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Sources and microbiological quality of domestic water in three rural communities in the southern Caribbean

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ABSTRACT

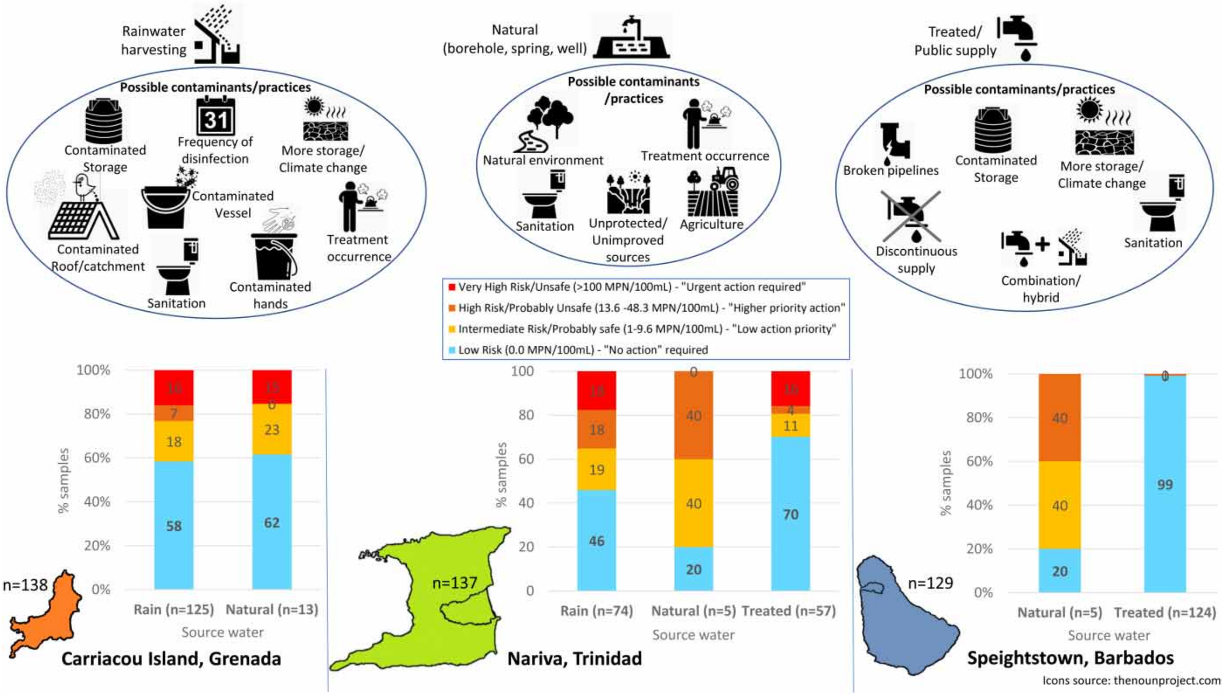
This study investigated the sources and microbiological quality of domestic water used by rural communities of Speightstown, Barbados; Carriacou, Grenada; and Nariva, Trinidad. The primary water source was harvested rainwater in Carriacou, and the public water supply for Nariva and Speightstown. Secondary water supplies of the communities came from untreated sources including rainwater, wells, boreholes and springs. *E. coli* was detected at higher frequencies in water from Carriacou (41.3%) and Nariva (47.4%) than Speightstown (3.6%). Generally, more untreated samples of rainwater (44.6%) and surface/ground water (58.3%) were *E. coli* positive than treated water obtained from the public supply (9.9%). These findings demonstrate the increased risk to residents in rural communities of the Caribbean who utilize untreated rainwater and environmental sources such as springs and wells. These results demonstrate the usefulness of traditional methods such as the compartment bag test in determining the microbiological quality of domestic water in resource-challenged rural communities of the Caribbean.

Key words: Caribbean, compartment bag test, drinking water, health risk, microbial water quality, rainwater harvesting

HIGHLIGHTS

- Residents from Carriacou depended on harvested rainwater while those in Speightstown and Nariva relied more on the public distribution system.
- *E. coli* was detected at higher frequencies in water samples from Carriacou and Nariva than Speightstown.
- More untreated samples of rainwater and surface/ground water were *E. coli* positive.
- The CBT method proved useful for determining microbiological water quality in rural communities.

GRAPHICAL ABSTRACT



INTRODUCTION

In 2020, an estimated 2 billion people lacked access to safely managed drinking water, globally (WHO 2021), making them susceptible to exposure to chemical and microbiological contaminants from utilizing alternative sources of water. Although largely preventable, every year approximately 829,000 people die from diarrhoeal-related illnesses due to the consumption of unsafe drinking water (WHO 2019). In an effort to improve the welfare of people, the United Nations adopted the Sustainable Development Goals 2030 agenda (UNDESA 2015), which includes ending waterborne disease epidemics (Goal 3) and ensuring universal and equitable access to safe drinking water (Goal 6) among their targets. However, meeting these goals would be a challenge for many developing countries, such as those in the Caribbean, due to weak physical infrastructure and institutional support systems, especially within rural communities.

Published data on microbial water quality in the wider Caribbean are limited. The detection of contaminated water is apparent in a few communities that have been surveyed (Agard *et al.* 2002; Lévesque *et al.* 2008; Baum *et al.* 2014; Mukherjee *et al.* 2016; Tiwari *et al.* 2021). Several retrospective studies characterizing epidemiological outbreaks have proven useful in understanding the continued risks associated with the incidence of a range of waterborne infectious diseases such as shigellosis (Pires *et al.* 2012), leptospirosis (Peters *et al.* 2018) and cholera (PAHO 2018) in the region. These reports highlight the need for continued identification and characterization of water sources and their risks to human health in resource-limited and socio-economically challenged communities such as those found in rural areas in the Caribbean.

Assessing the quality of different water sources in representative rural communities would contribute to understanding the microbiological hazards associated with their use in these settings. An analysis of how the behaviours and practices of households can influence domestic water quality would also be needed for assessing the risks of exposure to waterborne pathogens as recently specified in a study that characterized water resources using a water poverty index tool (Stewart *et al.* 2021).

