ACTA
AMAZONICA

http://dx.doi.org/10.1590/1809-4392202401583

HEALTH SCIENCES | ORIGINAL ARTICLE

Microbiological and antimicrobial evaluation of drinking water in floating houses of the Brazilian Amazon

Michel Nasser Corrêa Lima CHAMY[1*], Silvia Regina SECOLI[2], Fernando Mauro Pereira SOARES[3], Vanessa de Brito POVEDA[2]

[1] Universidade Federal do Amazonas, Instituto de Saúde e Biotecnologia, Estrada Coari-Mamiá 305, 69460-000, Coari, Amazonas, Brazil

[2] Escola de Enfermagem da Universidade de São Paulo, Av. Dr. Enéas Carvalho de Aguiar 419, 05403-000, São Paulo, Brazil

[3] Universidade Federal do Sul da Bahia, Instituto de Humanidades, Artes e Ciências, Campus Jorge Amado. Praça José Bastos, s/n, 45600-923, Itabuna, Brazil

*Corresponding author: clchamy@ufam.edu.br

ABSTRACT

Limited access to safe water and basic sanitation contributes to morbidity and mortality caused by waterborne diseases, and reinforces social inequalities. The aim of this study was to evaluate the microbiological quality of water consumed by residents of floating houses and the antimicrobial susceptibility profile of the isolates in the low and increasing flow regime in the Amazon River basin. The samples consisted of drinking water from floating domestic units located on the edges of cities in the Amazon region, Amazonas state, Brazil. Sampling occurred during the low (LWL) and raising river-water level (RWL) periods. Water samples were analyzed using the filtering membrane method. The antimicrobial susceptibility test was performed using the disk-diffusion method. The source of water for consumption was predominantly tubular/artesian wells (75.0% LWL; 72.7% RWL); the main storage form was in PET (polyethylene terephthalate) bottles or buckets (90.9%) and the majority of the residents (63.6%) did not treat the water before consumption. Most water samples were contaminated with *Escherichia coli* during both the LWL (86.3%) and RWL periods (82.5%). *Enterococcus* spp., *Vibrio* spp. and *Salmonella* spp. were identified in association with water contamination by *E. coli*. *Salmonella* spp. exhibited the highest resistance rate among the bacteria subjected to antimicrobial susceptibility testing, especially during the LWL period; 100% showed resistance to ampicillin and cefazolin, 68% were resistant to tobramycin and 64% to gentamicin. Therefore, raising public awareness about the consumption of safe water, through dissemination of proper water storage and disinfection procedures could help minimize contamination and reduce waterborne diseases.

KEYWORDS: water quality; antibiotic resistance; *Escherichia coli*; fecal pollution; public health

Avaliação microbiológica e antimicrobiana da água de consumo humano de casas flutuantes na Amazônia brasileira

RESUMO

O acesso limitado à água potável e ao saneamento básico contribui para a morbilidade e mortalidade causadas por doenças transmitidas pela água e reforça as desigualdades sociais. O objetivo do trabalho foi avaliar a qualidade microbiológica da água consumida por moradores de casas flutuantes e determinar o perfil de susceptibilidade antimicrobiana das bactérias isoladas durante os períodos de seca e cheia na Bacia Amazônica. As amostras consistiram de água de consumo humano de unidades domésticas flutuantes localizadas nas orlas de cidades da região amazônica, Amazonas, Brasil. As coletas ocorreram nos períodos de seca e cheia dos rios. As amostras de água foram analisadas pelo método de membrana filtrante. Os testes de susceptibilidade aos antimicrobianos foram realizados pelo método disco-difusão. A principal fonte de abastecimento de água para consumo foi de poços tubulares/artesianos (75,0% período seca; 72,0% período cheia); a forma de armazenamento predominante foi em garrafas PET (polietileno tereftalato) ou baldes (90,9%) e a maioria dos residentes (63,6%) não tratava a água antes do consumo. A maioria das amostras estava contaminada com Escherichia coli no período de seca (86,3%) e de cheia (82,5%). *Enterococcus* spp., *Vibrio* spp. e *Salmonella* spp. foram associadas a contaminação de *E. coli*. *Salmonella* spp. apresentou as taxas mais altas de resistência aos antimicrobianos testados, principalmente no período de seca; 100% apresentaram resistência a ampicilina e cefazolina, 68% foram resistentes a tobramicina e 64% a gentamicina. Portanto, a sensibilização da população quanto ao consumo de água segura e de qualidade por meio da divulgação de procedimentos adequados para armazenamento e tratamento da água poderiam ajudar a mitigar a contaminação e, consequentemente, as taxas de doenças transmitidas pela água.

KEYWORDS: qualidade da água; resistência a antibióticos; *Escherichia coli*; poluição fecal; saúde pública

CITE AS: Chamy, M.N.C.L.; Secoli, S.R.; Soares, F.M.P.; Poveda, V.B. 2024. Microbiological and antimicrobial evaluation of drinking water in floating houses of the Brazilian Amazon. *Acta Amazonica* 55: e55hs24158.

INTRODUCTION

Access to clean water and sanitation is fundamental for survival and economic-social development. Approximately two billion people do not have access to safe drinking water at home, and 3.6 billion do not have access to safely managed sanitation. From these, 494 million carry out their basic needs outdoors, mainly in rural areas, where eight out of ten people remain without basic sanitation services (WHO 2021). As a result, 2.3 billion people need basic hygiene services. Moreover, 28% of the population in 193 countries do not have facilities for washing their hands at home, and one in three people in rural environments do not have access to soap and water for hygiene (WHO 2021).

