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Water Poverty Indices of three rural communities in the southern Caribbean

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The paper is in memory of the late Professor Dave Duman Chadee.

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ABSTRACT

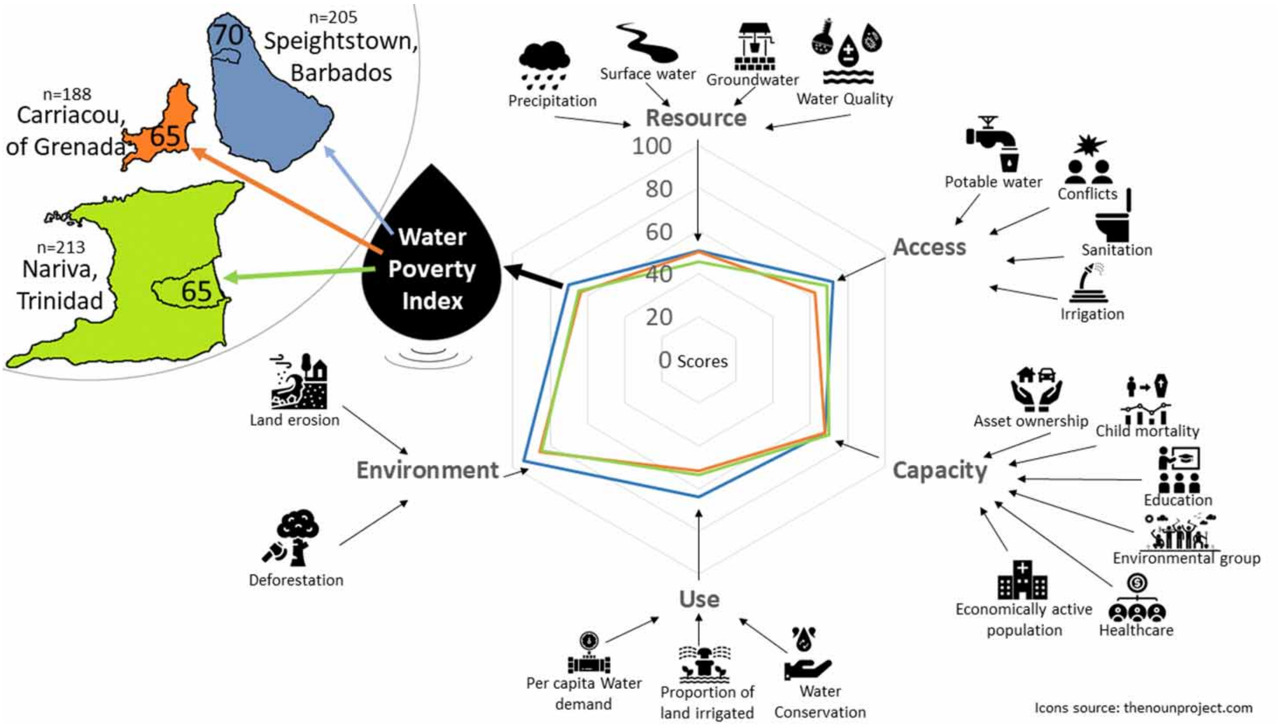
The Caribbean region experiences significant water supply challenges, especially for 30% of the population who live in rural areas. Improved water resource management in this region would enhance water availability for its population, but this requires reliable quantitative data to guide relevant policy decisions. The Water Poverty Index (WPI) and its components can be valuable sources of such data but there has not been any recent calculation of this index for countries or communities in the Caribbean. In this study, the WPI was determined for three rural communities in the southern Caribbean: Carriacou, Grenada; Nariva, Trinidad and Tobago; and Speightstown, Barbados. Using data collected from 606 surveys of households as well as published statistics, the overall WPI scores were calculated to be 65/100 for Carriacou, 65/100 for Nariva and 70/100 for Speightstown, which all fell in the 'medium-low' and 'low' water poverty scale respectively. Resource and Use components had the lowest scores and thus require urgent attention. There were no statistically significant differences across the major components, which demonstrates the common water-related challenges in these Small Island Developing States, despite geographical diversity. This research will aid in defining national water resource management policies in rural communities of the Caribbean.

Key words: Carriacou, Nariva, rainwater harvesting, Speightstown, water Poverty Index, water scarcity

HIGHLIGHTS

- WPIs were calculated to be 65 for Carriacou, Grenada, 65 for Nariva, Trinidad and 70 for Speightstown, Barbados.
- The Resource component had the lowest scores.
- Residents' water use practices afforded some resilience to the water supply in Carriacou.
- A higher water per capita in Nariva did not equate to a higher WPI.
- Improving water storage and rainwater harvesting can enhance water resilience in the region.

GRAPHICAL ABSTRACT



INTRODUCTION

Water resources are key determinants in the sustainable development of any country. The availability of water is critical for maintaining the health and welfare of people as well as supporting economic activities. However, water continues to be identified as one of the most 'critically stressed resources' and every year an estimated 4.3 billion people around the world face severe water availability challenges for at least one month (Mekonnen & Hoekstra 2016). The Caribbean region, with a collective population of ~43 million people, is one area that experiences significant water supply challenges, especially for 30% of the population that live in rural areas (Cashman 2014; Rajack-Talley 2016). Caribbean Small Island Developing States (SIDS) are likely to face additional water security challenges due to projected decreases in precipitation and increasing temperatures associated with the effects of climate change (Herrera & Ault 2017). The problem is further compounded by uneven water distribution in many of the island nations due to the variability in weather patterns, geology and topography (Cashman 2014).

The renewable internal freshwater per capita of all Caribbean states is ~51,799 m^3 which appears to be high, but it is reduced to 29,012 m^3 for the 15 Caribbean Community (CARICOM) countries (FAO AQUASTAT 2016). This generalisation of water availability also hides a number of disparities; for instance, the water resource insecurity in many CARICOM countries is evidenced by scheduling of the public water supply at various times during the year. Challenges to water resources in these states include population growth, urbanization, inadequate infrastructure, inadequate allocation of resources for improvements in water provisioning, poor water quality, and insufficient action from those in charge of water agencies. Additionally, increasing tourism-related water resource demand is particularly a concern in the region (Charara *et al.* 2011). Acute water challenges exist in the nations of Antigua and Barbuda, Barbados, Saint Kitts and Nevis, and Saint Vincent and the Grenadines, which have less than 1,000 m^3 per capita water availability. The situation is particularly extreme for Barbados as its per capita renewable freshwater resources is just 281 m^3, which is slightly less than the average of 292 m^3 for North African and Middle Eastern (MENA) countries (FAO AQUASTAT 2016).

Management of water resources is expected to become more important for the growth and stability of Caribbean countries (Donoso & Bosch 2015; Mycoo 2017). The development and implementation of appropriate management policies requires effective tools for assessing water resources and water resource vulnerabilities (Sullivan *et al.* 2003; Plummer *et al.* 2012;

Jemmali & Matoussi 2013; Shalamzari & Zhang 2018). Measuring the amount of available renewable water is used to quantify water resources, which in turn can be used as an estimate of water scarcity and vulnerability (Damkjaer & Taylor 2017). While this method gives a measure of the total amount of water resources of a country or region, it does not take into consideration socioeconomic and hydrological factors that influence the amount of water supplied or is accessible by a population or user (Lawrence *et al.* 2002; Damkjaer & Taylor 2017).

Alternative qualitative and quantitative tools have been developed to measure the availability of this essential resource that consolidate a wide range of data into a standard structure, which can then be compared across countries or regions within countries (Plummer *et al.* 2012). These alternative tools simplify complex data that encapsulates diverse scenarios and include various types of indices, which are summarized by Brown & Matlock (2011) and Plummer *et al.* (2012). The Water Poverty Index (WPI) is one of these commonly used tools, which measures poverty in the context of a 'lack of welfare' related to water resources (Sullivan *et al.* 2003). The data integrated into this index include water availability, access to safe water, measures of social and economic capacity, water use and environmental water demands (Sullivan *et al.* 2003). These datasets allow for characterizing and quantifying water resources, without necessarily being too exclusive for the average water manager. The index can also be calculated at different scales such as community level and then aggregated for a more sensitive assessment of water stress across diverse local settings (Sullivan *et al.* 2003; Shalamzari & Zhang 2018). Additionally, it can be used as a tool for assessing general developmental status and socio-economic conditions, as a supplement to other indices such as the Human Development Index (HDI) and the Gross Domestic Product (GDP) (Lawrence *et al.* 2002; Wurtz *et al.* 2019).