This study was conducted to identify the sources and assess the microbiological quality of domestic water used by households in three rural communities in the southern Caribbean. The study also investigated the linkages among water resources, water use practices and water quality.

METHODS

Three representative rural communities in the Caribbean with contrasting features were selected for this study: Carriacou in Grenada, Speightstown in Barbados and Nariva in Trinidad (Figure 1).

Study areas

Carriacou is one of many islands in the Grenadines, a chain of rocks and islets that exist between Grenada and St. Vincent. At 34 km^2, it is the largest land formation of the Grenadines and, together with the island Petite Martinique, is a dependency of the Government of Grenada. Carriacou and Petite Martinique combined constitute one of the seven parishes in the tri-island nation. Carriacou's population is approximately 8,000 people (Peters 2019).

With a population of 287,371 and size of 431 km^2, Barbados is one of the most densely populated countries in the Western Hemisphere (World Bank 2021). The generally rural town of Speightstown on the north-west of the island is ~8 km^2 and has a population of 5,606 people concentrated on the coast (Barbados Statistical Service 2013).

Nariva, on the east of the island of Trinidad, has several settlements that skirt the Nariva Swamp, a RAMSAR's Convention on Wetlands site. With a collective estimated population of 12,266 (CSO 2012), the area's settlements exist in landscapes comprising riverine, coastal and wetland ecosystems. This makes Nariva unique from Carriacou and Speightstown, both of which do not have rivers or significant streams. While Nariva has many natural sources of surface water, a supply of potable water to households is often a challenge.

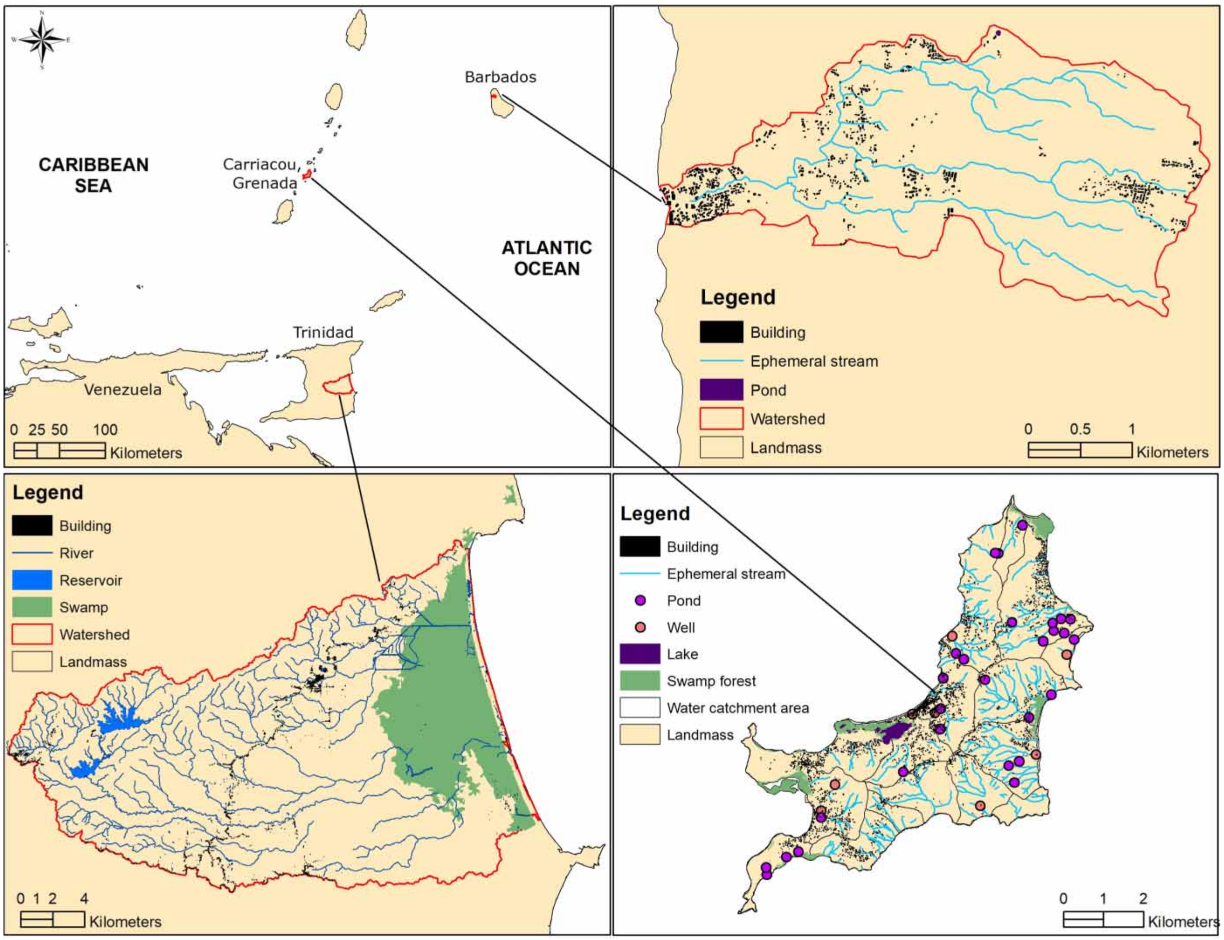


Figure 1 | Location of the study sites in the Caribbean.

Questionnaire instrument

Data on demographics, water use and water quality were collected from households of the three rural communities via a questionnaire instrument over the period from January 2015 to June 2016. The target number of questionnaires per community was 200 and a sampling of convenience method was used to collect the data. The team of interviewers that collected the survey data underwent a training programme on interviewing skills and were also instructed on the importance of data quality and consistency, and on the content and context of the questionnaire. The survey was pre-tested on control populations in Nariva and Carriacou before adjustments were made to consider the cultural practices of the different communities. Only selected data are presented here.

Water sample collection

A total of 404 samples of domestic water used by households in the three rural communities were aseptically collected: Nariva – 137 (67 wet season and 70 dry season); Speightstown – 129 (79 wet season and 50 dry season) and Carriacou – 138 (86 wet season and 52 dry season). The water samples were collected at the same time the questionnaire was administered, where possible. Samples were stored on ice and processed within 24 h. The consenting household member was asked to give a sample of water they used daily by most household members for drinking. Most samples were from inside the home, but some were also taken from sources outside the house that were used for consumption, such as protected boreholes and protected and unprotected springs.