The impacts caused by limited access to safe water and basic sanitation are not restricted to morbidity and mortality caused by waterborne diseases, but also reinforce social inequalities. A lack of adequate facilities in schools directly affects girls entering puberty, as observed in West Africa, where up to 25% of girls miss school due to menstruation (WHO 2020). In addition, it is common for women and girls to be responsible for collecting water for the family's needs, which increases the difficulty for girls to reconcile school hours with the water collection period (WHO 2017*a*).

The World Health Organization (WHO) suggests that universal access to clean water, sanitation, and adequate hygiene can reduce the global disease burden by up to 10%. For this reason, one of the Sustainable Development Goals (SDGs) of the United Nations (UN) regarding the water supply for Latin America and the Caribbean in the Agenda 2030 is to "ensure the availability and sustainable management of water and sanitation for all" (WHO 2012, OPAS/OMS 2019). Accordingly, it is essential to consider the particularities of the Amazon region, mainly because the rivers have multiple uses, such as the primary source of public water supply, domestic sewage drainage, navigation, fishing, and recreation (Fabré *et al.* 2017, Sousa and Cunha 2013, Queiroz *et al.* 2018). Additionally, the Amazonian environment is diverse, comprising forests and urban areas, crossed by rivers and streams. This environment, combined with the riverine population lifestyles, gives origin to clusters of floating houses on rivers and lakes, called floating communities or villages (Queiroz 2022).

Climatic events greatly impact the living conditions of this population residing on the rivers of the Amazon region, as extreme expressions can cause disruptions in the relationship established between communities and the environment (Sousa and Cunha 2013). Among them, floods and droughts stand out as the phenomena which most affect the region's socioeconomic system, and the extent of this impact mainly depends on the intensity and duration of these events (Langill and Abizaid 2020). These climatic events deserve to be highlighted due to the large number of people affected, especially in the Amazon region. For example, floods are risk factors for population illness and have an impact on increased mortality and morbidity from diseases transmitted by water contamination, particularly due to "fecal-oral" pathogens (Vieira *et al.* 2017). There is little evidence in the literature associating low river-water levels with water-related diseases. However, diarrheal diseases may be associated to low flow periods because of the increase in the fecal contamination concentration in the remaining water sources; the accumulation of fecal film on surfaces, which may cause peaks of pathogen transmission during torrential rains; increased number of flies; limited access to drinking water; and hygiene problems (Levy *et al.* 2018). Epidemics in the Amazon caused by these diseases are directly associated with weather events, often after long periods of rain or flooding of rivers, and especially in places where the population does not have access to basic sanitation services and drinking water (Peranovich 2019).

Another aggravating factor is sewage treatment, since according to the Brazilian National Water and Sanitation Agency (ANA), only 16% of the population in the North Region of Brazil has sewage collection and only 12% of this sewage is treated. The remainder is dumped into rivers, lakes and creeks close to housing areas (ANA 2020). As a result, the spread of waterborne diseases, mainly in the Amazon, may be related to three main factors: an increase in the pathogen load in the water as a result of continuous weather events; disorderly occupation of the river banks by floating dwellings; and sewage discharge, without treatment, into water bodies. The sum of these factors can directly affect the water quality for consumption and other activities, such as fishing and bathing practices (Fabré *et al.* 2017, Vieira *et al.* 2017). Therefore, added to the living conditions of floating populations and the deficiency in basic sanitation, the Amazonian environment probably increases the adverse effects caused by consuming poor quality water, meaning water which does not meet the potability parameters defined by regulatory bodies.

A total of 705 waterborne disease outbreaks were recorded between 2007 and 2021, resulting in 189,032 people affected in Brazil. Of these outbreaks, 17 occurred in the Northern Region and six in the Amazon, with coliform bacteria, including *Escherichia coli*, as the main etiological agents. Despite the non-alarming numbers compared to other regions of the country, these diseases may be underreported due to the generic symptoms and the long incubation period of the pathogens. The affected individuals in these cases do not associate the signs and symptoms with the consumption of contaminated water (Brasil 2021*a*).

In addition to the aforementioned problems related to contaminated water, the emergence of microorganisms which are resistant to antimicrobials identified in water samples has been considered a threat to the health of consumers

(Siedlecka *et al.* 2021). It is possible that anthropic activities not only affect the microbial load in aquatic environments, but also the composition of these colonies. Agents which cause bacterial stress (mainly from hospital, veterinary, agricultural and industrial activities) discharged into aquatic environments (mainly through untreated sanitary sewage), can exert positive pressure on the emergence of resistant bacteria (Sánchez-Baena *et al.* 2021). According to the United Nations Environment Program (UNEP), 4.5 million people died from complications associated with infections with antimicrobial-resistant microorganisms in 2019; of these, 1.27 million had antimicrobial-resistant infections as the leading cause of death. This number is estimated to reach 10 million deaths per year by 2050. In addition to the public health problem, microorganisms resistant to antimicrobials could cause estimated losses in the Gross Domestic Product (GDP) of R$3.4 trillion per year by 2030, possibly reaching up to 3.8% of GDP per year by 2050 (UNEP 2022).

Given the importance of water-borne diseases and the limited information associated to the specific situation of drinking-water supply to floating-house inhabitants, the aim of this study was to evaluate the microbiological quality of the water consumed by residents of floating houses and the antimicrobial susceptibility profile of the isolates, during the low and increasing water level periods of the Amazon Rivers, and the influence of this regime on the water contamination rates by microorganisms in three municipalities of the state of Amazonas.