There are limitations in many indices including the one dimensionality of using simple datasets and failure to incorporate socio-economic factors that may account for water scarcity, insecurity and quality (Rijsberman 2006). The lack of consideration of water quality in assessment of water resources is also a major limitation of most indices since an inadequate supply of potable water can lead to persons accessing alternative sources that may be of poor quality and potentially unsafe due to the presence of chemical or microbial contaminants (Bain *et al.* 2014). The Watershed Sustainability Index (WSI) is one index that includes water quality data (Chaves & Alipaz 2007); specifically, the long-term Biological Oxygen Demand (BOD_5). This indicator serves as proxy to other water quality parameters such as pollutant concentrations, dissolved oxygen and turbidity since correlations have been shown to exist among them.

The WSI is calculated using additional data that indicate the state of the watershed, namely per capita water availability, percentage area under natural vegetation as a measure of environmental health, the human development index (HDI) and policy information on institutional capacity in integrated water resources management. These data inputs are organized into the categories of hydrology, environment, life, and policy (Chaves & Alipaz 2007). While the WSI is a useful tool for policy makers, fewer specific details are included in its calculation when compared to the WPI. Only five major data points are included in the WSI, whereas the WPI has on average 20–25 data inputs allowing the latter to more comprehensively capture the complexity of water resources (Lawrence *et al.* 2002; Sullivan *et al.* 2003). This is particularly relevant as it incorporates several dimensions of poverty and United Nations Sustainable Development Goal (SDG) indicators including health (SGD 3), child mortality and education (SGD 4), living standards through ownership of assets (SDG1), access to improved drinking water (SDG 6) and sanitation (SDG 11) (Messerli *et al.* 2019). The advantages of the WPI, such as its practical nature in data-constrained settings, transparency and relevance of its structure, and its disadvantages, such as the potential inclusion of redundant inputs and statistical approaches for combining these inputs have been previously analysed (Garriga & Foguet 2010). The inclusion of BOD_5 as a broad indicator of water quality in the WSI does not provide much additional benefit as compared to the use of the vague 'access to clean water' parameter in the WPI (Sullivan *et al.* 2003).

The WPI has been previously applied in a global study including 147 countries by Lawrence *et al.* (2002) using data available in the literature, but because the sources of data were not revealed, the indices can serve only as preliminary estimates. In this study, the countries in the Caribbean and wider region assessed included Barbados (66), Belize (66.3), Guyana (75.8), Jamaica (57.7), Trinidad and Tobago (59.0) and Venezuela (65.0). Across 147 countries, the average WPI was 56.65, indicating that both Trinidad and Tobago and Barbados were above average when compared to the water resources situation in countries around the world. The lowest WPI was observed in Haiti (35.1) while the highest was noted in Finland (78.0).

The addition of microbial water quality parameters can enhance the value of indices as tools for assessing water resources, especially related to human domestic use. Water containing harmful microorganisms, which can be due to faecal contamination and poor sanitation, can seriously impact human health when used for domestic and recreational purposes (WHO 2017). Microbial contamination can result in bacterial, fungal, parasitic, and viral infections that can cause significant morbidity and mortality. There is a dearth of published data on quality of alternative sources of domestic water as compared to centralized water distribution systems (Bain *et al.* 2014). Global estimates for the year 2016 revealed that 829,000 annual deaths arise from some form of diarrhoeal illness associated with inadequate water and sanitation. This contributed to 1.9% of the global burden of all types of disease in disability-adjusted life years (WHO 2020). One study indicated that unimproved water sources such as unprotected wells and springs or tanker trucks accounted for 0.9% of total disease in disability-adjusted life years in the year 2010 (Lim *et al.* 2012). The risks of pathogenic contamination of water highlights the importance of ensuring good microbial quality of the domestic water supply of communities and the need for including microbial water quality estimates when assessing water availability resources.

Apart from the earlier study by Lawrence *et al.* (2002), the use of index-based water resource assessments in the Caribbean region is very limited and there is a need for updating the indices using verified data. In this study, we calculated the Water Poverty Indices for three rural communities in the Southern Caribbean using data collected by administering a questionnaire that was supplemented by data from published sources. Microbial quality of water, measured by detection and quantification of *E. coli*, a traditional faecal indicator organism, was also used as a parameter in calculating the WPI. The communities included in this study were Carriacou, Grenada; Speightstown, Barbados; and Nariva, Trinidad, which have contrasting water resource challenges that capture the range of many typical rural settlements in the southern Caribbean. The findings of this study would allow water resource managers to assess the extent of water poverty and identify action priorities for addressing water resource challenges in the rural communities of the southern Caribbean. Indices are often site or region-specific, and hence, the study outlines variables that would be appropriate for this region. Given the dynamic nature of the water resource sector, these results can also serve as a reference or benchmark for future studies. This work is also of relevance for other SIDS territories which face similar challenges to the Caribbean region.

METHODS

Study area

The study was conducted in three rural communities in three separate countries in the southern Caribbean, namely Carriacou in Grenada, Speightstown in Barbados and Nariva in Trinidad and Tobago (Figure 1).

Speightstown, Barbados

The catchment of Speightstown is located on the North-west coast of Barbados. It is the main town in the rural parish of St. Peter; one of eleven parishes on the island. Speightstown has an area of 8 km^2 and, according to the last census in 2010, the population was 5,606, with residents concentrated on the coast (BBS 2013). As much as 41% of GDP is estimated to be tourism-derived across the island (Peterson & DiPietro 2021) and Speightstown is an important tourist town in Barbados. The main land uses are agriculture (mixed and annual) (41%), scrub (31%), forests (primary and secondary) (18%) and urban settlements (8%) (MGI 2015).

The maximum elevation in the catchment is 250 m (MGI 2015) and the 30-year average rainfall for Barbados from 1986 to 2015 was 1,300.2 mm (CIMH 2016). There is a wet season that runs from June to November and a dry season spans December to May. Like the rest of the island, the Parish of St Peters does not have any rivers due to the permeability of Barbados' coralline geology, but there are some gullies that support riparian forests, which drain to, and feed, wetland features on the coast. Barbados has several springs and many wells scattered across the island including in Speightstown. Groundwater is the main source of water.

Barbados is one of the most water-scarce countries in the world (FAO 2016a). It is vulnerable to droughts due to many factors, which include population increase, high demand for water from the tourism sector, and groundwater demand (Government of Barbados 2010). Drought conditions occur with an average return period of approximately 3.33 years (Boruff & Cutter 2007). Recent drought events occurred in 2015, due in part to reduced production of wells and lower than normal rainfall (BWA 2015), and Barbados has experienced short- and long-term drought periodically over the last decade (CARICOF 2021). Groundwater resources are more resilient to drought conditions than surface water, which somewhat buffers the island compared to other islands in the Caribbean that rely on surface water resources. The temperature ranges from 20 °C to 32 °C (FAO 2016a).

Carriacou, Grenada

Located near the southern end of the Windward Islands, Carriacou is one of three islands that make up the state of Grenada. At approximately 26 km north-east of the main island of Grenada, the dependency of Carriacou is 34 km^2 in size and has a

