease in recharge (Konapala *et al.* 2020) has implications for the Amazonian wells, which typically have a shallow depth of around 30 m. Consequently, this leads to an increase in the concentration of solutes in the water, including manganese. However, the present study observed significant changes in the concentration of manganese in the dry and flood periods of the rivers. Despite the mean values being close, the manganese content during the period of lower precipitation (dry) was higher.

Aluminum (Al), while presenting values below the MPV of the ordinance, showed a significant increase in the flood period. No traces of aluminum were identified in the water samples during the dry period; in the period of greatest precipitation (flood), the mean value approached the maximum allowed, with some samples having values equal to the maximum recommended limit.

Like manganese, aluminum is a very common metal in the environment and one of the most abundant in the Earth's crust. Its consumption in excess or high concentrations can also cause adverse impacts on the nervous system, which may be associated with kidney problems, Parkinson's disease and Alzheimer's disease (Meyer *et al.* 2017; Maurice *et al.* 2019; Russ *et al.* 2020). Factors such as the geological nature of the soil, precipitation levels, depth and/or construction problems in tube wells and human activities can influence the levels of aluminum in the water. It is common in the Amazon region for sewage to be discharged directly or indirectly into surface or underground water sources through sewage galleries, rudimentary septic tanks or ditches during the river flood period. During floods, especially extreme ones, these sewage systems flood, contaminating surface waters with diluted urban effluents and human waste, contaminating groundwater and increasing metal levels in groundwater sources, including aluminum (Meyer *et al.* 2017; Costa *et al.* 2022).

Furthermore, with recent climate changes, the number of extreme events, including floods and droughts, is likely to increase. This can directly impact the global water balance, especially concerning drinking water, considering the close relationship between surface water and groundwater.

CONCLUSION

Despite the high levels of manganese in the water and the considerable increase in the aluminum content in the flood period of the rivers, the water distribution points for the population of interest were not evaluated, particularly the tubular wells located on the edges of the cities, the main source of water supply for residents of floating houses. Therefore, new analyses, including the general supply points of the municipalities, must be considered, in addition to the comparison of the water stored in the residences.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Aguilar Piratoba, A. R., Campos Ribeiro, H. M., Morales, G. P. & e Gonçalves, W. G. 2017 Caracterização de parâmetros de qualidade da água na área portuária de Barcarena, PA, Brasil. *Ambiente e Agua – An Interdisciplinary Journal of Applied Science* **12**(3), 435. doi: 10.4136/ambi-agua.1910.

Alencar, V. E. S. A., Rocha, E. J. P. d., Júnior, J. A. d. S. & Carneiro, B. S. 2019 Análise de Parâmetros de Qualidade da Água em Decorrência de Efeitos da Precipitação na Baia de Guajará – Belém – PA. *Revista Brasileira de Geografia Física* **12**(2), 661–680. doi:10.26848/rbgf.v12.2.p661-680.

American Public Health Association, American Water Works Association, and Water Environment Federation. 2017. *Standard Methods for Examination of Water and Wastewater*. 23nd edn. Washington, DC: Rodger B. Baird; Andrew D. Eaton; Eugene W. Rice.

Brasil 2016 Diretriz Nacional do Plano de Amostragem da Vigilância da Qualidade da Água para Consumo Humano. Ministério da Saúde, Secretaria de Vigilância em Saúde, Departamento de Vigilância em e Saúde Ambiental e Saúde do Trabalhador orgs. Available from: https://bvsms.saude.gov.br/bvs/publicacoes/diretriz_nacional_plano_amostragem_agua.pdf.

Brasil 2021 *Portaria GM/MS N^o 888, de 4 de maio de* 2021. Brasília. Available from: https://www.in.gov.br/en/web/dou/-/portaria-gm/ms-n-888-de-4-de-maio-de-2021-318461562 (Acesso em: 16 novembro 2022).

Cardoso, J. M. 2019 *AVALIAÇÃO DA QUALIDADE DA ÁGUA SUBTERRÂNEA DE POÇOS TUBULARES OUTORGADOS NO MUNICÍPIO DE CAMPO GRANDE MS*. Dissertação, Campo Grande – MS: UNIVERSIDADE ESTADUAL PAULISTA 'JÚLIO DE MESQUITA FILHO'.