MATERIAL AND METHODS

Study area

This study was conducted on floating houses in the municipalities of Codajás, Coari and Tefé, located in the Amazon River Basin, in the State of Amazonas, Brazil (Figure 1). The municipality of Coari is located in the Middle Solimões River region, 362 km in a straight line from the state capital, between Lago do Mamiá and Lago de Coari, 40 m above sea level. It has a territorial area of 57,970.768 km², with the Solimões River flowing through it from west to east, and borders the municipalities of Codajás, Tapauá, Anori, Tefé and Maraã (IBGE 2012). The municipality of Codajás is located in the Middle Solimões River region, on the right bank of the Solimões River, on flat terrain with little elevation, 240 km in a straight line from the state capital. It has a territorial area of 18,700.713 km² and borders the municipalities of Coari, Caapiranga, Maraã, Beruri and Anori (IBGE 2012). The municipality of Tefé is located in the Middle Solimões River region, 522 km in a straight line from the state capital, on the right bank of Lake Tefé. It has a territorial area of 23,692.233 km² and borders the municipalities of Maraã, Alvarães, Tapauá, Carauari and Coari (IBGE 2012).

The municipalities have a total of 304 registered tubular wells, 39 in Codajás, 151 in Coari and 114 in Tefé. They constitute important sources of drinking water supply, mainly in Coari and in the rural areas of Codajás and Tefé (CPRM 2022) (Table 1).

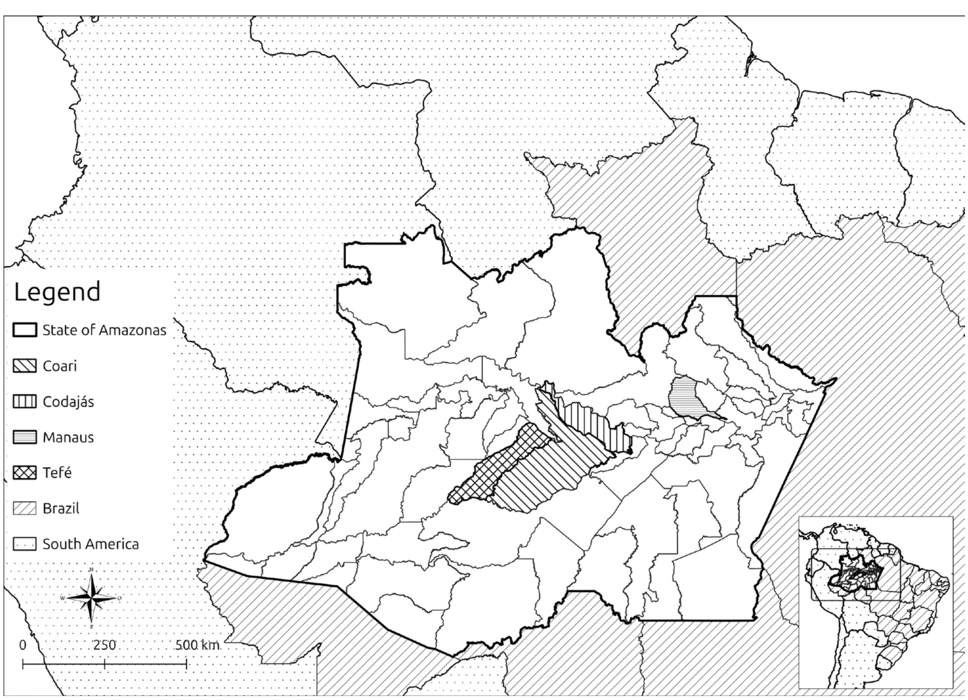

Figure 1. Geographical distribution of sampling municipalities in the state of Amazonas, Brazil.

Table 1. Percentage of the types of sewage collection and water supply for the population of Coari, Codajás and Tefé. Coari, Amazonas, Brazil, 2022 (IBGE 2012).

Cities/Characteristics	Coari		Codajás		Tefé	
	Urban	Rural	Urban	Rural	Urban	Rural
Sewage						
General sewage/ rainfall galleries	53	3	35	1	18	4
Discharge into rivers/lakes	25	39	16	72	20	32
Rudimentary sewer	11	36	22	7	24	38
Ditch	6	14	23	1	15	9
Septic tank	5	6	2	0	20	6
Others	1	1	2	20	2	11
Water supply						
Municipal Water Supply System	40	2	83	1	86	29
Other forms of supply	53	95	15	88	9	68
Groundwater/Artesian or Tubular Wells or spring	7	3	2	11	5	3
Rain water	0	1	0	0	0	1

The water level of Amazonian large rivers fluctuates along the year with roughly four phases: a raising water period, a high-water period when rivers flood the adjacent lands, an ebb season with decreasing water levels, and a low water period (Bittencourt and Amadio 2007, Franca and Mendonça 2015). The raising water period in the Middle Solimões River region lasts approximately eight months, starting in December and reaching its peak in July, while the ebb season lasts around four months, beginning at the end of July and reaching its low peak in November (ANA 2022).

Sampling and data collection

Sampling consisted of collecting drinking water samples at the final consumption point in the studied households, in two periods (low - LWL and raising river water level - RWL periods), with the sample size calculation following the National Guideline for the Sampling Plan for Environmental Health Surveillance related to the quality of water for human consumption and considering the population of the municipalities (Brasil 2016). The floating houses located on the edges of the municipalities were mapped and selected by simple random sampling.

The data collection followed the water fluctuation cycle of each studied river, taking place in Tefé during September 2021 (LWL) and May 2022 (RWL), and in Coari and Codajás during October 2021 (LWL) and June 2022 (RWL). A questionnaire was used to obtain information on residents' water consumption and storage habits. The water samples were collected according to the recommendations of Standard Methods for the Examination of Water and Wastewater for the collection of water samples for human consumption (Baird *et al.* 2017).

After collection, all samples were sealed, stored and transported under refrigeration (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 hours.