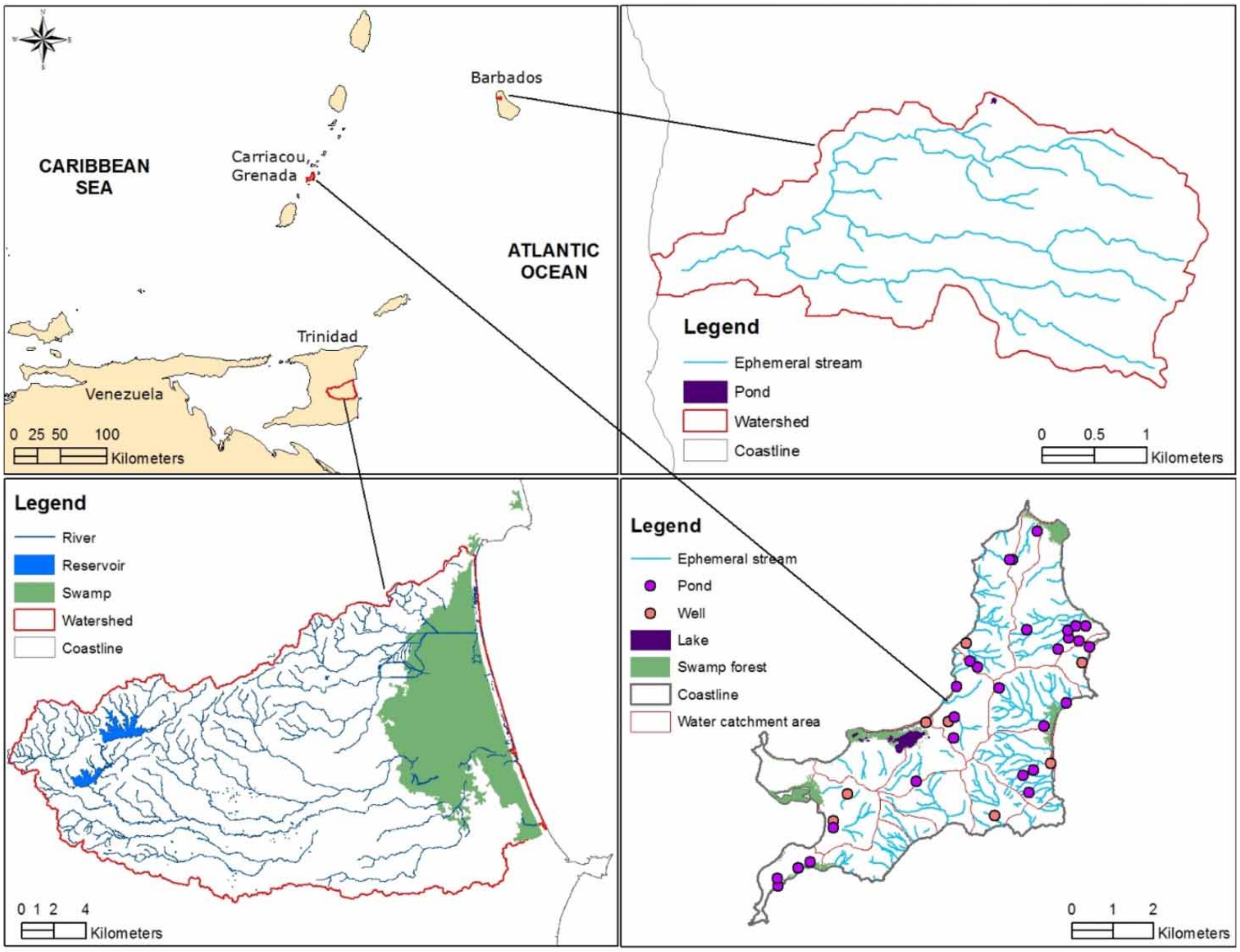


Figure 1 | Location of the study areas in the Caribbean. All three islands are situated in the Caribbean archipelago, in the Lesser Antilles. The islands of Grenada and Carriacou are located north of Trinidad. Barbados, the most easterly island in the Caribbean, is located to the west northeast of both Carriacou and Trinidad.

population of 9,595 according to the 2019 population census (Government of Grenada 2019). In Grenada, 23% of GDP is contributed through tourism activities (Peterson & DiPietro 2021), and economic activities on Carriacou are heavily tourism-dependent. The land use types on the island include ‘disturbed’ forest (58%), agriculture (25%), protected areas (10%) and buildings (0.2%) (MGI 2015).

At an elevation of only 290 m (Fitzpatrick *et al.* 2006), the average annual rainfall for Carriacou is approximately 1,000 mm (UNDESA 2012). By comparison, rainfall on the mainland coast of Grenada ranges from 990 to 1,500 mm at the coast to 3,750–5,000 mm at higher elevations (Niles 2013). The dry season spans January to May and the wet season runs from June to December (Peters, 2006).

Due to the small size, there are no perennial rivers, springs or streams on the island, which consists of 17 watersheds. Limited groundwater resources are available from several shallow aquifers that skirt the coast at a ~100 m distance. Groundwater that is abstracted is of poor quality with high levels of dissolved solids. There are 25 dug wells and 13 boreholes across the island (UNDESA 2012) as well as about 25 ponds that are used in agriculture. Rainwater is the main water source for all activities. Drought conditions were experienced in 2009/2010 and 2019 (CARICOF 2021), where rainfall decrease was as much as 60–75% of rainfall (UNDESA 2012). Fewer reports are available on droughts in Carriacou; however, there were recent drought episodes on the island in 2010 and 2015–2016 (Peters 2019). Residents of the island have adapted to droughts over the years through increasing rainwater storage, which includes 33 community cisterns (Peters 2019). During such periods, residents reduce consumption drastically, and utilize familial networks to access underutilized storage. The mean annual temperature reported for mainland Grenada ranges between 28.3 °C to a high of 33.3 °C (Niles 2013).

Nariva, Trinidad

The 419 km^2 Nariva catchment is located on the east coast of Trinidad in the island nation of Trinidad and Tobago. The catchment consists of several rivers across ten sub-catchments which flow from the western limits of the catchment and drain into the 90 km^2 RAMSAR protected Nariva swamp located on the eastern coastal edge of the catchment. Hydrological data for the catchment is limited; however, interim estimates indicate the sub-catchments collectively have an average annual discharge of 400 Mm^3 (UWI 2008). Though considered a water-rich area, inter-annual variability results in water resource and ecological challenges to residents, as the discharge for extreme hydraulic years has been estimated to be 387 Mm^3 in the dry season (January to May) and up to 1,166 Mm^3 in the wet season (June to December) (UWI 2008). The urban area in the catchment is approximately 3 km^2. There are a number of villages within the catchment and those included in this study were Plum Village, Plum Mitan, Biche and Kernahan. Administratively, the catchment spreads over parts of two of nine administrative regions in Trinidad, namely, Sangre Grande to the north east and Mayaro/Rio Claro to the south east. Many of the rivers in the catchment are used for irrigation. The population of Nariva was approximately 12,266 according to 2011 census data (CSO 2011) and the main land use types include forests (67%), marsh (10%), active agriculture (5%) and less than 1% urban settlements (MGI 2015).

The highest elevation of 269.76 m in the catchment is located to the western end, near Trinidad's central range. The 30-year average annual rainfall for Trinidad from 1981 to 2015 was 1,816.5 mm (CIMH 2016); however, the east coast including where Nariva is located is generally wetter. The dry season spans from January to May and the wet season from June to December. Some communities have access to piped water distributed by the Water and Sewage Authority (WASA); however, many areas also rely on rainwater harvesting to varying degrees during the year. Located in the upper catchment is also the Navet dam, which is 324 hectares and has a capacity of 1.9 Mm^3 which supplies areas in South Trinidad mainly outside the Nariva catchment (WASA 2008).

The island of Trinidad has been affected by recent droughts, including in 2009 to 2010, which was the worst in 40 years across the region (FAO 2016b). Trinidad also has experienced short- and long-term drought periodically over the last decade (CARICOF 2021). In a study calculating a livelihood vulnerability index for selected communities in Trinidad and Tobago, Shah *et al.* (2013) revealed that the highest vulnerability score in Nariva was for the water resources sub-component. Although there are no groundwater wellfields in the Nariva catchment, there are a few seasonal springs which are utilized by residents. Mean minimum and maximum temperature in Trinidad and Tobago ranges between 22.7 °C and 31.4 °C (Beharry *et al.* 2015).

Water Poverty Index calculation

To evaluate water scarcity in the catchments of Nariva, Carriacou and Speightstown, we used the Water Poverty Index (WPI) established by Sullivan *et al.* (2003), which consisted of five components:

1. Resources (R) – the total amount of available water, which includes both surface and groundwater, accounting for seasonal and inter-annual variability
2. Access (A) – the extent to which the population can obtain water for use, such as for domestic and agricultural activities
3. Capacity (C)- the ability to manage resources, including income that can be used to improve water infrastructure and education that can improve aspects of water related challenges
4. Use (U) – the different ways water is used in the specific catchment
5. Environment (E)- the measures of environmental integrity related to water, and that impact water, such as ecosystem goods and services.

All components were weighted equally and the WPI was calculated using the additive form of the WPI formula (Sullivan *et al.* 2003):

$$WPI = \frac{w_r R + w_a A + w_c C + w_u U + w_e E}{w_r + w_a + w_c + w_u + w_e}$$

where w refers to the weight applied and w_r, w_a, w_c, w_u and w_e refer to the respective weights for each component.

WPI components and normalization

A total of 20 indicators within 5 components were used to estimate the WPI in the three catchments, which are summarized in Table 1. All data was also normalized. The data was obtained from a survey conducted in this study or from published sources. *E. coli* was also detected and quantified as an indicator of microbial quality of water in this study.

Questionnaire instrument

A structured questionnaire was developed to capture data on some indicators relevant to households in this study, as detailed in Table 1. A cover letter introducing the study and requesting consent was also distributed. The survey was carried out during the period January 2015 to June 2016, with two sampling campaigns in each community to capture the dry and wet seasons. The target number of questionnaires per community was 200 and a sampling of convenience method was used to collect data. The survey was pre-tested on control populations before adjustments were made to consider cultural practices of the different communities. For all calculations, a final score of 100 indicated the least water-poor status and 0 was most water-poor.