Compartment bag test

Collection and processing of water samples for quantification of *E. coli* using the compartment bag test (CBT) (Stauber *et al.* 2014) were done according to the manufacturer's guidelines (Aquagenx 2013). Samples (100 mL) collected in sterilized bottles containing sodium thiosulphate to neutralize any chlorine that may be present were poured into compartment bags which were sealed and incubated at 35 °C for 24 h. The sub-compartments were then observed and scored before the concentrations of *E. coli* were estimated using most probable number (MPN) tables with risk categories (Aquagenx 2013). Positive controls spiked with *E. coli* and negative controls containing only distilled water were analysed along with the samples.

Statistical analysis

Data were coded and entered into Statistical Package for the Social Sciences (SPSS), Version 22 and the Shapiro–Wilk Tests of Normality were conducted. For the survey data which consisted of non-normally distributed data, the Kruskal–Wallis test was used to compare household size and the number of years residents had lived in the three rural communities. Pearson Chi-Square test (χ^2 Crosstabs), Fisher's exact test or Likelihood ratio were used to determine the levels of association among variables detailed in the results section.

For *E. coli* counts, because of the non-normal distribution of the MPN data, the non-parametric Kruskal–Wallis test was performed to determine significant differences in median values among the water type, communities and seasons. Pearson Chi-Square tests (Crosstabs) and Fisher's exact tests or Likelihood ratio were also used to determine the association between the presence of *E. coli* and the different variables, namely, water type, communities, seasons and health risk categories. For all tests, probability (p) values of less than 0.05 were used to indicate significant differences.

RESULTS

Questionnaire instrument

A total of 606 questionnaires were completed in the three rural communities (Carriacou = 188, Nariva = 213 and Speightstown = 205) (Table 1). The Kruskal–Wallis test showed that median household numbers (range = 3–4) were not significantly different among the three communities.

There was a statistically significant association among the three communities and their main source of water ($p < 0.001$). Harvested rainwater was the main source in Carriacou (97.3%) while treated water from the public distribution system was the main source for Nariva (66.2%) and Speightstown (99.0%).

In terms of water storage devices, concrete cisterns ($p < 0.001$) were only reported in Carriacou (64.9%) households while water storage tanks were primarily used in Nariva (84.0%) and Carriacou (64.4%), but few households in Speightstown (1.5%) also stored water in tanks ($p < 0.001$).Water piped into the house, either from the households' storage tanks with rainwater or

Table 1 | Sources of domestic water and households' water use practices in three rural communities in the southern Caribbean

Characteristics	Carriacou (188)		Nariva (213)		Speightstown (205)		Significance value (*p*)
	n	%	*n*	%	*n*	%	
Household size							
1–3	103	54.8	104	48.8	107	52.2	0.122[a]
4–5	60	31.9	65	30.5	68	33.2	
>6	25	13.3	44	20.7	26	12.7	
No response	NA	NA	NA	NA	4	1.9	
No. years resident in community							
<5 years	12	6.4	9	4.2	11	5.4	0.641[a]
5–9 years	21	11.2	14	6.6	17	8.3	
10–14	11	5.9	9	4.2	19	9.3	
15–19 years	12	6.4	13	6.1	18	8.8	
≥ 20 years	123	65.4	165	77.5	136	66.3	
No response	9	4.8	3	1.4	4	2.0	
Practices							
Main source of drinking water							
Harvested rain	183	97.3	57	26.8	0	0	<0.001[b]
Public treated	0	0	140	65.7	203	99.0	
Borehole/spring/well	0	0	3	1.4	2	1.0	
Mixed/other	5	2.7	11	6.1	0	0	
Secondary source							
Harvested rain	12	6.4	104	48.8	10	4.9	<0.001[b]
Public treated	0	0	20	9.4	2	1.0	
Borehole/spring/well/river	21	11.2	6	2.8	1	0.5	
Bottled water	1	0.5	0	0	0	0	
Truck-borne	10	5.3	26	12.2	1	0.5	
Mixed	0	0	5	2.3	0	0	
None	144	76.6	52	24.4	191	93.1	
Store water for domestic use							
Yes	188	100	206	96.7	86	42.0	<0.001[c]
No	0	0	7	3.3	119	58.0	
Type of storage used							
Concrete cistern	122	64.9	1	0.5	0	0	<0.001[b]
Water tank	121	64.4	179	84.0	3	1.5	<0.001[c]
Barrel	38	20.2	96	45.1	7	3.4	<0.001[c]
Bucket	37	19.7	37	17.4	46	22.4	0.362[c]
Bottle/small container	4	2.1	13	6.1	48	23.4	<0.001[c]
None	6	3.2	9	4.2	122	59.5	
Water piped indoors							
Yes	116	61.7	160	75.1	199	97.1	<0.001[c]
No/No response	72	38.3	53	24.9	6	2.9	

(*Continued*.)

Table 1 | Continued

Characteristics	Carriacou (188)		Nariva (213)		Speightstown (205)		Significance value (*p*)
	n	%	*n*	%	*n*	%	
Access to improved sanitation							
Latrine only	53	28.2	26	12.2	3	1.5	<0.001[c]
Latrine and soak away/septic tank	13	6.9	10	4.7	4	1.9	0.057[c]
Soak away/septic tank only	113	60.1	174	81.7	189	92.2	<0.001[c]
No response	9	4.8	3	1.4	9	4.4	0.122[c]
[d]**Clean storage vessels**							
Yes	134	71.3	188	96.4	76	90.5	< 0.001[c]
No	48	25.5	7	3.6	8	9.5	
[e]No response	6	3.2	7	3.3	0	0	
[e]Not applicable	0	0	11	5.2	121	59.0	
[f]**Stored water is treated**							
Yes	135	71.8	37	50.0	NA	NA	< 0.001[b]
No	53	28.2	35	47.3	NA	NA	
[e]No response	0	0	2	2.7	1	100	
[e]Not applicable	0	0	139	65.3	204	99.5	
Method of treating rain or natural water							
Boil	97	51.6	14	18.9	NA	NA	< 0.001[c]
Chlorinate	51	27.1	54	73.0	NA	NA	
Filter	24	12.8	6	8.1	NA	NA	
None	45	23.9	37	50.0	NA	NA	
Purchase bottled water							
Yes	89	47.3	136	63.8	96	46.8	<0.001[c]
Perception							
Waterborne illness noted							
Yes	32	17.0	19	8.9	20	9.8	0.004[b]