Microbiological and data analysis

Microbiological analyses included the filtration method and antimicrobial susceptibility test. For the membrane filtration method, 100 mL of the sample was subjected to vacuum filtration in a complete stainless steel Manifold filtration set using a sterile white checkered cellulose nitrate membrane filter with 0.45μm and 47mm diameter pore (Merck Millipore®), and then transferred to plates with specific culture mediums (Silva *et al.* 2017). All tests were performed in triplicate to ensure the accuracy of results.

Chromogenic Coliforms Agar (MERCK®) medium was used for *E. coli* analyses. Samples not meeting the potability standard required by Brazilian legislation – i.e. absence of coliforms in 100 mL (Portaria GM/MS No. 888, of May 4, 2021 in Brasil 2021*b*), were submitted to microbiological analyses for *Enterococcus* spp. (M-Enterococcus Agar base – HIMEDIA®); plates which showed pink, dark red, or brown colonies after incubation (36±2°C for 24-48 hours) were considered positive. Green to blue-green colonies were considered positive for *Pseudomonas* spp. (Cetrimide Agar Base – KASVI®), while yellow or green colonies were considered positive for pathogenic Form *Vibrio* spp. (TCBS Agar – Thiosulfate-citrate-bile-sucrose – ACUMEDIA®) and the presence of magenta colonies were considered positive for *Salmonella* spp. (Salmonella Chromogenic Agar – KASVI®). The control was performed with standard strains from the National Institute for Quality Control in Health (INCQS) of the Oswaldo Cruz Foundation (Fiocruz, Rio de Janeiro): *Escherichia coli* – INCQS: 00185; *Vibrio cholerae* – INCQS: 00279; *Pseudomonas aeruginosa* – INCQS: 00386 and from the Oswaldo Cruz Foundation - Leônidas and Maria Deane Biological Collection Institute (Fiocruz, Amazonas): *Salmonella enterica* – accession number: 0209; *Enterococcus faecalis* - accession number: 0281.

Isolated *Vibrio* spp., *Enterococcus* spp. and *Salmonella* spp. strains were submitted to the antimicrobial susceptibility test using the disk-diffusion method (Kirby-Bauer), following the guidelines of the Clinical & Laboratory Standards Institute 30th Edition – M100 Performance Standards for Antimicrobial Susceptibility Testing (CLSI 2020) and Clinical & Laboratory Standards Institute 3rd Edition – M45 Methods for Antimicrobial Dilution and Disk Susceptibility Testing of Infrequently Isolated or Fastidious Bacteria (CLSI 2015).

The antimicrobials tested for each bacterial strain and concentrations were: *Enterococcus* spp. (Ampicillin 10μg; Penicillin 10μg); *Vibrio* spp. (Ampicillin 10μg, Tetracycline 30μg, Trimethoprim-sulfamethoxazole 25μg, Chloramphenicol 30μg); and *Salmonella* spp. (Ampicillin 10μg, Cefazolin 30μg, Gentamicin 10µg, Tobramycin 10µg). Antimicrobials were selected from: Group A – Ampicillin, Penicillin, Cefazolin, Gentamicin, Tobramycin (appropriate for inclusion in routine primary tests); Group B – Tetracycline, Trimethoprim-sulfamethoxazole (used for cases of unresponsiveness to an agent in Group A; or as an epidemiological tool for infection control); and Group C – Chloramphenicol (alternative or complementary antimicrobial agents that should be tested in sites affected by endemic or epidemic strains resistant to several primary drugs).

A Linear Mixed Model (LMM) was used to model the behavior of the numerical variables of interest by evaluating the same subjects in two periods (LWL and RWL) and comparing three cities (Coari, Codajás, and Tefé). Fixed effects for period and the city were entered in the model including their interaction plus random intercepts for the subjects. Type III sum-of-squares ANOVA tables were computed for each model. Analyses were run on statistical package R version 4.4.1 and significance level was set at 5%.

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

Table 2. Microbiological analyses of the water for human consumption according to river water-level period and municipality, across Coari, Codajás, and Tefé, Amazonas, Brazil. 2022.

Variables	River water-level period	Absent		Present		p-value*		
		N	%	N	%	Period	City	Interaction
E. coli (n=84)						.905	.765	.972
Coari	LWL	3	17.6	14	82.3			
	RWL	2	12.5	14	87.5			
Codajás	LWL	1	9.0	10	90.9			
	RWL	1	10.0	9	90.0			
Tefé	LWL	2	12.5	14	87.5			
	RWL	4	28.6	10	71.4			
Enterococcus spp. (n=71)						.625	.919	.280
Coari	LWL	11	78.6	3	21.4			
	RWL	11	78.6	3	21.4			
Codajás	LWL	5	50.0	5	50.0			
	RWL	8	88.9	1	11.1			
Tefé	LWL	10	71.4	4	28.6			
	RWL	7	70.0	3	30.0			
Vibrio spp. (n=71)						.204	.594	.280
Coari	LWL	11	78.6	3	21.4			
	RWL	6	42.9	8	57.1			
Codajás	LWL	6	60.0	4	40.0			
	RWL	6	66.7	3	33.3			
Tefé	LWL	9	64.3	5	35.7			
	RWL	4	40.0	6	60.0			
Salmonella spp. (n=71)						.007	.426	.385
Coari	LWL	5	35.7	9	64.3			
	RWL	13	92.9	1	7.1			
Codajás	LWL	4	40.0	6	60.0			
	RWL	7	77.8	2	22.2			
Tefé	LWL	4	28.6	10	71.4			
	RWL	6	60.0	4	40.0			

*Linear Mixed Model. Type III Wald chi-squared tests.

RESULTS

A total of 84 water samples from 44 floating houses were analyzed, 44 on LWL (Codajás: 11 samples; Coari: 17 samples; Tefé: 16 samples) and 40 on RWL (Codajás: 10 samples; Coari: 16 samples; Tefé: 14 samples). There was a loss of 9.0% (n=4) sample units in the second data collection phase, as the residents of the floating houses were not found.