Resources (*R*)

The water resources component was determined using three indicators – water availability (R_1), water variability (R_2) and water quality (R_3) (see Table 1). R_1 was calculated using the normalization formula (Shalamzari & Zhang 2018) for coefficient of variation (CV) shown in Table 1, where R_{max} referred to maximum average groundwater storage (Speightstown) or surface discharge (Nariva) and R_{min} as the minimum average groundwater storage or surface discharge respectively, with values as estimated normalized water availability (Shalamzari & Zhang 2018). For Carriacou, no groundwater figure was included for water availability as sufficient temporal data was unavailable (Wilson & Mandal 2015) and the water supply is very limited (Peters 2019). For Speightstown, groundwater storage data from a Catchment Water Availability Model (SC-WAM) for the years 2000 to 2010 was used to estimate water availability (Maharaj 2016) and for Nariva, available streamflow data from 1976 to 2006 was sourced from the Water Resources Agency, Trinidad and Tobago. For water variability, R_2, the normalized coefficient of variation (CV) was calculated using rainfall data from 1981 to 2016 for Trinidad (10°35′43″N, 61°00′14″W) and Barbados (13°09′N, 59°37′W), and from 1994 to 2016 for Grenada (12°0′15″N, 61°47′17″ W), which were provided by the Caribbean Meteorology and Hydrology Institute.

Water quality was assessed in three ways, including the practice of treating water at the household level (R_{3a}); the microbial quality of water determined in this study using *E. coli* as an indicator organism of faecal contamination (R_{3b}) and chemical water quality assessed in this study and supplemented by published data (R_{3c}). From the field survey responses, the proportion of households indicating that they treat their household water was determined, where X_o is the observed number of households carrying out this practice and X_h is the total number of the households.

For the drinking water, potability was assessed using the WHO (2017) guidelines of less than one positive *E. coli* count per 100 ml. Briefly, samples were screened for *E. coli* using the multiple fermentation – enzyme substrate-based Compartment Bag Test (CBT) method (Stauber *et al.* 2014) and the mFC membrane filtration method described in Standard Methods for the Examination of Water and Wastewater, Section 9222 D (Baird *et al.* 2012). These two methods were used for increased sensitivity of detecting *E. coli*. The R_{3b} value given was based on the percentage of all samples in which *E. coli* was not detected, or reverse scoring, to reflect the positive proportion of this indicator. This allowed for consistency of the index, where 100 was most ideal and 0 was least ideal.

R_{3c} was assessed from water collected in the field from survey respondents' household's domestic supply in Speightstown (138), Carriacou (116) and Nariva (129). The water quality parameters tested were pH, salinity, specific conductivity, total dissolved solids (TDS) and Total Hardness. Other water quality data, where available, was sourced from published literature including sodium, chloride and sulphate ions. Values were averaged out of a score of 100, where 100 was the highest quality and 0 was undrinkable water based on six categories according to the Schuller Classification Method (Ehteshami *et al.* 2014).

Access (*A*)

Four indicators were used to determine the 'Access' component – access to safe water supply (A_1), reports of conflict related to water use (A_2), access to irrigation (A_3) and access to sanitation (A_4) (see Table 1). For A_1, A_2 and A_3, X_o is the observed number of the measure from the households and X_h is the total number of the household. For the proportion of the

Table 1 | WPI components and corresponding indicators utilized in calculating the three study areas, Speightstown, Carriacou and Nariva

				Data Source		
Component	**Indicator**	**Calculation**	**Scale**	**Speightstown**	**Carriacou**	**Nariva**
Resource (R)	R_1 – Available surface water and groundwater	Water availability: $R_1 = \frac{R_i - R_{min}}{R_{max} - R_{min}} * 100$	Catchment	Maharaj (2016)	NA Wilson & Mandal (2015)	WASA (2013)
	R_2 – Quantitative evaluation of variability of water resource	Precipitation coefficient of variation: $CV = (SD/\bar{X}) * 100$	Country/ Catchment	CIMH (2016)	CIMH (2016)	CIMH (2016)
	R_{3a} – Practice water treatment	$R_{3a} = \left(\frac{X_a}{X_h}\right) * 100$	Catchment	This study	This study	This study
	R_{3b} – Microbiological quality of water – faecal contamination	$R_{3b} = 100 - \left(\left(\frac{X_a}{X_h}\right) * 100\right)$	Catchment	This study	This study	This study
	R_{3c} – Chemical water quality	Schuller Classification Method (Ehteshami *et al.* 2014)	Catchment	Savory (2013)	Peters (2011), UNDESA (2012)	Bacon *et al.* (1979) and IMA (1998)
Access (A)	A_1 – Access to clean water – public piped water supply (%)	$A_1 = \left(\frac{X_a}{X_h}\right) * 100$	Catchment	This study	This study	This study
	A_2 – Reports of conflict over water use	$A_2 = \left(\frac{X_a}{X_h}\right) * 100$	Catchment	This study	This study	This study
	A_3 – Access to irrigation coverage	$A_3 = \left(\frac{X_a}{X_h}\right) * 100$	Catchment	This study	The study	This study
	A_4 – Households with access to improved sanitation (%)	$A_4 = \bar{X}\ (A_l,\ A_S,\ A_c)$	Catchment	This study	This study	This study
Capacity (C)	C_1 – Wealth assessed by ownership of durable items and land (%)	See text	Catchment	This study	This study	This study
	C_2 – Child mortality rate under 5 years (per 1,000)	$C_2 = 100 - \left(\left(\frac{C_m}{1{,}000}\right) * 100\right)$	Catchment	World Bank (2019)	World Bank (2019)	World Bank (2019)
	C_3 – Education level – at least primary school education	$C_3 = \bar{X}\ (C_n,\ C_p,\ C_s,\ C_t)$	Catchment	This study	This study	This study
	C_4 – Membership in water-users association (%)	$C_4 = \left(\frac{X_a}{X_h}\right) * 100$	Catchment	This study	This study	This study
	C_{5a} – Access to sufficient health care	$C_{5a} = \left(\frac{X_a}{X_h}\right) * 100$	Catchment	This study	This study	This study
	C_{5b} – Households reporting illness due to water supply (%)	$C_{5b} = 100 - \left(\left(\frac{X_a}{X_h}\right) * 100\right)$	Catchment	This study	This study	This study
	C_5 – Perceived health status	$C_5 = \bar{X}\ (C_{5a}, C_{5b})$	Catchment			
	C_6 – Households receiving a pension, remittances or wages (%)	$C_6 = \left(\frac{X_a}{X_h}\right) * 100$	Catchment	This study	This study	This study
Use (U)	U_1 – Domestic water use (litres per capita per day)	$U_1 = \left(\frac{X_a}{X_h}\right) * 100$	Catchment/ Country	Maharaj (2016)	Peters (2006)	Peters & Monrose (2016)
	U_2 – Agricultural water use, proportion of irrigated land to total cultivated land (%)	$U_2 = \left(\frac{X_a}{X_h}\right) * 100$	Catchment	FAO AQUASTAT (2016)	FAO AQUASTAT (2016)	FAO AQUASTAT (2016)
	U_3 – Water conservation practiced	$U_3 = \left(\frac{X_a}{X_h}\right) * 100$	Catchment	This study	This study	This study
Environment (E)	E_1 – Deforestation in last 5 years (%)	$E_1 = 100 - \left(\left(\frac{X_a}{X_h}\right) * 100\right)$	Catchment	This study	This study	This study
	E_2 – Land with no erosion (%)	$E_2 = 100 - \left(\left(\frac{X_a}{X_h}\right) * 100\right)$	Catchment	This study	This study	This study

population with access to safe drinking water (A_1), access referred to water that was connected to a public distribution water supply, on the assumption that such water would be treated in the context of standards set at a national level.

Access to improved sanitation (A_4) was estimated from the surveyed households where respondents were asked what type of sanitation system was used. These were then assigned a scale score based on principles described by Garriga & Foguet (2010). For this indicator, scores were assigned for use of pit-latrine (25%), soakaway and well (50%), septic tank (75%) and central distribution system (100%), the latter case being most ideal. For this equation, $A_l =$ number of householders who have access to a pit-latrine, $A_s =$ number of householders who have access to a soakaway and septic tank, $A_c =$ number of householders who have access to a centralized sewerage treatment system.

