

## REVIEW

# Water resource sustainability: Challenges, opportunities and research gaps in the English-speaking Caribbean Small Island Developing States

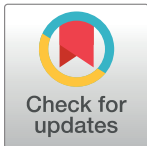
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## Abstract

Small Island Developing States (SIDS) face multiple developmental challenges including the adverse impacts of climate change. Among these complex challenges is the critical issue of devising strategies and plans to achieve water resource sustainability. The combined effects of hydro-climatic hazards such as droughts, rising sea levels, floods and increasing socio-economic pressures have already begun to adversely impact on SIDS water resources. This review article examined studies on ten English-speaking Caribbean SIDS to explore challenges and opportunities for enhancing water resource sustainability in the Caribbean and to identify emerging research gaps. A desk review and synthesis of existing data and available literature including reports, policy documents, peer-reviewed journal articles and books published over the last ten years were conducted to highlight research gaps in water resource sustainability. The conclusion presents a way forward for SIDS to cope with the consequences of climate change on their vital water resources. The findings from this paper can inform regional policies, strategies and plan and direct research to critical areas where information is needed to support evidenced-based decision making. The review is useful for academics, policymakers and practitioners.



## OPEN ACCESS

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## Introduction

The world is facing a climate crisis and Small Island Developing States (SIDS) are at the frontlines of an existential threat as they battle with rising sea levels, frequently occurring extreme weather events, and warming temperatures. SIDS are especially vulnerable, considering the nature of their economies, ecosystems, and inherent geophysical features [1]. Available literature has documented the frequency and intensity of hydro-climatic disasters in recent years and has noted widespread destruction such events have caused. Rising sea levels threaten coastal communities, infrastructure and tourism. Coral reefs, crucial for fisheries and tourism, are bleaching due to warming waters. Climate scientists belonging to the Intergovernmental Panel on Climate Change (IPCC) indicate that these challenges will likely worsen in the

coming decades. Global surface temperature increase has been more rapid since 1970 than in any other 50-year period over at least the last 2000 years, which underscores just how urgent is adaptation to climate change and global efforts aimed at mitigation of greenhouse gases [2]. The Caribbean Region is taking action, but the global community needs to make a concerted effort to rapidly curb emissions and provide climate financing support [3]. The Caribbean's plight highlights the urgent need for international climate cooperation [4]. The Region's water sector and associated water resources are a major concern because climate change impacts are becoming more noticeable. Due to the occurrence of more droughts, some Caribbean islands have already begun to experience water stress, which is defined as when annual water supplies drop below 1,700 m<sup>3</sup> per person. Higher sea levels, more frequent storms, tropical cyclones and droughts along with growing socio-economic challenges such as population growth, will worsen water stress from as early as the 2030s [5].

Water stress arising from insufficient potable groundwater could result in Caribbean atoll islands becoming uninhabitable by the 2030s [5]. Caribbean SIDS are deeply concerned about observed changes and projected impacts on water resource sustainability as their survival and habitability are at stake [6]. An understanding of the current status of water resources is therefore crucial in developing strategies to improve the Region's water resource sustainability in a changing climate.

## Research objectives

This review article aims to identify the challenges facing water resource sustainability among ten English-speaking Caribbean SIDS, discuss opportunities for enhancing water resource sustainability and highlight research gaps.

## Methodology

At the United Nations Conference on Environment and Development held in Rio de Janeiro in 1992, there was consensus that SIDS (38 United Nations (UN) member states) are unique because they face specific social, economic and environmental vulnerabilities. Those from the Caribbean are Antigua and Barbuda, The Bahamas, Barbados, Belize, Cuba, Dominica, Dominican Republic, Grenada, Guyana, Haiti, Jamaica, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Suriname and Trinidad and Tobago. SIDS also comprise 20 non-UN members/associate members of regional commissions which include those in the Caribbean: Anguilla, Aruba, Bermuda, British Virgin Islands, Cayman Islands, Curacao, Guadeloupe, Martinique, Montserrat, Puerto Rico, Sint Maarten, Turks and Caicos Island and U. S. Virgin Islands. SIDS generally have limited land masses and small populations. They suffer from remoteness from international markets, high transportation costs, vulnerability to exogenous economic shocks and fragile land and marine ecosystems [7, 8].

Sixteen SIDS classified by the UN are in the Caribbean Region, but this paper reviews the English-speaking Caribbean SIDS that form part of the Caribbean Community. Antigua and Barbuda, the Bahamas, Barbados, Dominica, Grenada, Jamaica, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines and Trinidad and Tobago were selected for this review. These ten countries are different in population size, land area, elevation, geology, topography, hydrology, water governance and economic characteristics (See Tables 1 and 2). The volcanic islands are mountainous and have more rainfall. The flat islands are invariably composed of porous limestone, have high levels of groundwater percolation and rely on aquifers as the main source of water, although there are some exceptions like Jamaica which is mountainous but relies on groundwater supplies to meet their water needs. Such differences in the sample of

**Table 1. Demographic and physical characteristics of Caribbean SIDS.**

Country	Population	Land Area (km <sup>2</sup> )	Highest Elevation (m)
Antigua and Barbuda	95,882	442	402
Bahamas	332,634	13,900	64
Barbados	293,131	430	336
Dominica	74,027	751	1,447
Grenada	112,207	344	840
Jamaica	2,812,090	10,991	2,256
St. Kitts and Nevis	53,094	261	1,156
St. Lucia	165,510	616	948
St. Vincent and Grenadines	101,844	389	1,234
Trinidad and Tobago	1,215,527	5,128	940

Source: Various

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countries selected allowed for a comprehensive analysis of water resource sustainability challenges faced in these Caribbean SIDS.