The origin of the water for consumption on both river-water levels was predominantly from tubular/artesian wells (75.0% LWL; 72.7% RWL). Only four (9.0%) households collected water for consumption from the river or rain during the RWL. The other residents collected water from the local water company distribution network. The most used water storage form was Polyethylene Terephthalate (PET) bottles or buckets (90.9%), followed by other storage forms, such as pots, gallon containers, and bowls. However, it is concerning that the majority (63.6%) of residents did not treat the water prior to consumption, potentially exposing themselves to health risks. When they did treat the water, they used sodium hypochlorite (31.8%), filtration (2.3%), or decantation (2.3%). The water used for cooking generally had the same origin as the water for consumption.

E. coli bacteria were identified in most samples during the LWL period (86.3%; 38), as well as during the RWL (82.5%; 33). Water samples that were positive for *E. coli* also showed bacteria of the *Enterococcus* spp. genus (12; 31.5% of the LWL period samples; and 7; 21.2% of the RWL period samples); *Vibrio* spp. (12; 31.5% of the LWL period samples; and 17; 51.5% of the RWL period samples); *Salmonella* spp. (25; 65.7% of the LWL period samples; and 7; 21.2% of the RWL period samples). *Pseudomonas* spp. were not identified in the analyzed samples (Table 2).

There was no significant difference between river water level periods or municipalities, or the iteration between these factors, in the levels of water contamination by microorganisms ($p < .05$), except for the tests carried out for *Salmonella* spp., which showed strong evidence that the water contamination rate by these bacteria was higher in the LWL period than in the RWL period ($p = .007$), Table 2.

All *Enterococcus* spp. strains isolated in the LWL period showed sensitivity to the antimicrobials tested. During the RWL period there was resistance to the antimicrobials ampicillin (3; 42%) and penicillin (6; 85%). Strains from two households in the municipality of Tefé and one household in Coari were resistant to ampicillin and penicillin.

All the strains of *Vibrio* spp. isolated during the LWL period showed resistance to ampicillin and were sensitive to trimethoprim-sulfamethoxazole, chloramphenicol and tetracycline. The resistance index was higher during the RWL period, with a predominance of resistance to ampicillin (13; 76.5%), followed by resistance to trimethoprim-sulfamethoxazole (8; 47.1%), chloramphenicol (9; 52.9 %) and tetracycline (5; 29.4%). Strains isolated from samples from four residences during the RWL period (two in Coari and two in Codajás) showed resistance to all the antimicrobials tested.

The resistance index of *Salmonella* spp strains to antimicrobials was higher during the LWL period. All strains were resistant to ampicillin and cefazolin, 17 (68.0%) were resistant to tobramycin, and 16 (64.0%) to gentamicin. There were higher resistance rates during the RWL period to ampicillin (5; 71.4%) and cefazolin (6; 85.7%). Only one strain was resistant to tobramycin (14.6%) and two to gentamicin (28.6%).

DISCUSSION

In this study we found that more than 80% of the water consumed by residents of floating houses in the three investigated cities was contaminated with *E. coli*, regardless of the river water-level period, and the contamination was associated with the presence of the genera *Vibrio*, *Enterococcus* and *Salmonella*. Additionally, *Salmonella* spp. samples were resistant to ampicillin and cefazolin, tobramycin, and gentamicin antimicrobials, mostly in the LWL period.

The identification of a high number of samples contaminated by *E. coli* highlights the need to understand the probable causes of water contamination, which could include the storage method or location, lack of treatment or incorrect treatment, or external contamination due to the influence of anthropic activities, population growth and/or urbanization (Odonkor and Mahami 2020). *Escherichia coli* is a gram-negative opportunistic pathogen, with a remarkable ability to survive in aquatic environments (Chen *et al.* 2017, Nowicki *et al.* 2021). It is commonly reported in the literature in water samples for human consumption, both in Brazil and in other countries, in urban or rural areas (Freitas *et al.* 2001, Rocha *et al.* 2010, Nunes *et al.* 2015, Mahmoud *et al.* 2020, Mugadza *et al.* 2021, Khan *et al.* 2022). Some of these findings show the paradoxes in the Amazon region, namely the abundance of water in the Amazon River basin, yet high contamination of the water, including by resistant microorganisms.

The Amazon is considered one of the water-richest regions on the planet (Jézéquel *et al.* 2020). Even though the local population has adapted to the area's hydrological flow regime patterns since pre-Columbian times, floating-house communities generally face daily subsistence challenges, especially in relation to drinking water. This is due in large part to the unique geographic features that surround their homes (Althor *et al.* 2018). We found that most of water for consumption by residents of floating houses came from tubular wells, regardless of the river water-level period, which are sources classified as "collective alternative solutions for supplying water for human consumption" (Brasil 2021*b*).

According to the Pan American Health Organization (PAHO), these water sources represent "non-improved" forms of supply and installations, meaning unpiped water sources coming from unprotected, dug wells (OPAS/OMS 2019). In addition, despite the low frequency (9.0%), some households obtained water for consumption directly from the river or rain during the raising river water-level period, which could impact human health.

The difficulties of obtaining water for consumption and the particularities of floating houses make the practice of storing water very common among residents, frequently on PET bottles. However, these storage containers can impact water quality due to improper handling or incorrect hygiene, which can lead to contamination of drinking water (Chalchisa *et al.* 2017). More than half of the units visited (63.9%) did not use any form of water treatment before consumption and when they did, they used sodium hypochlorite. Chlorine is one of the chemical products most used 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). Various chlorine-based products can be used, from household bleach to concentrated sodium hypochlorite solution, both of which are affordable (Nielsen *et al.* 2022).