Capacity (C_i)

The indicators used to assess this component were ownership of durable items and land (C_1), child mortality (C_2), level of education (C_3), membership in any environmental groups (C_4), access to adequate health care (C_5) and economically active population (C_6) (see Table 1). Calculations for durable items were based on ownership of tangible assets as follows:

$$C_1 = \bar{X}\left(\left(\frac{C_c}{X_h}\right)*100,\ \left(\frac{C_t}{X_h}\right)*100,\ \left(\frac{C_h}{X_h}\right)*100,\ \left(\frac{C_s}{X_h}\right)*100,\ \left(\frac{C_{tv}}{X_h}\right)*100,\ \left(\frac{C_{wm}}{X_h}\right)*100\right) + \left(\left(\frac{C_l}{X_h}\right)*100\right)$$

where C_c, C_t, C_h, C_s, C_r, C_{tv}, C_{wm}, $C_l =$ number of householders who own a car, telephone, house, stove, refrigerator, television, washing machine and land, respectively. $X_h =$ total number of household survey respondents.

Child mortality data (C_2) was sourced from published national data on the respective countries, where $C_m =$ national child mortality. To reflect low mortality rate as a positive attribute, the value as a percent was subtracted from one hundred.

The education (C_3) scores were determined by applying scale scores to the level of education, which allowed for capturing the nuances between the different countries beyond a standard definition of literacy rate, as defined by the percentage of the population that could read and write at 15 years of age. The scale scores were: no formal education, C_n, (25%), primary school, C_p, (50%), secondary school, C_s, (75%) and tertiary, C_t, (100%) education attainment level. These scale scores were used to add a level of sensitivity to this metric. The level of education indicator included respondents who did not attain any formal education (C_n), household respondents who attained primary school education (C_p), household respondents who attained secondary education (C_s) and household respondents who attained tertiary education (C_t).

For $C_{4\text{-}6}$, X_o is the observed number of the measure from the households and X_h is the total number of the household. C_4, established the proportion of households who have members that are part of an environmental group, which was used as a proxy to householders who are part of any water user's association. In terms of C_5, access to health, two datasets were used. The proportion of the population who indicated they had access to sufficient health care, C_{5a}, and the proportion of the population who indicated they did not get ill from drinking water in their community, C_{5b}, and both were averaged to provide the final C_5. The final measure of capacity was taken as the percent of persons within the economically active population (18–65 years of age) who received a wage or pensions. The information was sourced from the questionnaire.

Use (U_i)

Water use was assessed in three ways – domestic (U_1), and agricultural (U_2), and the practice of water conservation (U_3) (see Table 1). For $U_{1\text{-}3}$, X_o is the observed number of the measure from the households and X_h is the total number of the household. There are no substantial industrial activities in any of the catchments and tourism activity was higher in Barbados and Carriacou than Nariva (Maharaj 2016). The domestic water use was based on average litres per capita per day (lpcpd). The approach here sought to determine if there was enough water available for basic household requirements, based on a range from inadequate access (<5.3 lpcpd) to optimal access (>100 lpcpd) (Howard *et al.* 2020).

Agricultural water use was estimated as the proportion of irrigated land to the total cultivated area U_2, which was taken from national published data as reliable data was not available at the local level. For Barbados, data from 2005 was used based on stakeholder feedback suggesting increase in irrigation reflected national decreases in agriculture rather than changes in irrigation at a catchment level as well as the mixed agriculture use in Speightstown. For the proportion of persons who practiced water conservation, U_3, the data was sourced from the survey.

Environment (E_i)

To estimate the environment's contribution to water resources assessment, proxies were deforestation (E_1) and frequency of land erosion (E_2) in the last five years. For E_1 and E_2, X_o is the observed number of the measure from the household survey and X_h is the total number of households. For deforestation, data was also sourced from the survey where respondents were asked if deforestation had occurred in their area in the last 5 years. Similarly, for erosion, data was sourced from the survey where respondents were asked if erosion had occurred in their area in the last 5 years. To reflect lower scores for deforestation and erosion as positive attributes, reverse scoring was utilized, where values as a percent were subtracted from one hundred in calculating the WPI.

Aggregation

The additive approach was the aggregation method used for calculating the WPI. The calculation of the WPI may vary depending on the weighting assigned to the components. WPI with equal weighting, described by Sullivan *et al.* (2003), was used for this study. The values for the final WPI ranges from zero to 100, with increasing values representing a lesser water-poor situation and 100 representing an ideal or 'water rich' situation.

RESULTS

WPI components

A total of 606 surveys were used to collect data for calculating the WPI for Speightstown ($n = 205$), Carriacou ($n = 188$) and Nariva ($n = 213$). The normalized scores for all components and indicator are detailed in the following section.

Resources

The results calculated for water availability and per capita water supply for all three study sites are shown in Figure 2. All values are given as Log_{10} for better presentation of vastly different quantities of water across the sites. The Falkenmark's threshold of 1,000 m^3 as an indicator of water scarcity is indicated as a horizontal line. The water per capita per day (lpcpd) was similar in all the communities, despite their different sources of water. Additionally, the lpcpd values were lower than the Falkenmark Threshold of 1,000 m^3 per person per year for Carriacou and Speightstown.

The highest water availability per capita was observed in Nariva, which ranged from 34,188 m^3 for the dry season to 102,564 m^3 for the wet season in an average year using surface discharge estimates (UWI 2008), which was adjusted for population. This water is accessed in low levels for community supply and irrigation because of the very low population density in

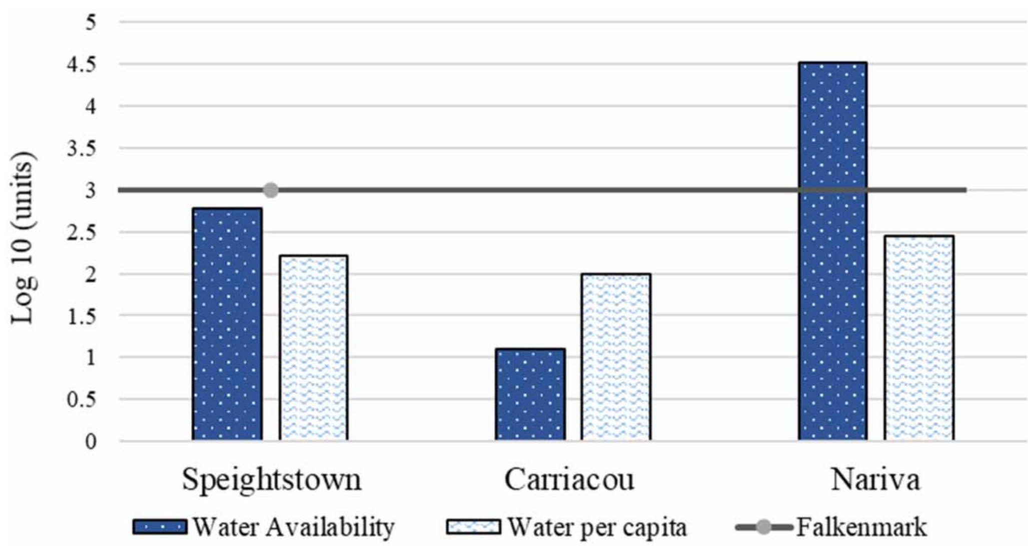


Figure 2 | Water availability (m^3) and per capita water availability (lpcpd) in Speightstown, Carriacou and Nariva. The Falkenmark Threshold (m^3) is indicated by the solid horizontal axis. All values are logarithm for data presentation purposes. Actual estimated water availability per capita per year was 32,610.47 m^3 for Nariva, 588.66 m^3 for Speightstown and 12.71 m^3 for Carriacou. Per capita water availability was 165 lpcpd for Speightstown, 100 lpcpd for Carriacou and 276 lpcpd for Nariva.

the area. Access to potable water from the public distribution system is limited to intermittent supply due to infrastructural challenges. From the survey data collected for this study, it was established that 26.9% of respondents used rainwater as their main water source and this proportion of the respondents was assigned an estimated value of 95 lpcpd as determined from metered data of average per capita consumption by Peters & Monrose (2016). A Regulated Industries Commission study (RIC 2018) found that water use in Trinidad and Tobago was 343 lpcpd, therefore this figure was used for the remaining proportion of the overall figure for Nariva, giving a figure of 276 lpcpd. While the Navet dam, a reservoir for supplying the national public water supply system, is in this catchment, most of the water is not utilized in the catchment but is redirected to densely populated communities to the west of the island. Drinking water is sourced from a central distribution supply, rainwater harvesting or from a truck-borne supply purchased or provided free by WASA.

In Speightstown the water availability from groundwater sources was estimated to be 589 m^3 per year, which indicates it is a water-scarce community. Both water per capita and water availability were lowest in Carriacou. The water availability in this community was reported to be as high as 121,910 m^3 per year, which was derived from groundwater data that was estimated to contribute 334 m^3 per day from a number of dug wells and boreholes (UNDESA 2012). When population was accounted for, this resulted in a value of 12.71 m^3 per capita per year, which indicates an absolute water scarcity situation for Carriacou.