[a]Statistical comparisons based on Kruskal–Wallis Test.
[b]Statistical comparisons based on Likelihood Ratio (when >20% of cells had expected counts of <5).
[c]Statistical comparisons based on Pearson Chi-square test.
[d]Percentages calculated for only the sub-populations that store water (Carriacou, $n = 188$; Nariva, $n = 195$; and, Speightstown, $n = 84$).
[e]Percentages calculated out of all samples, that is Carriacou, $n = 188$; Nariva, $n = 213$; and Speightstown, $n = 205$.
[f]Percentages calculated excluding treated centralized distribution supply water (Carriacou, $n = 188$; Nariva, $n = 73$ (including mixed rain and spring water); and Speightstown $n = 1$).

from the public distribution supply was also significantly different among the communities ($p < 0.001$). Overall, Speightstown (97.1%) had the highest rate of piped water indoors followed by Nariva (75.1%) and Carriacou (61.7%).

Improved sanitation was observed in all communities. The use of soakaway/septic tanks as the only means of sanitation was generally high for all three communities, but Speightstown (92.2%) had the highest rate of use, followed by Nariva (81.7%) and Carriacou (60.1%) ($p < 0.001$). The use of latrines as the sole sanitation facility was significantly ($p < 0.001$) different among the communities, with the highest use in Carriacou (28.2%), followed by Nariva (12.2%) and Speightstown (1.5%).

Nariva (96.4%) reported the highest number of households that carry out the practice of cleaning storage vessels, followed by Speightstown (90.5%) and Carriacou (71.3%). The practice of treating water for drinking from non-chlorinated sources was significantly higher ($p < 0.001$) in Carriacou (71.8%) than in Nariva (50.0%), the two communities that had significant numbers of households utilizing decentralized non-public water supplies. There was a statistically significant difference among communities for the use of treatment methods ($p < 0.001$). Boiling was the most common practice reported in Carriacou (51.6%) and Speightstown (15.1%, data not shown for treated water), whereas in Nariva (27.5%), the use of chlorine was the most common method.

Purchasing of bottled water occurred most frequently in Nariva (63.8%) but was also practiced by nearly half of the households in Carriacou (47.3%) and Speightstown (46.8%) ($p < 0.001$).

Quantification of *E. coli* using the CBT

A total of 404 samples of water were screened for *E. coli* using the CBT method in Carriacou (138), Nariva (137) and Speightstown (129), over both the wet and dry seasons (Table 2).

Comparisons of *E. coli* in water samples among communities

E. coli was detected in all communities and water source types using the CBT method. The Kruskal–Wallis test (performed after the ' > ' signs were removed from the MPN/100 mL upper limit values) showed that there was a statistically significant difference ($p < 0.001$) in *E. coli* MPN values among the three communities. A pairwise post-hoc Dunn's test with Bonferroni adjustments for multiple tests showed that Speightstown had lower (adjusted $p < 000.1$) *E. coli* MPN values than both Carriacou and Nariva. There were no statistically significant differences in *E. coli* levels between Carriacou and Nariva ($p > 0.05$). The percentage of *E. coli* positive samples among the communities also varied significantly ($p < 0.001$) for all water types combined, with Carriacou (41.3%) and Nariva (47.4%) having higher percent positive samples than Speightstown (3.6%).

Comparisons of water types from all communities

There were statistically significant differences in the proportion of samples of different water types that were positive for *E. coli* in Nariva ($p < 0.05$) and Speightstown ($p < 0.05$) but not in Carriacou ($p > 0.05$). In Nariva, samples from protected and non-protected springs (83.3%, $n = 5/6$) had a higher detection rate for *E. coli* than stored rainwater (55.6%, $n = 35/63$), mixed harvested rain and treated pipe-borne water stored in tanks (72.7%, $n = 8/11$) and public supply water directly from the distribution system or from household storage containers (29.8%, $n = 17/57$). Similarly, in Speightstown, although the numbers were small, a higher percentage of samples from protected and unprotected springs used by households (80%, $n = 4/5$) were positive for *E. coli* as compared to treated water from the public supply (0.8%, $n = 1/124$). In Carriacou, 38.5% ($n = 5/13$) of samples of natural water (from protected boreholes, protected wells and an unprotected spring) and 41.6% ($n = 52/125$) of harvested rainwater were positive for *E. coli* ($p > 0.05$).

Comparisons of *E. coli* present in water samples from the dry and wet seasons

There were no statistically significant differences in *E. coli* detected (presence/absence) across all water samples from all the communities between the wet ($n = 169$) and dry ($n = 235$) seasons. The overall detection of *E. coli* in Carriacou across all water samples was only slightly higher during the dry season (44.2%, $n = 23/52$) than in the wet season (39.5%, $n = 34/86$). Conversely, for all sample types combined, the wet season *E. coli* detection rate in Nariva (54.3%, $n = 38/70$) was higher ($p = 0.046$) than in the dry season (40.3%, $n = 27/67$). There was also a statistically significant difference in *E. coli* detection by water types in Nariva ($p = 0.003$).

E. coli detection in water from storage vessels

In Carriacou, rainwater stored in tanks (53.3%, $n = 16/30$) had a higher positive *E. coli* detection rate than rainwater stored in cisterns (39.1%, $n = 27/69$) or other containers (0%, $n = 0/3$) (Table 3). In Nariva, water stored in polyethylene plastic tanks (33.3%, $n = 6/18$) had significantly ($p = 0.022$) less *E. coli*-positive samples as compared to other water storage containers (85.7%, $n = 6/7$).

Detection of *E. coli* in polyethene storage tanks for mixed harvested rainwater/treated public supply water (72.7%, $n = 8/11$) and harvested rainwater (60%, $n = 30/50$) samples were both high in Nariva.