In this adverse context of water consumption, most of the water samples analyzed were contaminated by the *E. coli* bacteria, a species used by the Brazilian Ministry of Health as an indicator of microbial water contamination at consumption points. Although the presence of *E. coli* in the water does not necessarily indicate contamination by other pathogenic microorganisms, the data revealed contamination by pathogens of fecal origin, which can cause health problems. It was additionally observed that a portion of the samples that tested positive for *E. coli* were also contaminated with *Enterococcus* spp., *Vibrio* spp. and *Salmonella* spp. pathogens associated with disease outbreaks and waterborne diseases of high incidence and severity (WHO 2017*b*). These microorganisms are responsible for numerous disease outbreaks, including diarrhea (*E. coli*), cholera (*Vibrio cholerae*), typhoid fever (*Salmonella typhi*) and other gastroenteritis. These findings show the high contamination rate by pathogenic bacteria, a fact that requires attention from health authorities due to the potential impact on the local population's health (Robertine *et al.* 2021).

In addition to potential health problems, ingesting contaminated water can represent high human exposure to microorganisms resistant to antimicrobials (Taviani *et al.* 2022), as we found in this study. We found resistance of microorganisms (mainly from the *Vibrio* and *Salmonella* genera) to a broad range of antimicrobials. Antimicrobial resistant bacteria have become a global public health concern and are increasingly reported; not only in clinical settings, but also in environmental samples, including water (Taviani *et al.* 2022). Bacteria are presumed to acquire resistance traits (bacterial resistance genes) through horizontal gene transfer via mobile elements such as transposons or plasmids. These elements generally play important roles in genetic exchanges among microorganisms, especially in aquatic environments (Czekalski *et al.* 2014, Sánchez-Baena *et al.* 2021). Water systems can therefore become reservoirs of resistance genes and an important route for transporting and transferring these genes from one bacterium to another. In the long term this can become a cycle, as the continuous discharge of pollutants into water systems can increase the number of resistant microorganisms, and consequently the chances of these genes being transferred to humans and animals, in turn impairing the effectiveness of the antimicrobials in the future (Czekalski *et al.* 2014).

Furthermore, with recent climate changes, the number of extreme events, including floods and droughts, has been increasing. Extreme floods can cause groundwater pollution, since with rising river levels the contaminated surface water infiltrates into the flooded soil and subsoil and reaches the water table, directly affecting water quality. These contaminants can include micropollutants and pathogenic microorganisms (Uhl *et al.* 2022).

The present study was limited to the analysis of the microbiological aspects of the water, and the analysis exclusively took place at the consumption point in domestic units of floating houses on the river banks of three cities in the Amazon basin. Therefore, the study findings cannot be generalized to the Amazon region. Despite this, the information represents an important starting point for future epidemiological investigations concerning waterborne diseases, and provides support for the proposition of public policies in basic sanitation and population health.

CONCLUSIONS

This study has shown that the river water level periods did not have a significant influence on the contamination rate of drinking water by bacteria. Considering that the water supply for floating houses predominantly comes from tubular wells located along the banks of the studied municipalities (floodplain areas), the contamination may be associated with water collection and storage practices. In addition to storing their drinking water in reused containers (Polyethylene Terephthalate (PET) bottles or buckets), most individuals do not treat the water with sodium hypochlorite before consumption. The contamination by pathogenic bacteria, coupled with the high levels of antimicrobial resistance identified during the study, presents a significant public health concern for these riverine populations. Consequently, monitoring the drinking water quality in floating communities and developing public policies aimed at improving water collection and storage habits, as well as promoting the appropriate use of sodium hypochlorite, could mitigate this issue.

ACKNOWLEDGMENTS

This study was supported by the Fundação de Amparo à Pesquisa do Estado do Amazonas – call # 003/2020 PAINTER, and Coordenação de Aperfeiçoamento de Pessoal de Nível SSuperior (CAPES), Brazil - Financing Code 001.

REFERENCES

ANA. 2020. Agência Nacional de Águas. Atlas Esgotos: Despoluição de Bacias Hidrográficas. (https://metadados.snirh.gov.br/geonetwork/srv/api/records/1d8cea87-3d7b-49ff-86b8-966d96c9eb01). Accessed on 02 Dec 2022.

ANA. 2022. Agência Nacional de Águas. Portal do SNIRH - Agência Nacional de Águas. (http://snirh-web-hml.azurewebsites.net/). Accessed on 24 Nov 2022.

Althor, G.; Mahood, S.; Witt, B.; Colvin, R.M.; Watson, J.E.M. 2018. Large-scale environmental degradation results in inequitable impacts to already impoverished communities: A case study from the floating villages of Cambodia. *Ambio* 47: 747–759.

Baird, R.; Rice, E.; Eaton, A. 2017. *Standard methods for the examination of water and wastewaters*. 23rd ed. Water Environment Federation, American Public Health Association, American Water Works Association. Washington, D.C, 1504p.

Bittencourt, M.M.; Amadio, S.A. 2007. Proposta para identificação rápida dos períodos hidrológicos em áreas de várzea do rio Solimões-Amazonas nas proximidades de Manaus. *Acta Amazonica* 37: 303–308.

Brasil. 2016. Ministério da Saúde. Secretaria de Vigilância em Saúde. Departamento de Vigilância em Saúde Ambiental e Saúde do Trabalhador. Diretriz Nacional do Plano de Amostragem da Vigilância da Qualidade da Água para Consumo Humano. (https://bvsms.saude.gov.br/bvs/publicacoes/diretriz_nacional_plano_amostragem_agua.pdf). Accessed on 16 Nov 2022.