A desk review and a collation of available data and literature including reports, policy documents, peer-reviewed journal articles and books published over the last 10 years were conducted to identify challenges and research gaps in water resource sustainability among the selected Caribbean SIDS. The article is a review of academic and grey literature and a review based on the authors' expert knowledge.

## Historical perspective

The Caribbean's water challenges date back to its colonial past when islands functioned as sugarcane plantations and available water resources were mainly used for crop irrigation [9]. However, the sugar industry's decline led to a neglect of water infrastructure which eventually deteriorated. The Region's current water problems, including leakages and water loss can be partly attributed to its neglected, antiquated infrastructure built during colonial times [9].

In 1983, the Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region was established. It focused on the marine environment and not water resource sustainability challenges. Other initiatives were developed to address these challenges, one of the most significant being the Hyogo Framework for Action (2005–2015), which has as its key focus the significance of water in disaster risk reduction. This Framework for Action promotes the development of sustainable water management strategies among

**Table 2. Geographic characteristics and main source of water supply.**

Geographic Characteristics	Main Source of Water Supply			
	Groundwater	Surface water	Desalination	Rainwater Harvesting
Flat, low lying	Bahamas		Cayman	
Flat, corraline	Barbados		Antigua and Barbados (25%)	
Mountainous, Volcanic	St. Kitts	Dominica Grenada St. Lucia St. Vincent	Grenadines	Grenadines
Mountainous with coastal plains	Jamaica	Trinidad and Tobago		

Adapted from: Global Water Partnership. Integrated Water Resources Management in the Caribbean: The challenges facing Small Island Developing States. GWP 2014.

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Caribbean SIDS. The Sendai Framework (2015–2030), succeeded the Hyogo Framework placing more emphasis on natural hazard prevention and preparedness as opposed to response and recovery highlighting the need to invest in the proactive management of natural hazards.

The Sustainable Development Goals (SDGs), Agenda 2030, launched in 2015 by the United Nations recognized the high significance water plays in sustainable development. The SDGs increased coverage, extending beyond just developing countries and included a dedicated goal focused on water and sanitation representing a significant improvement from its precursor the Millennium Development Goals (MDGs). Among the 17 UN SDGs, SDG 6 aims to ensure availability and sustainable management of water and sanitation for all. Coming out of the 2015 launch of the SDGs by the UN, Caribbean SIDS have turned to tracking progress in attaining water and sanitation for all informed by 8 targets and 11 indicators of SDG 6.

## Current key water resource sustainability challenges

### Water resources, climate variability and climate change

In the last decade, the intensity and frequency of extremes have increased, where dry seasons are becoming progressively drier, and the rainy seasons have had unfamiliar torrential down-pours resulting in both flash and riverine flooding in many Caribbean countries [10].

A growing body of research exists on both the impact of climate change and anthropogenic drivers on freshwater resources. Caribbean SIDS have experienced droughts and freshwater shortages in the last decade, which have increased risks to freshwater lenses, groundwater salinization, and food security [11–13]. Drought events have severely reduced freshwater lenses (FWL) recharge. Higher extraction rates driven by increasing population demand and rapid urbanization pose a further threat to available groundwater quantities. Scientific studies have projected that increases in the frequency, intensity and severity of droughts, floods, heatwaves, and sea level rise (SLR) will exacerbate risks associated with water resources in vulnerable regions such as the Caribbean from moderate to high between 1.5°C and 2°C global warming level above pre-industrial levels. More risks associated with these temperature changes are likely where there are no or low levels of adaptation [14]. SLR, storm surges and waves will worsen coastal inundation and the potential for increased saltwater intrusion into aquifers [5]. Projections reveal that the Caribbean at 2°C global warming and above, will experience less rainfall during June-July-August which will persist in future decades. Increased aridity and more severe agricultural droughts are expected to occur due to declining rainfall and higher levels of evapotranspiration [14]. Available literature has confirmed that drying is expected to be less in the northern Caribbean and more in the south and southeast [14].

Although the climate change research has covered projected future risks and habitability of the English-speaking Caribbean SIDS due to freshwater shortages, research is lacking on costing population displacement, migration, economic shock, physical health, and psychological stress impacts arising from less water resources. The lack of data on key parameters, non-uniformity in data gathering and management and the quality and coverage of geo-spatial data, limit the accuracy of outputs of recognized climate projection models for the Caribbean region. These limitations prevent accurate discernment of trends and present significant challenges in understanding climate variability and change.

**Food security.** Food security is a growing concern that will be further compromised due to variations in rainfall and salinization of soils. In 2010, Trinidad and Tobago, Grenada, St. Vincent, Barbados, St Lucia, Dominica and Jamaica experienced intense droughts resulting in significant impacts on the agricultural sector. Antigua suffered severe drought seven years later in, October 2017 which was the second driest October since 2000 and the 13th driest on record dating back to 1928 [15]. These major droughts directly impacted food security by

limiting access to water for agriculture, thus reducing crop production. Drought is high on the policy agenda of the English-speaking Caribbean SIDS because 90% of agriculture is dependent on water from precipitation [16]. Hurricanes and floods also damage water infrastructure, for example irrigation lines and water storage tanks which impact on food security.

**Water quality, sanitation and health.** Water quality and sanitation in the Caribbean are critical issues that impact public health. Access to clean and safe drinking water varies across Caribbean nations, with some countries having made considerable progress in providing reliable water sources and improved sanitation facilities. However, challenges persist, particularly in remote and underserved areas, where access to both clean water and adequate sanitation remain limited. Inadequate wastewater treatment, weak control of land-based pollutants such as industrial waste and agro-chemicals together with the vulnerability of freshwater sources to climate change and contamination are ongoing concerns, affecting water quality in some areas [17]. (Within the Caribbean, efforts by governments, international organisations, and non-governmental organisations (NGOs) are aimed at improving water quality, water management and access to clean water and sanitation services. Continuous monitoring and data collection are critical to improve water quality and minimise sanitation issues in the Caribbean [18].