E. coli detection in primary and secondary water sources

Samples were further categorized into primary sources ($n = 326$), which were used on an everyday basis, and secondary supplies ($n = 49$), such as communal wells or boreholes, which were occasionally used. The occurrence of primary and secondary sources differed by communities ($p < 0.001$) (Table 4). The use of secondary sources of water was highest in Nariva (19.7%, $n = 26/132$), followed by Carriacou (13.2%, $n = 15/114$) and Speightstown (6.2%, $n = 8/129$). There were statistically significant differences in the detection of *E. coli* for primary and secondary sources ($p < 0.019$), across the communities ($p < 0.001$) and by season ($p < 0.001$). In Carriacou, primary sources (43.4%, $n = 43/99$) had higher rates of *E. coli* detected than in secondary sources (26.7%, $n = 4/15$). However, the reverse was true for Nariva (53.8%, $n = 14/26$ versus 45.3%, $n = 48/$

Table 2 | Number of samples (n), MPN/100 mL median values and percentage of domestic water samples positive that were collected in three rural communities using the CBT method

Source Site	Positive CBT samples Dry season			Positive CBT samples Wet season			Total positive CBT sample			Season	Water type
	n % + ve	MPN median	MPN Range	*n* % + ve	MPN Median	MPN Range	*n* % + ve	MPN median	MPN Range	*p* value	*p* value
Carriacou ($n = 138$)											
Public treated	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Harvested rain	21/48 43.8	0	0– > 100	31/77 40.3	0	0– > 100	52/125 41.6	0	0– > 100	>0.05[a]	NA
Borehole, spring, well	2/4 50.0	>1.7	0– > 100	3/9 33.3	0	0– > 100	5/13 38.5	0	0– > 100	>0.05[a]	NA
Overall	***23/52 44.2***	***0***	***0– > 100***	***34/86 39.5***	***0***	0– > 100	***57/138 41.3***	***0***	0– > 100	>0.05[a]	>0.05[d]
Nariva ($n = 137$)											
Public treated	10/37 27.0	0	0– > 100	7/20 35.0	0	0– > 100	17/57 29.8	0	0– > 100	>0.05[a]	NA
Harvested rain	11/23 47.8	0	0– > 100	24/40 60.0	1.5	0– > 100	35/63 55.6	>1.2	0– > 100	>0.05[a]	NA
Mixed	6/7 85.7	3.4	0– > 100	2/4 50.0	4.7	0– > 100	8/11 72.7	>4.1	0– > 100	>0.05[b]	NA
Spring	0	NA	NA	5/6 83.3	>9.5	0– > 100	5/6 83.3	>9.5	0– > 100	NA	NA
Overall	***27/67 40.3***	***0***	0– > 100	***38/70 54.3***	***0***	0– > 100	***65/137 47.4***	***0***	0– > 100	0.046[a]	0.003[c]
Speightstown ($n = 129$)											
Public treated	0/48 0.0	0	0	1/76 1.3	0	0–13.6	1/124 0.8	0	0–13.6	>0.05[b]	NA
Harvested rain	0	NA	NA	0	NA	NA	0	NA	NA	NA	NA
Spring	2/2 100	2.25	1.1–3.4	2/3 66.6	48.3	0–48.3	4/5 80.0	3.4	0–48.3	>0.05[b]	NA
Overall	***2/50 4.0***	***0***	***0.0–3.4***	***3/79 3.8***	***0***	***0–48.3***	***5/129 3.6***	***0***	***0–48.3***	>0.05[a]	>0.05[d]
Gross Total	**52/169 30.8**			**75/235 31.9**			**127/404 31.4**			**> 0.05**[d] **< 0.001**[e]	**0.007**[f] **> 0.05**[g]

Statistical comparisons based on [a]Pearson Chi-Square test, [b]Fisher's exact Test (cells have expected counts of <5) and [c]Likelihood Ratio (when >20% of cells had expected counts of <5) values for season for the detection of *E. coli* (absence/presence).

Statistical comparisons based on Pearson Chi-Square test were also performed by [d]season and [e]communities ($n = 404$) for the detection of *E. coli* (absence/presence).

Statistical comparisons based on Kruskal Wallis test were also performed by [f]season and [g]communities ($n = 404$) for MPN/100 mL values.

Table 3 | Detection of *E. coli* in different types of stored water in Carriacou, Nariva and Speightstown

Source Type / Site	Cisterns +ve (%) Dry	Cisterns Wet	Cisterns Total	Cisterns *Season p* value	Tanks +ve (%) Dry	Tanks Wet	Tanks Total	Tanks *Season p* value	Other containers +ve (%) Dry	Other Wet	Other Total	Other *Season p* value	All +ve (%) Season Total	Overall +ve (%) Season *p* value	Overall +ve (%) Storage *p* value
Carriacou															
Public treated	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Harvested rain	9/26 34.6	18/43 41.9	27/69 39.1	$>0.05^a$	9/14 64.3	7/16 43.8	16/30 53.3	$>0.05^a$	0/3 0.0	NA	0/3 0.0	NA	43/102 42.2	$>0.05^a$	$>0.05^c$
Borehole, well, spring	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nariva															
Public treated	NA	NA	NA	NA	2/13 15.4	4/5 80.0	6/18 33.3	$\mathbf{0.022}^b$	4/5 80.0	2/2 100	6/7 85.7	$>0.05^b$	12/25 48.0	$\mathbf{0.030}^b$	$\mathbf{0.030}^b$
Harvested rain	NA	0/1 0.0	0/1 0.0	NA	8/14 57.1	22/36 61.1	30/50 60.0	$>0.05^a$	1/6 16.7	2/3 66.6	3/9 33.3	$>0.05^b$	33/60 55.0	$>0.05^a$	$>0.05^b$
Mixed treated and rain	NA	NA	NA	NA	6/7 85.7	2/4 50.0	8/11 72.7	$>0.05^b$	NA	NA	NA	NA	8/11 72.7	NA	NA
Spring	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Speightstown															
Public treated	NA	NA	NA	NA	NA	NA	NA	NA	NA	0/1 0.0	0/1 0.0	NA	0/1 0.0	NA	NA
Harvested rain	NA	NA	NA	NA	NA	NA	NA	NA	NA	–	–	NA	NA	NA	NA
Spring	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total Season	9/26 34.6	18/44 40.9	27/70 38.6	NA	25/48 52.1	35/61 57.4	60/109 55.0	$>0.05^a$	5/14 35.7	4/6 66.7	9/20 45.0	$>0.05^b$	96/199 48.2	$>0.05^a$	NA
Total community *p* value	NA				$>0.05^a$				$>0.05^c$				$>0.05^a$		NA

The source type data is presented for 199 water samples from Carriacou ($n = 102$), Nariva ($n = 96$) and Speightstown ($n = 1$).