Chakraborty, T. K., Ghosh, G.C., Ghosh, P., Jahan, I., Zaman, S., Islam, S., Hossain, R., Habib, A., Biswas, B., Sultana, N. & Khan, A. S. 2022 Arsenic, iron, and manganese in groundwater and its associated human health risk assessment in the rural area of Jashore, Bangladesh. *Journal of Water and Health* **20**(6), 888–902. doi:10.2166/wh.2022.284.

Chalchisa, D., Megersa, M. & Beyene, A. 2017 Assessment of the quality of drinking water in storage tanks and its implication on the safety of urban water supply in developing countries. *Environmental Systems Research* **6**(1), 12. doi: 10.1186/s40068-017-0089-2.

Clebsch, C. A. S. 2018 *CARACTERIZAÇÃO HIDROGEOQUÍMICA E QUALIDADE DA ÁGUA DE POÇOS TUBULARES EM ALDEIAS INDÍGENAS NA REGIÃO DA AMAZÔNIA CENTRAL*. Dissertação, Manaus, Amazonas, Brasil: UNIVERSIDADE FEDERAL DO AMAZONAS.

Costa, F. R. C., Schietti, J., Stark, S. C. & Smith, M. N. 2022 The other side of tropical forest drought: Do shallow water table regions of Amazonia act as large-scale hydrological refugia from drought? *New Phytologist* n/a(n/a). Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/nph.17914 (Acesso em: 25 outubro 2022).

Frisbie, S. H., Mitchell, E. J., Dustin, H., Maynard, D. M. & Sarkar, B. 2012 World Health Organization discontinues its drinking-water guideline for manganese. *Environmental Health Perspectives* **120**(6), 775–778. doi: 10.1289/ehp.1104693.

Gama, A. S. M., Fernandes, T. G., Parente, R. C. P. & Secoli, S. R. 2018 Inquérito de saúde em comunidades ribeirinhas do Amazonas, Brasil. *Cadernos de Saúde Pública* 34. Available from: http://www.scielo.br/j/csp/a/nWyTKM4WRV5Gxr4pSVT4Mnp/?lang=pt (Acesso em: 17 outubro 2022).

Ghosh, G. C., Khan, M. J. H., Chakraborty, T. K., Zaman, S., Kabir, A. H. M. E. & Tanaka, H. 2020 Human health risk assessment of elevated and variable iron and manganese intake with arsenic-safe groundwater in Jashore, Bangladesh. *Scientific Reports* **10**(1), 5206. doi: 10.1038/s41598-020-62187-5.

Giatti, L. L. 2007 Reflexões sobre água de abastecimento e saúde pública: Um estudo de caso na *Amazônia brasileira*. *Saúde e Sociedade* **16**(1), 134–144. doi: 10.1590/s0104-12902007000100012.

Govindasamy, M., Wang, S.-F., Huang, C.-H., Alshgari, R. A. & Ouladsmane, M. 2022 Colloidal synthesis of perovskite-type lanthanum aluminate incorporated graphene oxide composites: Electrochemical detection of nitrite in meat extract and drinking water. *Microchimica Acta* **189**(5), 210. doi: 10.1007/s00604-022-05296-4.

Hossain, S., Cook, D., Chow, C. W. K. & Hewa, G. A. 2021 Development of an optical method to monitor nitrification in drinking water. *Sensors (Basel, Switzerland)* **21**(22), 7525. doi: 10.3390/s21227525.

Hossain, S., Chow, C. W. K., Cook, D., Sawade, E. & Hewa, G. A. 2022 Review of nitrification monitoring and control strategies in drinking water system. *International Journal of Environmental Research and Public Health* **19**(7), 4003. doi: 10.3390/ijerph19074003.

Hu, M., Zhou, P. & Chen, C. 2022 Spatial and temporal distribution and affecting factors of iron and manganese in the groundwater in the middle area of the Yangtze River Basin, China. *Environmental Science and Pollution Research* **29**(40), 61204–61221. doi: 10.1007/s11356-022-20253-7.

Iyare, P. U. 2019 The effects of manganese exposure from drinking water on school-age children: A systematic review. *NeuroToxicology* **73**, 1–7. doi: 10.1016/j.neuro.2019.02.013.