Brasil. 2021a. Ministério da Saúde – MS. Banco de dados de Transmissão Hídrica e por Alimentos no Brasil. (https://docs.google.com/spreadsheets/d/1XT4iffaWUcMgU_t-Q0mKZhX1UHUJsJxi/edit?gid=1026946243#gid=1026946243). Accessed on 13 Nov 2022.

Brasil. 2021b. Ministério da Saúde – MS. Portaria GM/MS Nº 888, de 4 de maio de 2021. Altera o Anexo XX da Portaria de Consolidação GM/MS nº 5, de 28 de setembro de 2017, para dispor sobre os procedimentos de controle e de vigilância da qualidade da água para consumo humano e seu padrão de potabilidade. (https://www.in.gov.br/en/web/dou/-/portaria-gm/ms-n-888-de-4-de-maio-de-2021-318461562). Accessed on 21 Feb 2023.

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: 12.

Chen, Z.; Yu, D.; He, S.; Ye, H.; Zhang, L.; Wen, Y.; *et al.* 2017. Prevalence of Antibiotic-Resistant Escherichia coli in Drinking Water Sources in Hangzhou City. *Frontiers in Microbiology* 8: 1133.

CLSI. 2015. *Methods for Antimicrobial Dilution and Disk Susceptibility Testing of Infrequently Isolated or Fastidious Bacteria – M45*. 3nd ed. Clinical and Laboratory Standard Institute. Wayne, 19p.

CLSI. 2020. *Performance Standards for Antimicrobial Susceptibility Testing*. 30th ed. CLSI supplement M100. Clinical and Laboratory Standard Institute. Wayne, 332p.

CPRM. 2022. Serviço Geológico do Brasil. Sistema de Informações de Águas Subterrâneas – SIAGAS. (http://siagasweb.cprm.gov.br/layout/pesquisa_complexa.php). Accessed on 12 Jan. 2023.

Czekalski, N.; Gascón Díez, E.; Bürgmann, H. 2014. Wastewater as a point source of antibiotic-resistance genes in the sediment of a freshwater lake. *The ISME Journal* 8: 1381–1390.

Fabré, N. N.; Castello, L.; Isaac, V. J.; Batista, V. S. 2017. Fishing and drought effects on fish assemblages of the central Amazon Basin. *Fisheries Research* 188: 157-165.

Franca, R.R.; Mendonça, F.A. 2015. A cheia histórica do rio Madeira no ano de 2014: riscos e impactos à saúde em Porto Velho (RO). *Hygeia*: 11 (21): 62 - 79.

Freitas, M.B.; Brilhante, O.M.; Almeida, L.M. de. 2001. Importância da análise de água para a saúde pública em duas regiões do Estado do Rio de Janeiro: enfoque para coliformes fecais, nitrato e alumínio. *Cadernos de Saúde Pública* 17: 651–660.

IBGE. 2012. Instituto Brasileiro de Geografia e Estatística. Censo Demográfico – 2010. (https://www.ibge.gov.br/estatisticas/sociais/populacao/9662-censo-demografico-2010.html). Accessed on 02 Feb 2023.

Jézéquel, C.; Tedesco, P.A.; Darwall, W.; Dias, M. S.; Frederico, R. G.; Hidalgo, M.; *et al.* 2020. Freshwater fish diversity hotspots for conservation priorities in the Amazon Basin. *Conservation Biology* 34: 956-965.

Khan, J.R.; Hossain, M.B.; Chakraborty, P.A.; Mistry, S.K. 2022. Household drinking water *E. coli* contamination and its associated risk with childhood diarrhea in Bangladesh. *Environmental Science and Pollution Research* 29: 32180–32189.

Langill, J.C.; Abizaid, C. 2020. What is a bad flood? Local perspectives of extreme floods in the Peruvian Amazon. *Ambio* 49: 1423–1436.

Levy, K.; Smith, S.M.; Carlton, E.J. 2018. Climate change impacts on waterborne diseases: moving toward designing interventions. *Current Environmental Health Reports* 5: 272–282.

Mahmoud, N.E.; Altayb, H.N.; Gurashi, R.M. 2020. Detection of carbapenem-resistant genes in *Escherichia coli* isolated from drinking water in Khartoum, Sudan. *Journal of Environmental and Public Health* 2020: 1–6.

Mugadza, D.T.; Nduku, S.I.; Gweme, E.; Manhokwe, S.; Marume, P.; Mugari, A.; *et al.* 2021. Drinking water quality and antibiotic resistance of *E. coli* and Salmonella spp. from different sources in Gweru urban, Zimbabwe. *Environmental Monitoring and Assessment* 193: 546.

Muniz, L. da S.; Filizola, N.P.J. 2015. *Noções de Hidrogeografia: conhecendo o meu Rio Madeira*. Editora INPA, Manaus. 36p.

Nielsen, A.M.; Garcia, L.A.T.; Silva, K.J.S.; Sabogal-Paz, L.P.; Hincapié, M.M.; Montoya, L.J.; *et al.* 2022. Chlorination for low-cost household water disinfection – A critical review and status in three Latin American countries. *International Journal of Hygiene and Environmental Health* 244: 114004.

Nowicki, S.; Laurent, Z.R.; Villiers, E.P. de; Githinji, G.; Charles, K.J. 2021. The utility of *Escherichia coli* as a contamination indicator for rural drinking water: Evidence from whole genome sequencing. *Plos One* 16: e0245910.

Nunes, S.S.; Soares, F.M.P.; Reis, J.S. 2015. Análise bacteriológica da água de reservatórios domiciliares do município de Coari – Amazonas. *SaBios-Revista de Saúde e Biologia* 10: 9–14.