In terms of variability of water resources, the normalized precipitation coefficient of variation was highest for Carriacou (47.64), followed by Nariva (44.35) and Speightstown (34.37). Higher values reflect higher variability, which may be due to geographical and meteorological characteristics of the catchments and the extent of higher extremes in very dry versus very wet periods.

Overall water quality scores were highest in Speightstown (68.08%), followed by Carriacou (64.48%) and Nariva (62.99%). In terms of microbial water quality, *E. coli* (culture-based method) was detected in all three study areas. Using reverse scoring to reflect a positive status with lower number of positive samples, Speightstown scored highest (93.30%). This score could have even been higher, but a few households used environmental sources of water occasionally, which had a relatively high prevalence of *E. coli*. Scores for Nariva (48.60%) and Carriacou (38.30%) were lower than Speightstown, which was due to higher use of poorer quality stored water and rainwater in both communities.

The summary of the indicator for calculating the Access, Capacity, Use and Environment components of water resources is given in Table 2 and a comparison among the three communities is shown in the radar plot in Figure 3. Access to safe water was defined as having a public supply and this indicator was the lowest in Carriacou (0.53%) with largely no access to a public

Table 2 | Calculated indicators for Speightstown, Carriacou and Nariva

Components	Indicators	Speightstown	Carriacou	Nariva
Resource	Availability	45.42	–	30.05
	Water variability	38.37	47.64	44.35
	Water quality	68.08	64.48	62.99
Access	Access to safe water	100	0.53	74.65
	Population not experiencing conflicts over water use	100	97.87	95.31
	Access to irrigation	0.00	65.00	25.42
	Access to improved sanitation	89.57	82.13	81.34
Capacity	Ownership of land and durable items	52.87	54.71	58.56
	Population not affected by child mortality rate (per 1,000) (%)	98.80	98.50	98.20
	Education attainment	86.70	87.18	79.87
	Membership in community environmental group	0.98	7.45	7.04
	Economically active population	77.07	78.87	81.91
	Perceived health status	91.95	81.91	94.13
Use	Average litre per capita per day	100	100	100
	Proportion of irrigated land to the total cultivated area	39.00	4.00	7.02
	Water conservation measures practiced	52.68	79.81	37.77
Environment	Population not experiencing deforestation in the last 5 years	91.49	97.07	85.45
	Population not experiencing land erosion in the last 5 years	96.59	74.47	83.57

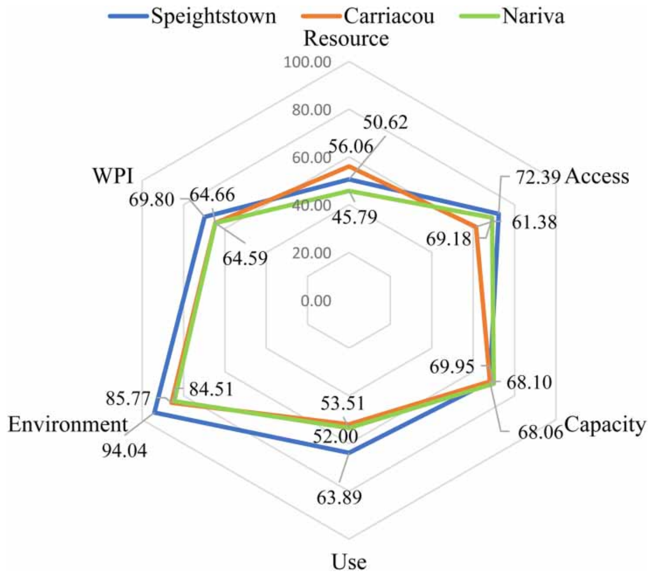


Figure 3 | Radar chart of all five components of the WPI and the final calculated WPI for Carriacou (values closet to data lines), Nariva (values on the inner side of data lines) and Speightstown (values on the outside of data lines). Calculated values for Carriacou – WPI = 64.66, *R* = 56.06, *A* = 61.38, *C* = 68.10, *U* = 52.00 and *E* = 85.77; for Nariva – WPI = 64.59, *R* = 45.79, *A* = 69.18, *C* = 69.95, *U* = 53.51 and *E* = 84.51; and for Speightstown – WPI = 70.32, *R* = 50.62, *A* = 72.39, *C* = 68.06, *U* = 63.89, *E* = 94.04.

distribution supply as compared to Speightstown (100%) and Nariva (74.65%). Generally, all Access indicators were high except irrigation, as this practice occurs only to minor degrees in the different catchments. In Speightstown (0%) and Nariva (25.42%), irrigation was low based on data from respondents in the various communities interviewed. In terms of access to improved sanitation, the score was lowest in Carriacou (83.25%) because of the relatively higher use of pit latrines. Also, across all communities, the lack of connection to a centralized sewage treatment facility lowered scores.

For the Capacity component, ownership of land and durable items was low for all three communities, mainly due to low ownership of land, ranging from 30.24% in Speightstown to 36.70% in Trinidad. The childhood mortality rate, level of education, economically active population and health related scores were generally high, ranging from 70 to 99%. However, a notable difference was observed in two areas. One was in the indicator of membership in community environmental groups, with all communities having exceptionally low scores (Speightstown, 0.98%, Nariva, 7.04% and Carriacou 7.44%). The indicator for education, using categorized data, was over 10 units lower in Nariva (62.56%); a figure attributed to the number of respondents who indicated they had not completed any formal education.

The Use component had quite different scores for the three indicators. For domestic water use, all countries scored a total of 100% based on water use from national data. The proportion of irrigated land to total cultivated area was generally low, but the highest was in Speightstown (39%) based on published national data, although no respondents previously indicated they utilized irrigation. Identified engagement in water conservation practices was highest in Carriacou (79.81%), followed by Speightstown (52.68%) and Nariva (37.77%).

Finally, for environment, observation-based deforestation rates were low, thus scores were high for Carriacou (97.07%), Speightstown (91.49%) and Nariva (85.45%). However, observation-based erosion impacted Carriacou the most with the lowest value of 74.47%, followed by Nariva (83.57%) and Speightstown (96.59%).

WPI aggregation

A one-way ANOVA test showed there was not a statistically significant ($p>0.05$) difference among WPI scores across the three sites. Speightstown (70.32%) had the highest WPI score, followed by Carriacou (64.66%) and Nariva (64.59%). These results correspond to calculations based on equal weighting. According to a classification system by Azqueta & Montoya (2017), scores for the different water poverty categories are: <48 = severe; 48–55.9 = high, 56–61.9 = medium; 62–67.9 = medium–low; and 68–77.9 = low. A value of 100 represents no water poverty. Based on this classification, Carriacou and Nariva experience medium-low water poverty and Speightstown experiences low water poverty.

DISCUSSION

Utilizing the framework established by Sullivan *et al.* (2003), the WPI was calculated for the communities of Speightstown, Nariva and Carriacou. Previous calculations using the WPI method by Lawrence *et al.* (2002) at the country level were slightly lower for Barbados (66) compared to Speightstown (70) in the current study but higher for Trinidad and Tobago (59) when compared to the calculated value for Nariva (65). However, different indicators and scales were used for both studies, so they should not be closely compared. For instance, in the Resource component, there was no accounting of water variability in the study by Lawrence *et al.* (2002) for the national level WPI. The inclusion of additional parameters in this WPI, such as water quality, makes it more robust and better able to reflect the water resource context and related implications, as has been done in other indices (Chaves & Alipaz 2007) but not traditionally included in WPI calculations. Similarly, the indicators used for the Capacity component in the Lawrence *et al.* (2002) study included Log GDP, UNDP education index and the Gini coefficient, data which was not available at the community level and for which more suitable approximates were sourced directly from the community.

Most studies on water poverty have been explored in large countries where even catchments were orders of magnitude larger than the sites examined here (Nadeem *et al.* 2018). The current analysis characterizes Small Island Developing States such as those in the Caribbean, so comparisons to other studies on larger regions or countries may be of limited relevance in this context. Nonetheless, WPI from other studies in the last 10 years have ranged from severe water poverty in Egypt (WPI = 39.8 average, 14 indicators, 22 governorates) (Jemmali & Sullivan 2014) to low for the Nepalese Kali Gandaki River Basin (WPI = 49.2, average, 14 indicators, 13 administrative areas) (Manandhar *et al.* 2012). At the village level in Pakistan, with scales similar to this study, WPI scores were in the medium range (WPI = 60.3 average, 22 indicators, 10 villages) (Nadeem *et al.* 2018). All these WPIs contained different sub-components in their calculations that were location specific, so comparisons are more relevant for socio-economic issues and an assessment of the methodology applied.