Statistical comparisons based on [a]Pearson Chi-Square test and [b]Fisher's exact test (cells had expected counts of <5) and [c]Likelihood Ratio (when $>20\%$ of cells had expected counts of <5) value for season for the detection of *E. coli* (absence/presence) are shown for season and community (under Total).

Table 4 | Summary of *E. coli* positive samples in primary and secondary water sources

Sample Source / Community	Primary Sources +ve % Dry	Wet	All	Source %	Secondary Sources +ve % Dry	Wet	All	Source %	All *E. coli* Seasons *p* value	All *E. coli* Primary–secondary *p* value
Carriacou	18/40 45.0	25/59 42.4	43/99 43.4	99/114 86.8	2/7 28.5	2/8 25.0	4/15 26.7	15/114 13.2	NA	NA
Nariva	19/49 38.8	29/57 50.1	48/106 45.3	106/132 80.3	5/13 38.5	9/13 69.2	14/26 53.8	26/132 19.7		
Speightstown	0/47 0.0	1/74 1.3	1/121 0.8	121/129 93.8	2/3 33.3	2/5 40.0	4/8 50.0	8/129 6.2		
Total	37/136 27.2	55/190 29.4	92/326 28.2	Season *p* <0.001	9/23 39.1	13/26 50.0	22/49 44.9	Season *p* <0.001	<0.001	<0.001
Community p value				<0.001				<0.001	<0.000	<0.001

Data shown for 375 samples. Pearson Chi-square test was performed on primary water samples ($n = 327$), secondary water samples ($n = 48$) and both primary and secondary samples ($n = 375$) for community and season.
Primary source values were derived by summing all primary sources in Carriacou (cisterns and tanks), Nariva (tanks, cisterns, treated pipe-borne water), Speightstown (treated pipe-borne water).
Secondary source values were derived by summing all secondary sources in Carriacou (natural, public standpipe and other stored water), Nariva (other stored water, public standpipe, natural water and one cistern) and Speightstown (natural, public standpipe and one storage container).

106, respectively, for secondary and primary sources) and Speightstown (50.0%, $n = 4/8$ versus 0.8%, $n = 1/121$, respectively, for secondary and primary sources), where the percent samples positive for *E. coli* was higher for secondary sources when compared to primary sources.

Safety assessment of drinking-water quality

The different water types were also categorized into different risk groups based on WHO's guidelines for drinking-water quality (WHO 2017). The risk categories were: *Low Risk/Safe (0 MPN/100 mL)*, *Intermediate Risk/Probably Safe (1–10 MPN/100 mL)*, *High Risk/Probably Unsafe (10–100 MPN/100 mL)* and *Very High Risk/Unsafe (>100 MPN/100 mL)* (Table 5).

Carriacou (16.0%, $n = 22/138$) and Nariva (16.8%, $n = 23/137$) had higher proportions of samples in the *Very High Risk/Unsafe* category, whereas no sample was reported in this category in Speightstown ($p < 0.001$). For public treated water and harvested rainwater sources, the *Low Risk/Safe* category had the highest frequency of all the categories. There was a statistically significant difference in the risk categories detected in water obtained from the public supply among the communities ($p < 0.001$). In Nariva, the *Very High Risk/Unsafe* categorization accounted for 15.8% ($n = 9/57$) of treated water samples which consisted mainly of stored water. A similar trend was observed in the *Intermediate Risk/Probably Safe* category, with 10.5% ($n = 6/57$) samples from Nariva falling into this category. It is of note that there were no statistically significant differences across the risk categories for harvested rainwater for Carriacou and Nariva. Overall, among the three communities, 18.3% ($n = 74/404$) of the samples were in the *High Risk/Probably Unsafe* and *Very High Risk/Unsafe* categories.

DISCUSSION

The sources and management of domestic water in the rural communities of Carriacou, Nariva and Speightstown in the southern Caribbean were found to be highly variable, which was not surprising given their differences in water resources and socioeconomic status. Common sources included harvested rainwater and water from the public distribution system with a lower dependency on surface and ground water. The communities also utilized different storage and treatment methods. In Carriacou, low use of a secondary water supply (6.4%, $n = 12/188$) suggests a measure of water security as the supplies from rainwater appear to meet the needs of the households surveyed. This was also evident from the higher levels of use of bottled water in Nariva (59.6%, $n = 81/136$) and Speightstown (59.4%, $n = 57/96$) as compared to Carriacou (15.7%, $n = 14/89$).

Table 5 | Health risk categories of water from different sources from Carriacou, Nariva and Speightstown based on CBT MPN *E. coli* levels

Sample source	Health Risk Category	n	Overall *E. coli* % detection	Risk category (%): Low Risk/Safe (MPN/100 mL = 0.0)	Intermediate Risk/Probably Safe (MPN/100 mL = 1 − 9.6)	High Risk/Probably Unsafe (MPN/100 mL = 13.6 − 48.3)	Very High Risk/Unsafe (MPN/100 mL >100)	*p* value[a]
Public treated	Carriacou	NA	17/181 (9.4)	NA	NA	NA	NA	< 0.001[b]
	Nariva	57		40 (70.2)	6 (10.5)	2 (3.5)	9 (15.8)	
	Speightstown	124		123 (99.2)	0	1 (0.8)	0	
Harvested rainwater	Carriacou	125	84/188	73 (58.4)	23 (18.4)	9 (7.2)	20 (16.0)	0.410[b]
	Nariva	63	(44.6)	31 (49.2)	10 (15.9)	12 (19.0)	10 (15.9)	
	Speightstown	NA		NA	NA	NA	NA	
Borehole, spring, well	Carriacou	13	14/24 (58.3)	8 (61.5)	3 (23.1)	0	2 (15.4)	0.104[b]
	Nariva	6		1 (16.7)	2 (33.3)	2 (33.3)	1 (16.7)	
	Speightstown	5		1 (20.0)	2 (40.0)	2 (40.0)	0	
Mixed	Carriacou	NA	8/11 (72.7)	NA	NA	NA	NA	NA
	Nariva	11		3 (27.3)	4 (36.3)	1 (9.1)	3 (27.3)	
	Speightstown	NA		NA	NA	NA	NA	
Total	Carriacou	138	123/	81 (58.7)	26 (18.8)	9 (6.5)	22 (16.0)	< 0.001[a]
	Nariva	137	404(30.4)	75 (54.7)	22 (16.1)	17 (12.4)	23 (16.8)	
	Speightstown	129		124 (96.1)	2 (1.6)	3 (2.3)	0	