In Barbados, the droughts of 2009–2010 and 2014 put pressure on the health sector, resulting in poor water storage which led to gastroenteritis among the population [19]. Additionally, the *Aedes aegypti* mosquito, the vector responsible for the transmission of dengue, chikungunya, and Zika, proliferated in Barbados and Dominica [20, 21].

The Caribbean Institute for Meteorology and Hydrology (CIMH), Food and Agricultural Organisation (FAO), and Caribbean Public Health Agency (CARPHA) have been collecting more data, which can assist sound policymaking and decision-making in water resources management. Although more data exists in the English-speaking Caribbean SIDS there remains a research gap on the economic costs of impacts on physical and mental health associated with limited water resources due to droughts, floods and SLR. Additionally, despite the vulnerability of the Region, the Caribbean, compared to other regions has fewer peer-reviewed climate and health publications and research on public health preparedness to tackle floods and droughts [22].

## Water supply sources

Trends in supply and demand have been well documented for the selected case study Caribbean SIDS, but research gaps remain. Despite the availability of varied water sources research on water supply projections for SIDS rarely assesses their reliance on multiple water sources [23]. For example, rural communities frequently rely on several water sources, but have a strong dependence on rainwater [13]. The main source of water varies by topography and geology as shown in Table 2. Although an island may be mountainous and volcanic, it relies on groundwater as for example St. Kitts. In contrast, Dominica, Grenada, St. Lucia and St. Vincent, which have similar characteristics, are dependent on surface water [24].

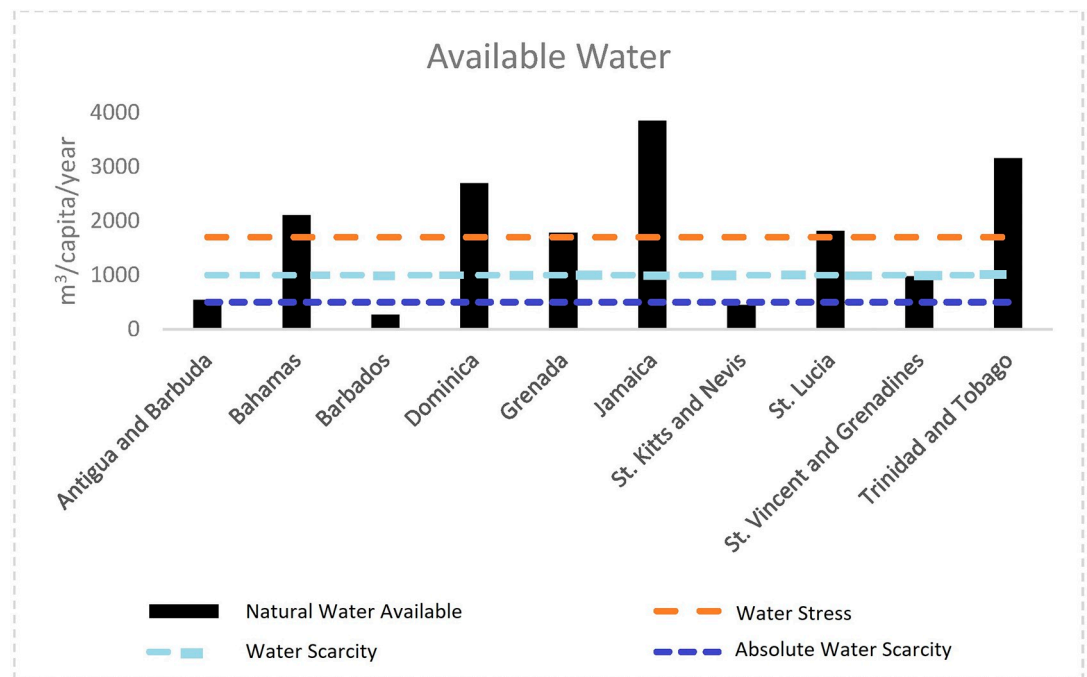
As mentioned earlier, surface and groundwater sources are threatened by land-based pollutants. Approximately 85% of the Caribbean Region's wastewater is untreated [25]. Declining surface water quality is a significant issue among the selected Caribbean SIDS case studies. Some rivers are contaminated with pollutants from several sources including agricultural and urban runoff, industrial activities, and inadequate wastewater treatment [26, 27]. Several rural communities have burgeoned on hillsides without planning permission from town and country planning agencies and are highly dependent on community-based surface water sources which may not meet public health standards [28]. During periods of aridity when rainwater storage is inadequate to meet basic household water needs, Caribbean SIDS rely on

groundwater, specifically freshwater lenses (FWLs), to satisfy the demand for water [29, 30]. However, Caribbean islands are also facing the consequences of SLR, therefore groundwater sustainability cannot be ensured without adequate aquifer protection [27]. Coastal aquifers are endangered due to SLR and require investments to protect them from saline intrusion. There are no recent studies for the selected case studies, which quantify ground water and make projections on the amount of water that may be impacted by different SLR scenarios and droughts.

Desalination has become a common alternative for freshwater supply in the Caribbean, with some countries relying on it for over 70% of their water supply during the dry season [26, 31]. Desalination, however, can have negative consequences such as high energy consumption, increasing production costs, and degradation of the marine environment [32]. Marine resources are a key part of the blue economy and desalination may make it an unsustainable option for many Caribbean countries. More research is required on desalination impacts on ecosystems, ocean resources and implications for the blue economy including jobs in the fisheries and tourism sectors.