Konapala, G., Mishra, A. K., Wada, Y. & Mann, M. E. 2020 Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nature Communications* **11**, 3044. https://doi.org/10.1038/s41467-020-16757-w.

Kullar, S. S., Shao, K., Surette, C., Foucher, D., Mergler, D., Cormier, P., Bellinger, D. C., Barbeau, B., Sauvé, S. & Bouchard, M. F. 2019 A benchmark concentration analysis for manganese in drinking water and IQ deficits in children. *Environment International* **130**, 104889. doi: 10.1016/j.envint.2019.05.083.

Li, P. 2021 Concise review on residual chlorine measurement: Interferences and possible solutions. *Journal of Cleaner Production* **323**, 129119. doi: 10.1016/j.jclepro.2021.129119.

Maurice, L., López, F., Becerra, S., Jamhoury, H., Le Menach, K., Dévier, M. H., Budzinski, H., Prunier, J., Juteau-Martineau, G., Ochoa-Herrera, V., Quiroga, D. & Schreck, E. 2019 Drinking water quality in areas impacted by oil activities in Ecuador: Associated health risks and social perception of human exposure. *Science of the Total Environment* **690**, 1203–1217. doi: 10.1016/j.scitotenv.2019.07.089.

Medeiros, A. C., Lima, M. d. O. & Guimarães, R. M. 2016 Assessment of the quality of water for consumption by river-bank communities in areas exposed to urban and industrial pollutants in the municipalities of Abaetetuba and Barcarena in the state of Pará, Brazil. *Ciencia e Saude Coletiva* **21**(3), 695–708. doi:10.1590/1413-81232015213.26572015.

Meyer, C. M. C., Rodríguez, J. M., Carpio, E. A., García, P. A., Stengel, C. & Berg, M. 2017 Arsenic, manganese and aluminum contamination in groundwater resources of Western Amazonia (Peru). *Science of the Total Environment* **607–608**, 1437–1450. doi: 10.1016/j.scitotenv.2017.07.059.

Neal, A. P. & Guilarte, T. R. 2013 Mechanisms of lead and manganese neurotoxicity. *Toxicology Research* **2**(2), 99–114. doi: 10.1039/C2TX20064C.

Organização Pan-Americana da Saúde 2019 Agenda 2030 para abastecimento de água, esgotamento sanitário e higiene na América Latina e Caribe: Um olhar a partir dos direitos humanos. 31 dezembro. Available from: https://iris.paho.org/handle/10665.2/51837.

Palzes, V. A., Sagiv, S. K., Baker, J. M., Rojas-Valverde, D., Gutiérrez-Vargas, R., Winkler, M. S., Fuhrimann, S., Staudacher, P., Menezes-Filho, J. A., Reiss, A. L., Eskenazi, B. & Mora, A. M. 2019 Manganese exposure and working memory-related brain activity in smallholder farmworkers in Costa Rica: Results from a pilot study. *Environmental Research* **173**, 539–548. https://doi.org/10.1016/j.envres.2019.04.006.

Rahman, M., Tushar, M. A. N., Zahid, A., Mustafa, M. G., Siddique, M. A. M. & Ahmed, K. M. 2021 Spatial distribution of manganese in groundwater and associated human health risk in the southern part of the Bengal Basin. *Environmental Science and Pollution Research* **28**(30), 41061–41070. doi: 10.1007/s11356-021-13577-3.

Russ, T. C., Killin, L. O. J., Hannah, J., Batty, G. D., Deary, I. J. & Starr, J. M. 2020 Aluminium and fluoride in drinking water in relation to later dementia risk. *The British Journal of Psychiatry* **216**(1), 29–34. doi: 10.1192/bjp.2018.287.

Sarkar, S., Gill, S. S., Das Gupta, G. & Kumar Verma, S. 2022 Water toxicants: A comprehension on their health concerns, detection, and remediation. *Environmental Science and Pollution Research* **29**(36), 53934–53953. doi: 10.1007/s11356-022-20384-x.

Schullehner, J., Thygesen, M., Kristiansen, S. M., Hansen, B., Pedersen, C. B. & Dalsgaard, S. 2020 Exposure to manganese in drinking water during childhood and association with attention-deficit hyperactivity disorder: A nationwide cohort study. *Environmental Health Perspectives* **128**(9), 097004. doi:10.1289/EHP6391.

