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Water Security under Climate Risk in Small Island Developing States (SIDS): A Hydro-Socio-Metabolic Risk (Hydro-SMR) Approach

Waterloo Climate Institute Technial Brief

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Abstract

Water is a critical resource that enables the function of environmental, social and economic systems. Small Island Developing States (SIDS) face some of the most severe water security challenges in the world because of both physical and economic water scarcity. Worsening climate change impacts such as floods, droughts and sea level rise exacerbate these challenges, resulting in an urgent need for adaptation measures. Understanding water availability, use and the distribution of costs and benefits allows policy makers to identify and address systemic vulnerabilities to promote future resilience. The Hydro-Socio-Metabolic Risk (Hydro-SMR) framework was developed for such analysis. This

technical brief introduces the Hydro-SMR framework and applies it to 17 Caribbean SIDS, using indicators of availability, consumption, self-sufficiency, access and water stress. Key findings include worsening demand-supply gaps, decline in water availability due to climate change, compromised water infrastructure and persistent inequities in access to reliable and quality water. Some island nations are responding to water crisis through hard engineering and highly technical interventions such as the desalination of seawater to meet local water demand. The decreasing water self-reliance in countries transitioning to desalinization of seawater using imported fossil fuels is likely to create future "lock-ins" and compound risks related to energy security. Achieving long-term water security in Caribbean SIDS requires a shift from reactive, engineering-centred responses towards integrated systems approaches that recognise interdependencies among ecosystems, infrastructure, governance, energy and social equity. Solutions that combine appropriate infrastructure (such as rainwater harvesting, managed aquifer recharge and wastewater reclamation) with source protection, demand management, adequate asset maintenance, energy-water nexus planning and social protection are encouraged.

Key Messages

- Caribbean Small Island Developing States (SIDS) face increasing threats to water security because of climate change including changing precipitation patterns and extreme weather events.
- A critical step in reducing vulnerability and promoting resilience is taking a whole-system perspective on water systems to mitigate "socio-metabolic risks".
- The Hydro-socio-metabolic Risk (Hydro-SMR) approach offers a systems-based perspective on water (in)security challenges and is applied to 17 Caribbean nations.
- Long-term water security requires a shift from reactive engineering solutions to integrated systems approaches linking ecosystems, infrastructure, governance, energy and social equity.

Introduction: Water Security and Climate Change in Caribbean Small Island Developing States (SIDS)

Water security means having sustainable water supplies and the institutional, economic, infrastructural and ecological conditions needed to ensure reliable, equitable and affordable access to safe water (MacAlister et al., 2023; UNESCO, 2024). Caribbean SIDS face critical and diverse challenges across these dimensions. Six of the seventeen countries included in this study face water scarcity (FAO, 2026a; Forde et al., 2024). Countries with comparatively abundant freshwater resources nevertheless experience water insecurity in other aspects, namely inadequate infrastructure, watershed degradation, insufficient storage capacity, financial constraints and limited institutional capacity (Cashman, 2014; Forde et al., 2024; Gheuens et al., 2019; Janson et al., 2021).

Climate change projections for the Caribbean include an increasingly drier climate with higher intensity and frequency of storm events, rising sea levels and increasing temperatures (CSGM 2022). These will affect water systems through both slow onset impacts and rapid shocks. Sea level rise, longer droughts and higher temperatures increase saltwater intrusion and evaporation, reducing freshwater availability and supply stability, while sudden shocks such as hurricanes can increase flooding and landslides (CSGM 2022).

Water infrastructure is vulnerable to these impacts which regularly threaten to interrupt critical water provisioning services (Burunciuc, 2026; Medina et al., 2021). Often, regions do not have adequate time for recovery between these climate extremes (CSGM 2022). Worsening climate change impacts, along with growing water demands, mean that conditions of water scarcity are becoming the new normal for Caribbean SIDS (CAF, 2025; CWWA, 2019). Risk in water systems cascades across sectors to threaten food security, public health and economic activities including tourism (Burunciuc, 2026). Understanding the interacting biophysical, socio-economic and institutional dimensions from a "Hydro socio-metabolic risk" (Hydro-SMR) perspective is essential for designing adaptation strategies that address systemic water insecurity in Caribbean SIDS.

Background: Understanding the Hydro Socio-Metabolic Risk (Hydro-SMR) Framework

"Socio-metabolic risk" (SMR) is based on the idea of "social metabolism," which describes how societies depend on the natural environment and other societies for

the materials and energy they need to survive and grow. Social metabolic research, by extension, analyzes resource-use patterns in socio-economic systems in space and time. It offers a systems-based perspective of metabolic flows occurring within and between societies, generating valuable place-based knowledge that can be leveraged to inform climate adaptation decisions. Simply put, if a society's metabolism is problematic (e.g. high dependence on imports across complex supply chains, or the over reliance on critical materials and non-renewables, or generates outflows or waste that can't be safely managed, etc.), the system may become susceptible to environmental and economic shocks.