More recent WPIs have applied weights to the sub-components in the calculation of the WPI. This approach is subjective by design (Garriga & Foguet 2010), and thus can have the potential to diminish the ability to compare indices across studies, although details and justification of the various weights used in local contexts are usually provided. Also, the effect of individual sub-components such as poor water quality or access to water during a natural disaster crisis can have disproportionately significant effects on the main component (Garriga & Foguet 2010).

With respect to the previous attempts at categorization of water poverty (Azqueta & Montoya 2017), the results of this study suggest that Carriacou, Nariva and Speightstown fall into the medium-low to low water poverty categories. While it is tempting to equate the lower WPI scores to higher water poverty or lower water related welfare, the various individual inputs in the index must also be taken into consideration when assessing the overall welfare related to the water resources, and may be as important in making conclusions and guiding decisions as the overall score itself (Sullivan 2002). These sub-components also have important implications for meeting SDGs where it is noted that 'focusing on individual Goals and targets – would imperil progress across multiple elements of the 2030 Agenda' (Messerli *et al.* 2019). In the case of the three communities in this assessment, the relatively high scores from the Environment and Access components assisted in buffering or even eclipsing (Garriga & Foguet 2010) the lower scores of other components.

Resources

The resources component of the WPI generally had the lowest scores across all study sites. These communities have limited available data on water resources, suggesting the need for further monitoring and data collection especially in Carriacou where substantive temporal data on water resources was unavailable (Wilson & Mandal 2015). Very few households access groundwater, recent estimates of 9 m^3/day, which is used mainly for non-potable activities because of its salinity (Peters 2019). This also limits the extent of comparison across the three indices, but the effect of using measured data for Nariva and Speightstown was considered to outweigh the use of alternative methods. Interestingly, national renewable internal freshwater resources per capita were lower for Barbados (279 m^3) in 2017 (World Bank 2019) when compared to the estimate for Speightstown (588 m^3), which was mainly due the lower population density of this catchment. Conversely, Grenada's (1,804 m^3) internal freshwater resources per capita was higher than Carriacou, which are different islands. In the case of Trinidad (2,774 m^3), when compared to Nariva catchment, the water availability per capita was magnitudes higher because of the very high precipitation experienced in Trinidad in general but also specifically on the east coast of the island and the low population density of the Nariva catchment.

For the availability sub-component, other researchers have utilized a range of measurement methods, which included *water quantity sufficiency and reliability of supply* data from district level water audits (Garriga & Foguet 2010), *per capita annual water resources* (Manandhar *et al.* 2012), *internal freshwater flows* (Jemmali & Sullivan 2014) and *existence of a water supply in close proximity* (Azqueta & Montoya 2017). For variability, the normalized score for coefficient of variation was lowest in Speightstown (38.37), which suggests the potential for a higher climate related risk such as from the vulnerability related to harvesting of rainwater when compared to Nariva and Carriacou (Hamouda *et al.* 2009; Aladenola *et al.* 2016).

A greater focus on water infrastructure conservation (e.g. water recycling) and augmenting water supplies (e.g. increased rainwater harvesting) would further aid in the development of the water resources sector. A study of the Caribbean showed that many countries are highly impacted by hurricanes and storm events, so improving community level water infrastructure would also be important to reduce vulnerability by increasing capacity to deal with natural disasters (Mohan 2016). This would also be important given that some degree of severe to moderate drought and drought-like conditions were experienced in Trinidad and Barbados during part of the year within recent times (CARICOF 2021).

The benefits of the water infrastructure that has been adapted to low water availability are already evident in Carriacou, with the high usage of rainwater harvesting in cisterns and tanks which contributes to a higher degree of resilience. However, this did not confer a statistically significant difference in the calculated WPI when compared to the other study sites. In Nariva the figure of 276 lpcpd which was derived using a combination of data from the RIC (2018) and field data from Peters & Monrose (2016) appears to be high given that there is an intermittent water supply on the island (RIC 2018) and the number of days without water per month has been reported to be as high as 10 days in Nariva (Shah *et al.* 2013). However, metered rainwater data from another community, Toco, in Trinidad was also high at 240 lpcpd (Peters & Monrose 2016) reflecting the impact of higher rainfall in Trinidad and Tobago, which is especially the case on the east of the island, on water use practices. While conservation measures are practiced, they are often rudimentary and highly variable based on the survey responses for this study. There was limited implementation of technology-based approaches such as utilization of lower flush toilets, rainwater harvesting or irrigation, which would increase water efficiency.

Water scarcity resilient practices and culture

As noted above, Carriacou is a good example why using physical water scarcity to assess the water resource situation is not ideal. While the water per capita values based on available data are acutely below the Falkenmark indicator of 1,700 m^3 per year, residents' practices afforded some resilience to their water supply. Additionally, for Carriacou, domestic rainwater harvesting storage across the island was estimated to be 526 m^3/d in 2016 with estimated deficits due to demands from tourism, climate change and increasing per capita demand (Peters 2019). From field observations and responses from survey respondents, there is a significant sense of community and camaraderie among residents, and persons without cisterns indicated they are freely allowed to use the water from neighbours who are absent from the island for extended periods of time. Practices such as this, as well as water 'loaning' within families (Peters 2019), would serve to counter the low score (7.45%) response rate for respondents who indicated that they were not active in any community environmental groups. Thus, the overall score was far from indicative of a severely water stressed area.

Storing water has been the main practice that allows communities to have water available for domestic use. Over the years increased storage infrastructure has been occurring on the island as residents gain resources to do so. Carriacou, like Nariva also employs several shallow ponds that are important for livelihoods, especially irrigation and fisheries in a few communities during the dry season. Additionally, the variability in precipitation from dry to wet season is such that there are periods of low, or no flow, especially in Nariva, which have had ecohydrological and socioeconomic consequences for communities that rely on rivers for crop irrigation.

In terms of water resources, the practice of treatment of water is an interesting indicator of cultural differences related to water quality. From survey data, the frequency of treatment of water showed that respondents in Carriacou (71.81%) indicated the highest rate of treating water by any means, followed by Nariva (40.38%) and then Speightstown (29.26%). This suggests communities with higher rates of water storage see the practice as an important one. Furthermore, storage of water and interruptions in water supply can both affect water quality as sources of contamination may be introduced (Hamilton *et al.* 2019).

Unimproved water sources and the inclusion of water quality variables

All communities use water from 'unimproved' sources for drinking at some point during the year, particularly in the dry season. Unimproved sources include unprotected springs, small tanks and drums, truck borne water, untreated surface water, and bottled water (WHO 2017). According to the Guidelines for drinking-water quality, bottled water may be deemed improved supply 'only when the household uses drinking-water from an improved source for cooking and personal hygiene' (WHO 2017). These have consequences for the microbial contamination which can impact human health. Also, in terms of safety, water piped indoors is another measure that should be considered in the context of water safety. Additional data collected from the survey showed that, while households had access to a safe supply of water, it is not often piped into the home and this can introduce sources of contamination due to collection, usually from a standpipe in the yard, and then transportation, handling, and storage in the home.

For water quality, although *E. coli* continues to be an important microbial water quality indicator and the results show that the relative abundance of this indicator organism was low in treated water samples. However, environmental sources of water that were not treated had relatively high prevalence rates for *E. coli* and hence increasing the practice of water treatment in households that use these water sources would contribute to improve the score of this component. For Speightstown, the coastal zone supports the highest level of international tourism as well as urbanization. This has implications for water quality, such as high concentration of nitrates entering the coastal environment (Sealy 2009). Given that water quality is not routinely measured, additional studies are required to make further assessments on possible impacts to water resources. While water availability for Speightstown may be relatively low as there are concerns about the effect of abstraction on water quality and the risk of saline intrusion, additional pressure is put on water resources due to water demand for the tourism sector.

Overall, for the Resource component, water availability data are not routinely measured on a catchment scale in all three sites. For instance, in the absence of rainfall data for Carriacou itself, data was instead used for the main island of the country, Grenada. Exact rainfall resources may be slightly different or have a higher coefficient of variation for precipitation. This would be important in the future, to provide a long-term assessment of water resources in the catchment. Estimates were made available based on limited data and low data resolution. This may result in different values as compared to yearly measurements taken over a longer time frame on the island.

Use and availability

The Use component contributed the second lowest scoring component of the overall WPI. This arose due to lower scores for sub-components in proportion of irrigated land to cultivated area, and the extent to which water conservation measures were practiced. In Nariva, abstraction for irrigation from river water sources is one area of interest for water conservation especially from an environmental perspective. In certain rivers and channels that support the Nariva Swamp at the end of the catchment, such as the Poole River and the Jagruma cut, ongoing abstraction activities warrant attention. However, there have been no detailed studies on the rate of abstraction of these rivers.