MPN/100 mL = 0.0 for *Low Risk*/Safe; 1–9.6 for *Intermediate Risk/Probably Safe* (Categories *1–3.7 for *Intermediate Risk/Probably Safe* and *3.1–9.6 for *Intermediate Risk/Possibly Safe* have been lumped together based on WHO (2017) guidelines); *High Risk/Probably Unsafe* for 13.6–48.3 (Categories *13.6–17.1 for *Intermediate Risk/Possibly UNSAFE* and 32.6–48.3 for *High Risk/UNSAFE* have been lumped together based on WHO (2017) guidelines); >100 for *Very High Risk/Unsafe*.

[a]Pearson Chi-Square test and [b]Likelihood Ratio (when >20% of cells had expected counts of <5) value for season for the detection of *E. coli* (absence/presence) are shown.

Centralized water systems

Centralized treated water systems can become contaminated with harmful microorganisms (Agard *et al.* 2002; Kumpel & Nelson 2013). The discontinuous supply of piped water from the public system in Nariva can also increase the risk of contamination when compared to a continuous water supply (Kumpel & Nelson 2013). This is because soil and contaminants can enter the water distribution system through breaks in the pipelines when internal pressure is low during periods when water is not being pumped. The community of Speightstown may be similarly at risk of contaminants entering the water mains since the infrastructure is reported to be very old and susceptible to leaks (Cashman 2011), with contamination more likely in low-pressure periods when maintenance work is being performed (WHO 2017). However, the general practice following pipeline repairs is to flush the lines with chlorine, which serves to mitigate the microbial contaminant risk (WHO 2017).

Water storage practices

Important contributing factors to the contamination of stored water, especially in open containers such as cisterns, include contaminated hands (Schriewer *et al.* 2015) and utensils such as dipping cups and buckets (Psutka *et al.* 2011). Respondents from Carriacou often indicated their cisterns never go empty; however, nor were they cleaned frequently or thoroughly.

In Carriacou, while many people stated that they treat stored harvested rainwater (71.8%, $n = 135/188$), this result is inconsistent with reports from UNDESA (2012) which found that only 15% of the population treat their water with chlorine tablets and another 6% by other methods. The households in Carriacou that do not treat their rainwater (28.2%, $n = 53/188$) would likely be at a higher risk of waterborne illnesses. It is of note that 11.2% ($n = 21/188$) of residents of Carriacou utilize environmental sources of water as a secondary water supply. These include protected wells, protected boreholes and unprotected spring sources.

The storage of treated water obtained from the public distribution system was common in Nariva. While the chlorine present in treated water can kill microorganisms, storage will lead to diminished chlorine concentrations over time, which could allow bacterial survival and multiplication (Baker *et al.* 2013). The increased risk of recontamination and multiplication of microorganisms also exists for stored boiled water (Psutka *et al.* 2011), which is also utilized by some households in Nariva. The use of these practices then can contribute to increased risks and thus requires continual re-evaluation.

The low use of storage in Speightstown is also contrary to the status of Barbados as a water-scarce country and this may contribute to the vulnerability of the island in having an adequate and consistent long-term supply. Recently, the country had to import water from regional neighbours, Guyana and Dominica, to augment supplies for the clean-up of ash deposited on the island from the April 2021 eruption of the La Soufriere volcano in the nearby island of St. Vincent. Barbados's vulnerability is further increased by challenges of climate change due to projected longer drought periods regionally (Reyer *et al.* 2017).

Some households do not have pipe-borne water indoors in Carriacou (38.3%, $n = 72/188$) and Nariva (24.9%, $n = 53/213$). This practice can introduce additional routes of contamination at different steps of the process, including storage outside the house, collection, transport into the house and additional storage inside the house.

Truck-borne water as a secondary water source

Truck-borne water is especially important during the dry season, particularly in Nariva, but the quality of this water is not known. During the period the questionnaire was administered, there was observed to be limited regulation of water quality from trucks. Some respondents in Nariva had the perception that truck-borne water was sometimes sourced from the nearby Ortoire River, which was closer than sourcing treated water from the Navet water treatment plant. It is possible that this perception by household members may be due to the presence of suspended particles in the water that may originate from the vessel. Thus, cleaning and maintenance processes of delivery trucks and their water containers should be reviewed as well.

Microbiological water quality assessment

Over one third of the water samples screened using the CBT method in Nariva and Carriacou would be considered unsuitable for human consumption based on this criterion. WHO (2017) guidelines recommend action levels based on risk categories due to levels of *E. coli* in water, from 'no action' (*Low Risk*, 0–2), 'low action priority' (*Intermediate Risk*, 3–5), 'higher priority action' (*High Risk*, 6–8) and 'urgent action required' (*Very High Risk*, 9–10). Overall, most of the samples (99.2% of public supply water) from Speightstown fell into the *Low Risk* category, which may be due to the community's high access to treated water. However, while 58.4 and 49.2% of harvested rainwater samples from Carriacou and Nariva, respectively, were in the *Low Risk* category, both communities had a relatively small proportion of samples (16.0 and 15.9%, respectively) in the *Very High Risk* category. Overall, among the three communities and all water types, 7.2% ($n = 29/404$) of samples were categorized as *Intermediate Risk/Probably Safe Very* and 11.1% ($n = 45/404$) as *High Risk/Unsafe,* which suggests almost one fifth of water samples require priority or urgent action to reduce risk to members of these communities. Infrastructural improvements in unprotected wells and unprotected springs as well as changes in practices such as methods of storage and treatment can be explored.