Odonkor, S.T.; Mahami, T. 2020. *Escherichia coli* as a Tool for Disease Risk Assessment of Drinking Water Sources. *International Journal of Microbiology* 2020: 2534130.

OPAS; OMS. 2019. *Agenda 2030 para abastecimento de água, esgotamento sanitário e higiene na América Latina e Caribe: Um olhar a partir dos direitos humanos.* Organização Pan-Americana da Saúde e Organização Mundial de Saúde (https://iris.paho.org/handle/10665.2/51837). Accessed on 23 Jan 2023.

Peranovich, A. 2019. Waterborne diseases in Argentina and Brazil at the beginning of the 21st century. *Saude e Sociedade* 28: 297–309.

Queiroz, K.O.D. 2022. Floating territorial arrangements of the river lake of Tefé and Coari in the Amazonas. *Mercator* 21: e21011.

Queiroz, M.S.; Soares, A.P.A.; Neto, A.G.T. 2018. Comunidades rurais ribeirinhas e as águas do rio Solimões no município de Iranduba - Amazonas. *Revista Brasileira de Meio Ambiente* 4: 1.

Robertine, L.-F.; Payne, V.K.; Honorine, N.T.; Mounchili, S.; Saturine, M.M.; Manjuh, B.R.; *et al.* 2021. Trends of potential waterborne diseases at different health facilities in Bamboutos Division, West Region, Cameroon: a retrospective appraisal of routine data from 2013 to 2017. *Journal of Water and Health* 19: 616–628.

Rocha, E.S.; Rosico, F.S.; Silva, F.L.; Luz, T.C.S. da; Fortuna, J.L. 2010. Análise microbiológica da água de cozinhas e/ou cantinas das instituições de ensino do município de Teixeira de Freitas (ba). *Revista Baiana de Saúde Pública* 34: 694–694.

Sánchez-Baena, A.M.; Caicedo-Bejarano, L.D.; Chávez-Vivas, M. 2021. Structure of bacterial community with resistance to antibiotics in aquatic environments. A systematic review. *International Journal of Environmental Research and Public Health* 18: 2348.

Siedlecka, A.; Wolf-Baca, M.; Piekarska, K. 2021. Microbial communities of biofilms developed in a chlorinated drinking water distribution system: A field study of antibiotic resistance and biodiversity. *Science of The Total Environment* 774: 145113.

Silva, N.; Junqueira, V.C.A.; Taniwaki, M.H.; Gomes, R.A.R.; Okazaki, M.M. 2017. *Manual de Métodos de Análise Microbiológica de alimentos e água*. 5nd ed. Editora Edgard Blücher Ltda, São Paulo, 560p.

Sousa, T.B.; Cunha, E.B. 2013. Valoração econômica ambiental: uma estimativa do valor de uso e valor de não uso do rio Amazonas no litoral da Capital Amapaense. *Revista Meio Ambiente e Sustentabilidade* 4: 264–286.

Taviani, E.; Berg, H.; Nhassengo, F.; Nguluve, E.; Paulo, J.; Pedro, O.; *et al.* 2022. Occurrence of waterborne pathogens and antibiotic resistance in water supply systems in a small town in Mozambique. *BMC Microbiology* 22: 243.

Uhl, A.; Hahn, H.J.; Jäger, A.; Luftensteiner, T.; Siemensmeyer, T.; Döll, P.; *et al.* 2022. Making waves: Pulling the plug - Climate change effects will turn gaining into losing streams with detrimental effects on groundwater quality. *Water Research* 220: 118649.

UNEP. 2022. *Environmental Dimensions of Antimicrobial Resistance - Summary for Policymakers*. United Nations Environment Programme. (https://wedocs.unep.org/bitstream/handle/20.500.11822/38373/antimicrobial_R.pdf.). Accessed on 27 Jan 2023

Vargas, T.F.; Baía, C.C.; Machado, T.L. da S.; Dórea, C.C.; Bastos, W.R. 2021. Decay of free residual chlorine in wells water of northern Brazil. *Water* 13: 992.

Vieira, C.B.; Abreu Corrêa, A.; Jesus, M.S.; Luz, S.L.B.; Wyn-Jones, P.; Kay, D.; *et al.* 2017. The impact of the extreme amazonian flood season on the incidence of viral gastroenteritis cases. *Food and Environmental Virology* 9: 195–207.

WHO. 2012. *Global costs and benefits of drinking-water supply and sanitation interventions to reach the MDG target and universal coverage*. World Health Organization. (https://iris.who.int/bitstream/handle/10665/75140/WHO_HSE_WSH_12.01_eng.pdf). Accessed on 19 Jan 2023

WHO. 2017a. *Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines*. World Health Organization. (https://www.who.int/publications/i/item/9789241512893). Accessed on 15 Jan 2023.

WHO. 2017b. World Health Organization. *Guidelines for drinking-water quality: first addendum to the fourth edition*. World Health Organization. (https://www.who.int/publications/i/item/9789241549950). Accessed on 19 Jan 2023.

WHO. 2020. *Progress on drinking water, sanitation and hygiene in schools: special focus on COVID-19*. United Nations Children's Fund and World Health Organization. (https://www.unicef.org/reports/progress-on-drinking-water-sanitation-and-hygiene-in-schools-focus-on-covid-19) Accessed on 19 Jan 2023.

WHO. 2021. *Progress on household drinking water, sanitation and hygiene 2000-2020*: Five years into the SDGs. World Health Organization and the United Nations Children's Fund. (https://www.who.int/publications/i/item/9789240030848). Accessed on 15 Jan 2023.

RECEIVED: 02/05/2024
ACCEPTED: 28/10/2024
ASSOCIATE EDITOR: Carlos José Sousa Passos
DATA AVAILABILITY: The data that support the findings of this study are not publicly available.