### Water stress and water scarcity

Of the ten Caribbean SIDS assessed, only four (Bahamas, Dominica, Jamaica, and Trinidad and Tobago) are above the water stress threshold of 1,700 m<sup>3</sup> per person and are considered water secure [33]. (See Fig 1). Grenada and St Lucia are nearly water stressed. According to the United Nations, when annual water supplies drop below 1,000 m<sup>3</sup> per person, the population faces water scarcity, and below 500 cubic metres "absolute scarcity". St. Vincent and the Grenadines is close to becoming water scarce. Antigua and Barbuda, Barbados and St. Kitts and Nevis currently face the most significant challenges with all three countries considered to be



**Fig 1. Renewable annual freshwater volume for the selected Caribbean islands with indicators of water scarcity, absolute water scarcity and water stress.** Caption Credit: Winters ZS, Crisman TL, Dumke DT. Sustainability of the water-energy-food nexus in Caribbean Small Island Developing States. *Water*. 2022; 14(3):322.

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facing absolute water scarcity. Barbados is using almost 100% of its available water resources and is in the top 15 water scarce countries in the world [34]. Caribbean islands facing absolute water scarcity are concerned because with such limited water resources they will be unable to meet the basic needs of the population, as well as support economic activities such as agriculture, tourism, and industry. In several of the English-speaking Caribbean countries there is a growing gap between freshwater demand and the ability to fulfil such demand. Research is lacking on the quantification of land cover changes and increased water stress. Furthermore, very limited research has been conducted to better comprehend interactions between the water cycle and related priority issues such as improper land use, land degradation, ecosystem functions and vulnerability to hydro-climatic hazards.

A review of the literature revealed that other Caribbean SIDS suffer from a water deficit which occurs when water demand exceeds the available water supply in a given environment [34]. This can occur due to a variety of factors such as increased water consumption, low precipitation, and high evapotranspiration rates [35]. For example, St. Lucia has a 35% water deficit, Nevis 40%, and Trinidad and Tobago has a water deficit dating back to 2000 [25]. Fig 1 shows indicators of water scarcity, absolute water scarcity and water stress in selected Caribbean SIDS for which data was available.

Water scarcity is increasing due to anthropogenic activities associated with the expansion of the tourism industry, accelerated population growth, urbanization, more affluent societies, ineffective water management, and declining water quality. Further, climatic factors will likely result in more droughts [36]. Dominica, Grenada, St. Lucia, St. Vincent and the Grenadines, which rely on surface water, have conducted minimal exploration of freshwater resources such as groundwater [24].

## Water resources management

In accordance with SDG 6, sustainable water resource management aims to achieve various objectives, which include providing adequate water resources to facilitate economic growth, meeting a population's daily water needs, preserving a pollution free water environment, ensuring access to safe potable water, and preventing disasters triggered by flooding and water-logging [37]. By prioritizing these objectives, sustainable water resource management can help to ensure that water resources are available to meet current and future needs while minimizing negative impacts on the environment [37].

Based on available literature and the inputs of Caribbean water managers at the Economic Commission for Latin America and the Caribbean (ECLAC) meeting in 2021, the case study SIDS face a myriad of challenges which stymie water resource management. These challenges include aging infrastructure; excessive water consumption and wastage due to the tariff system; non-revenue water; poor water governance; insufficient data collection and management; and limited implementation of integrated water resources management. Over the last decade these issues have been researched, but research gaps still exist and are elaborated upon in this section.

**Subsidised tariffs and water demand management.** In many English-speaking Caribbean SIDS, residential user tariffs are considerably low due to cross-subsidization policies aimed at ensuring equity and access to potable water among the poor and vulnerable to ensure public health and sanitation [38]. Average water tariffs range from as low as USD0.06 m<sup>3</sup> of water in the Bahamas to USD2.35m<sup>3</sup> in Jamaica [39]. Table 3 shows the average water tariff in this sample is USD1.05 per m<sup>3</sup> and the residential water tariff is USD1.60 m<sup>3</sup>. In particular, the residential monthly bill for Trinidad and Tobago's consumers is extremely low compared to other SIDS in the Caribbean Region due to highly state-subsidized water rates. The country's

**Table 3. Tariffs of water utilities in the Caribbean.**

Water Utility	Abbreviation	Jurisdiction	Average Water Tariff (USD/M <sup>3</sup> )	Average Residential Water Tariff (USD/M <sup>3</sup> )	Residential Monthly Water Bill in 2019 (USD at 15 M <sup>3</sup> )
National Water Commission	NWC (2020)	Jamaica	2.35	1.92	21.40
Dominica Water and Sewerage Company Limited	DOWASCO (2020)	Dominica	1.31	1.11	19.11
Water and Sewerage Authority	WASA (2020)	Trinidad and Tobago	0.51	0.38	4.42
Water and Sewerage Corporation	WSC (2018)	Bahamas	0.06	2.78	37.21
Barbados Water Authority	BWA (2019)	Barbados	N/A	1.84	20.77
National Water and Sewerage Authority	NAWASA (2019)	Grenada	N/A	N/A	21.32
Water and Sewerage Company	WASCO (2016)	St. Lucia	N/A	N/A	16.33
<b>Average</b>			<b>1.05</b>	<b>1.60</b>	<b>23.87</b>

Source: Inter-American Development Bank (IDB). Water Governance in the Caribbean. 2021. IDB joins Alliance for Hydromet Development.