The findings of this study are similar to other CBT-based assessments of local water sources in regions with resource-constrained settings. For example, Baum *et al.* (2014) reported 47.7% ($n = 95/199$) of improved water samples from the Dominican Republic were in the *High* to *Very High Risk* category while Apecu *et al.* (2019) found 71% ($n = 142/200$) of protected spring, river water, unprotected dug well and channel water samples from Uganda were in this category. Comparatively lower was a study in Peru, where Wang *et al.* (2017) reported 22.9% ($n = 41/179$) of unimproved drinking-water samples fell into the *High–Very High Risk* category. Rapid water quality assessments in communities where surveillance of water quality may be less likely to occur can contribute to interventions for reducing risks to consumers.

Natural sources

While natural water sourced from protected and unprotected springs and protected wells had high frequencies of *E. coli*-positive samples in Nariva and Speightstown, the actual numbers of this sample type were small. However, the number and frequency of persons accessing these supplies warrant a closer review as the use of such sources, if untreated, can increase the risk of exposure to infectious pathogens. This was noted in a study on two Caribbean Columbian rural communities where reported cases of diarrhoea were linked to utilization of unimproved water sources (Ruiz-Díaz *et al.* 2017). An increase in the frequency of use of this water type may be expected in times of crisis, such as after a hurricane.

Harvested rainwater

Harvested rainwater had a high frequency of *E. coli* detection as has been observed in several studies summarized by Ahmed *et al.* (2011). Faecal coliforms have been detected in rainwater from other rainwater harvesting communities in Trinidad (Welch *et al.* 2000; Saunders *et al.* 2003; Omisca 2011). These observations have significant implications given the proportion of households that use this source of water in Carriacou, and to a lesser extent, in Nariva. Dry deposition, air-blown dust and animal droppings are some common causes of contamination of rainwater harvesting systems (Chidamba & Korsten 2015). The method and frequency of cleaning water storage containers would also influence the levels of microbial contaminants.

Disinfection and recontamination

One half of the households (50.0%, $n = 37/74$) in Nariva reported not disinfecting harvested rainwater, and this mirrored the relatively high positive *E. coli* detection (55.6%, $n = 35/63$) in this water type for both seasons combined. Many of the households in Nariva have plumbing systems that were adapted from rainwater harvesting systems, so water is often not collected directly from centralized distribution connections but from storage tanks connected to the public supply. This may have contributed to the high positive detection of *E. coli* in mixed samples (75%, $n = 6/8$) in Nariva since tanks are not always secured sufficiently from various roof-based and aerosolized contamination sources. Additionally, the high national average for unaccounted for water (43%) has been attributed to 'leaks in old and undersized transmission and distribution systems, and illegal water connections' (Government of Trinidad and Tobago 2017) which could result in contamination of water from a centralized distribution system.

The case of aged infrastructure

In Speightstown, the water quality system can be considered as 'excellent' based on compliance of more than 90% of samples negative for *E. coli* (WHO 2017) due to chlorination of the distribution supply. However, one sample had very high counts, which may have been a result of repair works that were being conducted by the Barbados Water Authority during the sample collection period.

Speightstown, like some other areas in Barbados, has very aged water infrastructure which can increase the risk of contamination when there are breakages in the distribution line, resulting in water quality concerns. Some sections of the distribution supply are estimated to have been installed in the 1860s and have undergone minimum upgrades over the years (Cashman 2011). Additionally, as much as 50% of water pumped into the public distribution system is unaccounted for in Barbados (Cashman 2014) which suggests the existence of leaks in the line that could be a potentially important source of contamination in a centralized distribution system.

Environmental sources

Environmental groundwater sources may be contaminated by faecal matter from humans, warm-blooded animals and from agricultural practices. For instance, in Carriacou, there is a high prevalence of pit latrines, which can potentially introduce faecal bacteria into groundwater, which increase the risk associated with water-related diseases (Ruiz-Díaz *et al.* 2017). The frequency of pit latrines in Carriacou was at least 28.2% ($n = 53/188$) but lower in Speightstown (1.5–3.4%, $n = 205$) based on responses for this study. While there is no published data for Nariva, the national average for Trinidad and Tobago is 18.8% (Kairi Consultants Limited 2007), which is similar to that observed for this study (12.2–16.9%, $n = 213$).

The overall higher *E. coli* detection rate in the wet season in Nariva and Speightstown follows expected patterns in terms of seasonal differences in faecal contamination (Kostyla *et al.* 2015). The higher counts in the wet season may be due to increased microbial loadings from rainfall events.

While *E. coli* detection results were found to be high in this study, there are several reports that suggest the presence of faecal indicator organisms does not always infer human health risk (Allen *et al.* 2015). This may be due to community-level immunity to strains of bacteria, asymptomatic cases, overall under-reporting of morbidity from drinking water or lack of association of causative agents in waterborne disease cases. Thus, an important limitation of this research was the lack of assessment of the cohort population for Acute Gastroenteritis. In future studies, this would allow the evaluation of *E. coli* and other microbial agents as faecal indicator organisms in tropical environments such as the Caribbean.

CONCLUSION

This study found that residents from the three rural communities utilize a range of water sources for domestic use. The fact that some of the water types used are not treated or are stored before use presents multiple scenarios for microbial contamination. Based on the WHO's Guidelines for Drinking-water Quality, priority action is recommended in this region, as almost one fifth of domestic water samples had potentially unsafe levels of contamination across the three communities. These results indicate that testing for faecal contamination using the CBT method can be an important tool for rapid assessments of water quality.

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AUTHOR CONTRIBUTIONS

AS, AC, JA, DC and AR were responsible for conceptualization of this work. AS and CS did data curation. AS and AR did formal analysis and visualization of the manuscript. AS, CS and AH did the field work investigation. AS, DC and AR finalized the Methodology. Funding Acquisition, Project Administration and Resources were supported through the efforts of JA, AC and AR. Writing – Original draft preparation was done by AS and AR. All authors were involved in Writing – Review and Editing.

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.

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