In Carriacou, rainwater storage sustains most of the residences on the island. Additionally, many residences are unoccupied for periods of the year as residents live abroad, which would reduce the per capita water needs. However, disparity in rainwater harvesting infrastructure is also a concern in Carriacou where a greater catchment area could lead to improved water per capita for residents (Peters 2006). In Barbados, no data was collected from the tourism sector. This could affect the WPI values collected, further dropping the value as water use from the tourism sector is higher than local use as detailed by Charara *et al.* (2011). Another point to note for the Use component is that water demand can vary depending on local habits and cultural practices. In general, water usage is high in the Caribbean. Standards and reference values on water use efficiency, conservation and typical amounts of water that should be used, need to be established to aid in water resource management.

Capacity

The capacity component had relatively high values, but the first sub-component related to ownership and durable items as proxy for wealth was low. Additionally, both education and the economically active population sub-components were not as high as other sub-components. These contributed to lowering of the overall Capacity component score, which suggests there is room for improvement towards an overall higher WPI score as Capacity contributes to well-being within a population, both in economic and physical terms. This has for instance been observed in rural Caribbean Columbian coastal communities where Ruiz-Díaz *et al.* (2017) have demonstrated direct linkages between water supply, health and socio-economic factors (education and income).

Climate related effects on Capacity are also important as the climate change impacts as a cost of GDP is high in the small island tourism-based economies (SITEs), averaging as high as 0.51 (Peterson & DiPietro 2021). Barbados and Grenada are SITEs and respondents from both Speightstown and Carriacou included those involved in tourism-related professions such as cooks, managers, landscapers, outdoors seamen, boat builders and farmers. Ruiz-Díaz *et al.* (2017) noted that income is affected by the type of job and that the nature of a job can affect its stability. Reliance on tourism, which is impacted by climate and is vulnerable to natural disasters, could affect welfare and poverty levels. Thus, the vulnerability of individuals depending on this sector may affect their willingness or ability to prioritize investments to improve their water resource infrastructure at the household level.

The practice of underground cisterns has been used to sustain the water resource needs in Carriacou, but this form of storage may also have potential application in Speightstown, to supplement the high water use in this tourism-dependent community (Charara *et al.* 2011). As a water-rich area, Nariva is currently moving away from rainwater harvesting, but increased storage could aid in augmenting the community's water supplies. This can be combined into a flood management plan as well, since there are often periods during the year when there is excess water that can be stored or delayed (Collentine & Futter 2018; Castillo & Crisman 2019). The use of ranking for educational level attainment can help to characterise education beyond the literacy rate, and values of Nariva were indeed lower than national mean. However, for future studies, education attainment levels should be calculated for the entire household, as family members who stay at home and were available during the times when the survey was conducted are often the ones supporting members who are working or studying. All capacity measures are important as they point to factors that can contribute to better management of water resources.

Access variables across the communities

Access values measured from four indicators were generally high across the three study sites, with Environment being the only component with a higher score. The scores were highest for Barbados (72.39%) and Nariva (70.11%), but expectedly lower for Carriacou (61.66%) due to the heavy reliance on rainwater harvesting, which was also the case with Nariva, but to a lesser degree. There are also very few water conflicts in the communities, which are limited to the provision of water in the dry season for truck-borne supply in Carriacou and Nariva.

Access to improved sanitation was 10 to 15% lower than national data for the three sites, mainly because a new and different method for qualifying improved sanitation was used in this study, beyond just presence or absence of an improved sanitation system. Ranking sanitation methods was done to indirectly consider potential impacts to groundwater and related environmental issues that connection to a centralized wastewater treatment system would reduce, if not negate. Alternatively, the use of alternative green infrastructure-based wastewater management can be explored in such rural areas as well (Castillo & Crisman 2019). This approach added a degree of sensitivity to the overall access component. This assisted in capturing households that used sewer systems not connected to a central treatment system, and pit latrines that may have some environmental implications in rural communities.

Irrigation usage was high in Carriacou (65.00%) based on those interviewed. This may be due to the long-standing practice of using pond water on this island but may be an over-estimation of the situation in terms of industrial scale agriculture, which involves high volume demand irrigation systems. Respondents expressed concern regarding lower rainfall affecting the availability of water for their crops, with corn and peas being the most noted crops. Longer dry spells were also important because the absence of sufficient rain resulted in additional costs to pay for animal feed to sustain their livestock.

Environmental indicators in the Water Poverty Index

The Environment component perhaps has the most variable number of inputs across all sub-components. Environmental sub-components from other studies include number of pollution sources (Garriga & Foguet 2010), chemical fertilzer use per cultivated area (Manandhar *et al.* 2012), perceived quality of the natural environment (Azqueta & Montoya 2017), risk of flooding and risk of desertification (Shalamzari & Zhang 2018). The choice of inputs for this sub-component can affect the overall score of the WPI. Additionally, one of the early versions from the WPI has 5 inputs including *water quality*, *water stress*, *regulation and management capacity*, *informational capacity* and *biodiversity* (Lawrence *et al.* 2002). However, such indices are not easily available at the local community level and in the current study, water quality was included in the Resource component. Another early version had 3 inputs – *people's use of natural resources*, *reports of crop loss* and *% households reporting erosion* (Sullivan *et al.* 2003) which is more appropriate for data-scarce contexts. The current study collected data on crop loss, but this was not included in the WPI calculations because it was not representative of activities at the community level as only a subset of respondents engaged in agriculture. Additionally, crop loss via this approach was deemed very subjective.

For the Environment component, a lack of environmental or community groups was observed across the three study sites. These are important as they can serve as avenues to lobby for environmental issues. Of note also in the environmental component is the relatively high erosion expressed in Carriacou (25.53%) and Nariva (16.43%). Environmental degradation due to activities such as deforestation, selective logging and mining affects vegetative cover as well as river and stream health. Additionally, in Carriacou, these issues result in increased run off rates, which may ultimately decrease groundwater recharge. Soil characteristics make some sites more vulnerable than others. For instance, the highest reported observation of erosion was from Carriacou and may be due to the fact that soils in Carriacou are not very fertile and combined with characteristically high erosivity, high erodibility and very low ability to retain water, the environmental conditions can be considered as vulnerable (CCA 1991). Additionally, drought followed by periods of heavy rainfall may hasten soil erosion and environmental degradation, especially associated with sustained subsistence agriculture and grazing pressure (CCA 1991).

CONCLUSIONS

This study sought to assess the WPI, including water quality in the Resource component, to provide a more complete picture of the water scarcity status of three rural communities in the Caribbean. The calculated WPI provided a context specific assessment of the water resource situation and showed that there are many positive attributes of water resource management in the Caribbean. However, Resource and Use components require urgent attention based on the availability and quality of data inputs. Further improvements to the WPI may be possible by having a greater focus on water quality, drought and water conservation policies including in the areas of rainwater harvesting and irrigation, which are especially important in diverse tropical environments. Other improvements in the three communities included increased attention to sanitation as the reported use of pit latrines decreased the Access score. To improve Resource, longer term strategies for conservation of the river basin in Nariva and the watershed in Barbados would protect river courses and aquifers from deterioration, which has a direct effect on water supply.

FUTURE WORK

The Water Poverty Index study can be calculated for other rural communities and at a national scale for the islands of Barbados, Grenada and Trinidad and Tobago, as well as for other countries in this region using similar metrics identified in this study. This would add to the knowledge base available on the water resource vulnerabilities of these island nations and could be further evaluated with continued stakeholder consultations. There is a need for detailed water monitoring programmes to assist in temporal assessments and water resource planning. The debate on water as a determinant of welfare will only increase due to climate change and variability, and thus the use of tools such as the WPI can assist in advancing this discussion. The case of Carriacou being largely water independent is a model for reference for the entire Caribbean that should be further explored regionally for developing rainwater harvesting policies. A measured assessment of conservation practices, such as uses and recycling of wastewater, could prove crucial to water resources management in the future. This is particularly relevant for Trinidad where water per capita use is remarkably high (RIC 2018). Greater separation of biophysical and human determinants can strengthen the final WPI analysis in future studies. Continued direct community inputs as was done in this survey, though sometimes deemed subjective, can add a rich dimension to futures studies involving assessment tools such as the Water Poverty Index.

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AUTHOR CONTRIBUTIONS

AS, AC, 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 field work investigation for this research. AS, AC, DC and AR finalized the methodology and VT validated the methodology. Funding Acquisition, Project Administration and Resources were supported through the efforts of JA, AC and DC. Writing – Original draft preparation was done by AS and AR. All authors were involved in Writing – Review and Editing except DC.

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DATA AVAILABILITY STATEMENT

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

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