<https://doi.org/10.1371/journal.pwat.0000222.t003>

residential user tariff is not calculated on volumetric consumption but is based on the annual rateable value of property, which has not been revised for more than a decade. The last rate increase was in 1993. Except for Trinidad and Tobago, all other SIDS in Table 3 are charged by volumetric consumption. The reasons for low water tariffs can be traced to Trinidad and Tobago's high level of state paternalism due to oil wealth, public protests over rate increases, and a failure to implement metering due to a weak political will [1, 38, 40]. Research has shown that if tariffs are set too low, there may be a lack of funds to invest in the maintenance and expansion of water infrastructure and it is difficult to manage water demand. A comparative analysis of the advantages and disadvantages of using different tariff systems and their impact on water resource management among the case study Caribbean SIDS has not been researched.

**Financing water resources management.** Water infrastructure is capital intensive and finance is necessary to cover upfront construction costs. As a result, capital costs are absorbed by public utilities and not the private sector in the English-speaking Caribbean SIDS. In the selected case study Caribbean SIDS funding is often limited due to the reliance of public water utilities on state subventions. These subventions are usually directed towards the development of physical infrastructure, operational activities, watershed and flood management, land management practices, and monitoring and reporting. However, recent data collected for fourteen Caribbean islands indicates that most of the financing is allocated to basic water services and improving access to water for domestic and commercial use [41]. Insufficient financing undermines adequate water resources management, research, monitoring, efficient data collection and reporting [42].

**Non-revenue water.** Water resource sustainability is undermined by water loss stemming from Non-Revenue Water (NRW), which is the difference between the amount of water that enters the distribution system and the amount of water billed to consumers. NRW compromises water resource sustainability and reduces revenue generation necessary for improving the sustainability of water resources. It is identified as one of the main constraints facing public water utilities and water companies in the Caribbean [43]. Table 4 shows that the selected case study utilities in the English-speaking Caribbean have NRW levels ranging from 25% to 58% which varies from good to poor. Jamaica's NWC has the highest (58%) NRW in contrast to Grenada's NAWASA with the lowest (25%) NRW.



**Table 4. Nonrevenue water across English-speaking Caribbean water utilities.**

Utility and Country	Nonrevenue Water
National Water Commission Jamaica (2015)	58%
Dominica Water and Sewerage Company (2014)	40%
Water and Sewerage Authority Trinidad (2010)	40%
WSC Bahamas (2015)	38%
Barbados Water Authority (2012))	55%
National Water and Sewerage Authority Grenada (2012)	25%
Water and Sewerage Company St Lucia (2013)	54%

Adapted from: Burdescu R, van den Berg C, Janson N, Alvarado O. A benchmark for the performance of state-owned water utilities in the Caribbean. World Bank Group. 2020.

<https://doi.org/10.1371/journal.pwat.0000222.t004>

Management of NRW is complex and requires a comprehensive understanding of its magnitude, source and cost so that effective measures can be implemented to reduce NRW. Effective solutions must address the underlying causes of NRW, which may include inadequate or old infrastructure, inefficient billing systems, and poor management practices [44]. The Inter-American Development Bank (IDB) 2021, summed up the key technical issues related to NRW. The list included unauthorised water consumption such as by squatters, inaccurate meters to measure volumetric consumption; data handling errors; distribution and transmission pipeline leakage; and the failure of pipelines to deliver water up to the point of the customer.

Many public water utilities in the English-speaking Caribbean have not taken a comprehensive approach to addressing NRW. This has led to persistent water losses and revenue shortfalls, which limit the capacity of these countries to invest in infrastructure and efficient service delivery. A holistic approach, which focuses on investment in infrastructure, technology, and human resources, as well as improvements in management practices and billing systems, is fundamental to transforming water resources management among Caribbean SIDS [39]. Although research has been conducted on the sources of NRW among Caribbean SIDS selected for this review, research is lacking on the effectiveness of measures for reducing NRW where they have been implemented. Quantification of reduced NRW after measures were implemented is unavailable and requires research to inform policy and practice.

**Water governance, legislation and institutional arrangements.** Water governance and institutional arrangements in the English-speaking Caribbean case study countries vary due to differences in geography, politics, and socio-economic factors. However, water governance remains primarily the responsibility of national governments [24]. At the national level, the national water authority's mandate is to promote policy development, undertake regulation, and manage water resources. Water user associations manage water at the local level and ensure equitable distribution amongst all users. Environmental agencies are responsible for ensuring that water resources are protected and conserved. Regional bodies such as the Caribbean Water and Wastewater Association (CWWA) and the Caribbean Community Climate Change Centre (CCCCC) provide technical assistance and support to member states to improve water resource management [39].

There has been no major transformation among water management institutions and governance procedures and monitoring systems have not changed significantly for more than six decades [40, 45]. Such inertia is attributed to the on-going sectoral approach to water management, centralised decision-making and contemporary politics [45]. Historically, most of the English-speaking Caribbean SIDS have employed a command-and-control approach (CCA)

in managing their water resources, which emphasises constructing infrastructure such as reservoirs for water storage during the rainy season to ensure the availability of water in drought periods [46]. Research conducted by Belmar et al., (2016) highlighted that the command-and-control approach is characterised by five aspects. One aspect of the CCA is that it employs a centralised or top-down, scientific-based approach to water management [46]. Another characteristic is that it tends to be expert driven rather than be broad based in seeking inputs to water management from a variety of stakeholders. CCA also is highly reliant on empirical evidence based on the assumption that this leads to objective decision-making [46]. Additionally, the CCA is highly dependent on both the capacity of the political directorate and policymakers to make and implement informed decisions. Furthermore, Belmar et al. (2016) concluded from their research that excessive political interference in day-to-day operations and long-term planning and management erodes positive outcomes in water management in Caribbean SIDS.