Semenza, J. C. 2020 Cascading risks of waterborne diseases from climate change. *Nature Immunology* **21**(5), 484–487. doi: 10.1038/s41590-020-0631-7.

Shi, H., Fu, L., Chen, F., Zhao, S. & Lai, G. 2022 Preparation of highly sensitive electrochemical sensor for detection of nitrite in drinking water samples. *Environmental Research* **209**, 112747. doi: 10.1016/j.envres.2022.112747.

Silva, A. M. B. da, Bouth, R. C., Costa, K. S. da, Carvalho, D. C. de, Hirai, K. E., Prado, R. R., Araújo, S. G. de, Pereira, A. C. de L. & Ribeiro, K. T. S. 2014 Ocorrência de enteroparasitoses em comunidades ribeirinhas do Município de Igarapé Miri, Estado do Pará, Brasil. *Revista Pan-Amazônica de Saúde* **5**, 7–7. https://doi.org/10.5123/S2176-62232014000400006.

Silva, J. P., Mesquita, K. F. C., Pereira, J. A. R., Sousa, R. R. de, Varela, A. W. P., Sousa, P. H. C., Santos, R. M. & Santos, M. de L. S. 2020 Índices de qualidade da água no sistema de captação de água da região amazônica (Brasil). *Scientia Plena* **15**, 1–10. https://doi.org/10.14808/sci.plena.2019.124301.

Simões, M. C., Morales, G. P., Sarmento, P. S. D. M., Ferreira, I. P., Domingues, R. J. & Bichara, C. N. C. 2020 Avaliação da qualidade da água de poços domésticos em comunidades rurais no Arquipélago de Marajó-PA. *Revista Brasileira de Geografia Física* **13**(5), 2462. doi: 10.26848/rbgf.v13.5.p2462-2475.

Slavik, I., Oliveira, K. R., Cheung, P. B. & Uhl, W. 2020 Water quality aspects related to domestic drinking water storage tanks and consideration in current standards and guidelines throughout the world – a review. *Journal of Water and Health* **18**(4), 439–463. doi: 10.2166/wh.2020.052.

Tiago, E. R. 2014 *Ambiente Flutuante: Os Significados e Identidade de Lugar de Moradores de Casas Flutuantes*. Dissertação, Manaus, Amazonas, Brasil: Universidade Federal Do Amazonas.

Vargas, T. F., Baía, C. C., Machado, T. L. d. S., Dórea, C. C. & Bastos, W. R. 2021 Decay of free residual chlorine in wells water of Northern Brazil. *Water* **13**(7), 992. doi: 10.3390/w13070992.

Vasconcelos, C. H., Andrade, R. C. de, Bonfim, C. V., Resende, R. M. de S., Queiroz, F. B. de, Daniel, M. H. B., Grigoletto, J. C., Cabral, A. R., Redivo, A. L., Lacerda, J. C. V. & Rohlfs, D. B. 2016 Surveillance of the drinking water quality din the Legal Amazon: analysis of vulnerable areas. *Cadernos Saúde Coletiva* **24**, 14–20. https://doi.org/10.1590/1414-462x201500040142.

Wasserman, J. C., Damaceno, V. M., Lima, G. B. A. & Wasserman, M. A. 2019 Spatial distribution of water quality in the Amazonian region: Implications for drinking water treatment procedures. *Journal of Water and Health* **17**(5), 749–761. doi: 10.2166/wh.2019.005.

World Health Organization 2021 *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2020: Five Years Into the SDGs*.

Yoon, M., Ring, C., Van Landingham, C. B., Suh, M., Song, G., Antonijevic, T., Gentry, P. R., Taylor, M. D., Keene, A. M., Andersen, M. E. & Clewell, H. J. 2019 Assessing children's exposure to manganese in drinking water using a PBPK model. *Toxicology and Applied Pharmacology* **380**, 114695. https://doi.org/10.1016/j.taap.2019.114695.

Zini, L. B. & Gutterres, M. 2021 Chemical contaminants in Brazilian drinking water: A systematic review. *Journal of Water and Health* **19**(3), 351–369. doi: 10.2166/wh.2021.264.

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