Other studies found that existing water governance arrangements within Caribbean countries are weak and incapable of addressing the water challenges they are facing [24]. While some Caribbean SIDS have comprehensive legal frameworks that clearly articulate the government bodies' responsibilities and powers, most have outdated, overlapping and fragmented legislation which discourages a separation between water services and water resource management responsibilities [47]. The focus is on water service provision at the expense of water resource management which in practice has become secondary to service provision [47]. Additionally, these functions are often centralised within the same body, reflecting a predominant supply side paradigm that views water resources as an extension of water supply services [47].

For Caribbean SIDS with underdeveloped water legislation, although attempts have been made to adopt water resource legislation to address the array of issues in the water sector, their water governance system has proven to be resistant to change [24]. The English-speaking Caribbean SIDS possess water laws, but most are in dire need of reforming. Legislative reform is justifiable given that government-owned companies or statutory authorities undertake water supply and wastewater services thereby undermining independent oversight and evaluation. The absence of a water resources agency to coordinate water resources allocation by the state-operated water utility and quasi-government entities, presents a formidable challenge for water resource sustainability [48]. Legislative and administrative reform have been recommended to address these shortcomings in water resources governance [42].

Apart from St. Lucia, Jamaica and Trinidad and Tobago, water management responsibilities are dispersed across and within several government agencies or ministries with diverse mandates and which are hamstrung by poor institutional coordination. Several authorities have legal mandates relating to water management, but no single authority has an explicit mandate for watershed management. Although commissioned with water resource management responsibilities, Grenada's National Water and Sewerage Authority focuses primarily on water service provision. Additionally, in many countries coordination of closely inter-related issues of finance, agriculture, tourism, health, water and wastewater is absent at the national level.

Although there is a plethora of legal provisions to promote the sustainable development and management of water resources, they are inadequate and fragmented. In Grenada, the provisions of water resource management legislation are fragmented for the most part and insufficient, if not absent. A water resource management policy or legislation that defines and clearly articulates water resources management is lacking in St. Vincent and the Grenadines [49]. (United Nations Development Programme Japan-Caribbean Climate Change Programme 2019). In Trinidad and Tobago, laws pertaining to the development of water resources are not integrated or harmonized. Efforts to align existing legislation with relevant

international agreements and promote and operationalise cross-sectoral coordination and integration have stalled [48]. Progress in approving and adopting draft water bills has been slow in St. Vincent and the Grenadines and Barbados. The lack of reform of inadequate and fragmented water services and outdated water resource management legislation have made the implementation of water resource management cumbersome across the Region.

Integrated Water Resource Management (IWRM), defined by GWP (2014) as a process promoting the co-ordinated development and management of water, land and related resources, to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems, is endorsed by most case study countries. However, many of these countries lack an IWRM policy, plan, strategy, or clear guidance for integrated management and development of the water sector [24]. Jamaica is an exception as its Water Resources Authority manages the country's water resources through a Water Resources Development Plan which is mandated by law. This Master Plan defines and quantifies the total water resources of the country, including the estimated available supply and demand by users. Reasons for successfully developing this plan may be attributed to stronger political will due to severe droughts experienced in recent years. The selected Caribbean SIDS of St. Kitts and Nevis and St. Vincent and the Grenadines score low and the others medium-low on the degree of implementation of IWRM [50]. In most instances the sector is governed by legislation, policies and strategies that are inadequate because they are either archaic or remain in draft form for protracted period. The resulting fragmentation of the mandate across several institutions with no designated agency with a clear responsibility for water resources management leads to inefficiencies and poor execution of the principles of IWRM [24]. A lack of leadership, political will, broad stakeholder engagement, capacity building and targeted and consistent communication with stakeholders have helped undermine the adoption of IWRM policies, plans and strategies in the selected case study countries.

### Opportunities for achieving water resource sustainability

Opportunities for achieving improved water resource sustainability calls for strategies which include prioritizing water conservation, water demand management, rigorously controlling water pollution, utilizing wastewater as water, energy, and fertilizer resources, and reducing the risk of flooding and harvesting rainwater [37]. Among the English-speaking Caribbean SIDS, implementation of these strategies has been traditionally dependent on governments.

A concerted effort is needed in Caribbean SIDS to drastically reduce water consumption and minimise non-revenue water (NRW) because of increasing droughts which are expected to worsen in the coming decades if global warming exceeds 2°C [38]. A reduction in consumer water wastage requires government approval of a water pricing method, which recovers production and transmission costs, considers water scarcity, and ensures that all households have access to potable water [38]. Adopting water saving devices can help reduce water wastage and should be scaled up in Caribbean SIDS, but this will require fiscal incentives if it is to succeed [38]. Water recycling should also be encouraged in sectors such as tourism, as for example its use in golf course irrigation to reduce demand pressure on existing water resources. This water conservation measure has been adopted by hotels in Barbados, St. Lucia and Jamaica [28]. In many parts of the world, treated effluent can be recycled and reused to provide water for agriculture, firefighting, flushing of toilets, industrial cooling and other non-potable needs. Implementation of these measures requires government intervention in tariff setting, offering fiscal incentives for use of water saving devices and water recycling. Fiscal policies such as tariff setting, subsidies and tax incentives remain a government function.

With current high levels of unaccounted-for-water and observed and projected droughts in Caribbean SIDS, opportunities for detecting water loss require further exploration. Geospatial technologies to support IWRM databases, information systems and disaster planning and management were recommended by Crichlow [48]. An array of technologies such as Geophones, Hydrophones, Infrared Thermography and Ground Penetrating Radar are technologies which present opportunities to monitor pipeline leakage [38]. Furthermore, private sector engagement in providing these technologies can support government action [38]. Additionally, government investments in pipeline replacement and upgrading are fundamental to tackling water loss from pipelines as these types of projects do not appeal to private investors operating in Caribbean SIDS [38]. Innovative technologies and pipeline retrofitting will involve additional operating costs. Research into the use of such technologies in the English-speaking Caribbean SIDS is needed including acquisition and maintenance costs, training costs and a cost-benefit analysis of which of these technologies would be most appropriate to apply in the selected case study countries.

Caribbean SIDS require scaling-up rainwater harvesting (RWH) during the wet season to increase water storage in reservoirs which would enhance water availability during droughts. Although the building of cisterns is a statutory requirement in some English-speaking Caribbean SIDS such as Barbados and the Bahamas [28], this should be legislated in all of them. Increased technical knowledge via training workshops and offering fiscal incentives for rainwater harvesting to households, farmers, and commercial operators, provide opportunities to minimize water use from reservoirs during the rainy season and help reduce water rationing during the dry season. Currently, the actual use of RWH in the selected Caribbean SIDS is low due to initial start-up construction costs households must bear, the ongoing cost of maintenance which some households cannot afford, a lack of interest and incentives for households to invest in RWH [28]. Additionally, studies conducted in Barbados found *Legionella* in water tanks and regular water quality testing was recommended to ensure that microbial activity within residential and school water tanks do not have pathogens such as *Legionella* which causes life threatening diseases such as Legionnaire's disease which can lead to lung disease with pneumonia-like symptoms [51]. Among the case study countries, a research gap remains in quantifying the uptake of RWH by water users and rigorous data collection and analysis are needed to establish the relationship among variables such as the age of tanks, tank materials, operational modes, temperature, chlorine, and the presence of pathogens which pose a threat to public health [51].

According to the United Nations Environment Programme (UNEP), Ecosystem Based Adaptation (EBA) is defined as "the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people and communities adapt to the adverse effects of climate change." EBA holds much promise for coping with salinization of groundwater due to sea level rise and reduced surface water arising from droughts. EBA, through its role in conserving, rehabilitating, and managing ecosystems sustainably, can reverse ecosystem degradation and foster a society's ability to become more resilient to climate impacts. For example, mangrove protection can help purify water. Mangrove restoration can slow run-off, reduce flood risk, increase soil water, and recharge groundwater resources. These measures will require financial support from Caribbean governments and local community engagement. Nature based solutions have been understudied and undervalued in the Caribbean Region including the case study SIDS reviewed. Research on cost-benefit analysis of EBAs to restore and protect water resources is lacking and economic valuation tools would need to be applied to measure the value of ecosystems.

Water resource constraints also impact the regional agricultural sector, limiting the quality and quantity of produce. Crop production is predominantly rainfed resulting in seasonal

fluctuations in output and associated prices. Additionally, unpredictable weather patterns attached to a changing climate can lead to reduced crop yields, water stress, and food security issues. To mitigate these challenges, farmers are increasingly adopting water-efficient practices, such as rainwater harvesting and crop diversification, while governments and organizations are promoting climate-resilient agriculture and investing in water management infrastructure. To effectively address these challenges further research is required to identify climate resilient cultivars that can adapt to adverse changes in climate. Significant effort is also required to improve access to water and to build infrastructure to support increased irrigation coverage.

Implementation of IWRM plans and policies is integral to flood mitigation, water resource loss, and water pollution [37]. This requires enforcement of land use planning regulations by government agencies such as height and slope restrictions on building in hilly areas as is utilised in Trinidad for watershed protection or land use zoning regulations to protect groundwater aquifers from pollution as is employed in Barbados [37]. Market incentives to encourage compliance with land use and building regulations can also help facilitate compliance with regulations. Tax subsidies may be applied to encourage watershed re-afforestation on privately owned lands which would enhance sediment control and lower water treatment costs. Countries such as the Bahamas that are reliant on groundwater sources have called for a three-pronged approach which includes a groundwater monitoring programme to be incorporated into a spatial decision support system, a managed aquifer recharge project to adapt to climate change and the development of a groundwater manual to guide decision-making [52].

The projected decrease in freshwater resources in Caribbean SIDS has stimulated discussion on whether desalination and atmospheric water generation can help address water stress or scarcity. They both present opportunities for Caribbean SIDS to cope with water scarcity, however, there are merits and demerits associated with their use. Desalination utilizes sea water which is an abundant resource in the Caribbean. A recent UN study found that desalination plants present significant environmental challenges such as elevated levels of energy consumption and damage to marine ecosystems when toxic by-products, for example brine, are released into the ocean [53]. More research is needed on the impacts of desalination on the blue economy of Caribbean SIDS.

Data collection and analysis of water resources is long overdue and the most recent initiative by international financial institutions presents an opportunity for capacity building. The IDB recently joined the Alliance for Hydromet Development with the World Meteorological Organization, which will foster access to multi-hazard early warning systems, climate services, and underdeveloped data collection measures with a specific focus in the Caribbean Region [38]. The Caribbean Institute for Meteorology and Hydrology is hosting a Climate Impacts Database, which is an inventory of geo-referenced, historical climate-related impacts for nineteen Caribbean countries to facilitate the development of new impacts-based forecasting information for droughts and impacts on climate sensitive sectors [54] such as agriculture, tourism, and health. The need for the establishment of well-functioning hydrometric networks to monitor water resources and assessment of available resources is critical.

Robust data management tools to enable the preparation of accurate information for modelling and projections and to support planning and development aimed at improving water resource sustainability have been suggested [1]. To achieve this the institutional capacity for data generation must be strengthened. The specific water information needs are listed in Table 5 some of which have been identified by Fletcher [55].

Several experts in the Region have concurred that there is a shortage of IWRM specialists as many of them find more lucrative employment in the energy sector [56]. Due to a limited pool of hydrologists and IWRM personnel, water resources management is hampered [47]. Insufficient funding is allocated to water resources management and tends to be concentrated on the

Table 5. Water information needs in Caribbean SIDS.

Water Information Needs
• Establish a central water-related data repository to support implementation of a National Water Information System.
• Improve quantity, type, placement, and maintenance of instrumentation for data collection for sea level rise, groundwater aquifers, river flows, flood mapping and renewable water.
• Assessment of impact of land cover and land use changes on water resources
• A water census to value water resources.
• Planning, including flooding and drought management.
• Establishment of a fully functioning water resources management unit.
• Expansion of existing water information systems to include forecasting and early warnings.
• Training and capacity building in data entry, analysis, and dissemination.
• Regular reporting on the State of the Water Sector.

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direct services offered to the public as water supply and distribution [47]. A shortage of skills in hydrology and hydrogeology amongst other water sciences has therefore emerged [47]. More research should investigate the training programmes at the University of the West Indies to determine how best to close this gap in expertise and stem the brain drain [56]. All countries in the selected case studies would need to ascertain their IWRM current and projected needs and invest in training.

## Conclusion

A major concern in Caribbean SIDS is that future water resource sustainability is expected to be further compromised due to climate change and socio-economic drivers. A growing body of evidence highlights that the window of opportunity is closing for acting against droughts, which are likely to be exacerbated by global warming above 2°C, and saline intrusion of groundwater aquifers arising from sea level rise or overextraction of groundwater resources. Reduced surface water due to rapid urbanisation and accompanying watershed destruction also pose a significant threat to future water resource sustainability. Many atoll islands may become uninhabitable due to water scarcity which may trigger migration to other islands within the Region and countries outside the Caribbean. Water scarcity is an existential threat to Caribbean SIDS with wide ranging impacts on food security, human health and well-being and freshwater ecosystems. The economic and environmental costs associated with desalination plants as a means of coping with water scarcity would be a burden for these SIDS, many of which were already indebted before COVID-19.

If the case study Caribbean SIDS are to survive, they must pivot to novel approaches to minimise a potential water crisis and work towards achieving water resource sustainability. Adopting innovative technologies, reforming water governance, and embracing the use of ecosystem-based adaptation strategies are all instrumental in managing water resource sustainably for a more secure future. Structured conservation efforts through public awareness campaigns, encouraging increased implementation of rainwater harvesting and wastewater reuse should address scarcity. Water related policies must be enhanced and supported by legislation and enforcement to facilitate equitable fulfilment of water demands and strengthen resilience to climate change. In this regard, there is need to further strengthen the application of climate information and the links between meteorological and hydrological services. Policies and



**Table 6. Summary of research gaps.**

Research Gaps
<ul style="list-style-type: none"> <li>■ Research is lacking on costing population displacement, migration and economic decline arising from climate change impact on water resources.</li> <li>■ Research gap on the economic costs of impacts on physical and mental health associated with limited water resources due to droughts, floods and SLR. The Caribbean has fewer peer-reviewed climate and health publications than any other region and there is limited research on public health preparedness in response to floods and droughts.</li> <li>■ There are no recent studies for the selected case studies, which quantify ground water and make projections on the amount of water that may be impacted by different SLR scenarios, saltwater intrusion, floods and droughts.</li> <li>■ More research is required on desalinisation impacts on water resource sustainability, ecosystems and implications for the blue economy of English-speaking Caribbean SIDS.</li> <li>■ Research is lacking on the quantification of land cover changes and increased water stress.</li> <li>■ Research outlining the implications of improper land use, land degradation, deforestation, soil sealing and urbanization on water-related disasters remains limited.</li> <li>■ A comparative analysis of the advantages and disadvantages of using different tariff systems and their impact on water resources management among the case study Caribbean SIDS has not been researched.</li> <li>■ Although extensive research has been conducted on the sources of NRW among Caribbean SIDS selected for this review, research is lacking on the effectiveness of measures for reducing NRW where they have been implemented. Quantification of reduced NRW after measures were implemented is unavailable.</li> <li>■ Research into the use of innovative technologies in the English-speaking Caribbean SIDS is needed including acquisition and maintenance costs, training costs and a cost-benefit analysis of which of these technologies would be most appropriate to apply in the selected case study countries.</li> <li>■ A research gap remains in quantifying the uptake of rainwater harvesting among water users in the selected case study Caribbean SIDS.</li> <li>■ Research on cost-benefit analysis of EBAs to restore and protect water resources is lacking.</li> <li>■ More research on the applicability of 'virtual water' is needed as it will impact agricultural policy and domestic food security.</li> <li>■ More research should investigate the training programmes at the UWI to determine how best to close this gap in expertise and stem the brain drain [56]. All countries in the selected case studies would need to ascertain their IWRM current and projected needs and invest in training.</li> </ul>

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strategies need to be informed by science, include innovative technologies for management and use of water resources, and encourage water use efficiency and wastewater reuse.

Much work still needs to be done including the implementation of a strategy to guide of research projects to address knowledge gaps and priorities highlighted in this review. A summary of research gaps is provided in [Table 6](#). The research capabilities of the University of the West Indies, CIMH, CCCCC, CARPHA and other regional science institutions should be strengthened. Further, access to research fundings should be a priority as is an interdisciplinary approach to research.

Inaction exacerbates losses and damages for SIDS, some of which can be irreversible. The survival of SIDS is at stake based on the evidence provided. The time for action toward achieving integrated water resources management and aligning climate action (SDG 13) with SDG 6 is now.

## Author Contributions

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