Similarly, understanding SMR can be understood by extending the analogy of biological metabolism. Just as poor metabolism can fail to support human health when not properly managed, problematic socio-metabolic flows can critically threaten society and the economy. This has been termed "socio-metabolic risk" (SMR) and is defined as, "systemic risk associated with the availability of critical resources, the integrity of material circulation and the (in)equitable distribution of derived products and services in a socio-ecological system" (Singh et al., 2022, p. 1). SMR are to islands as circulatory health problems are to humans – both constrain the entity's ability to withstand significant shocks and changes. Hurricanes, droughts, flooding, a breakdown of supplies from war, increased fossil prices or a pandemic, can severely impact a society's metabolism and its ability to sustain critical resource flows of food, energy, water or construction materials over time (Figure 1).

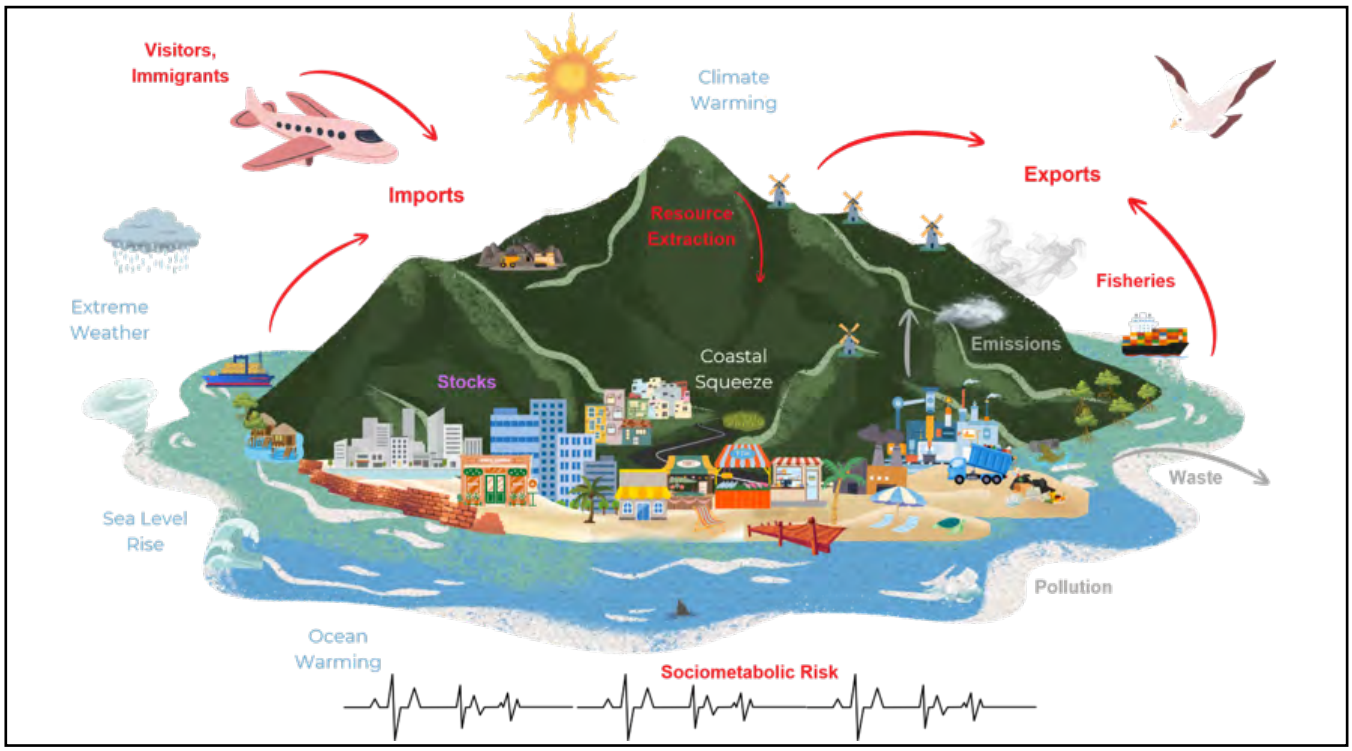


Figure 1: A heuristic representation of island social metabolism and stressors [Illustration by Shubhi Singh and Simron Singh]

For over two decades, islands have been the subject of socio-metabolic research, given their distinct boundaries, remoteness and smallness (Singh et al., 2021). Being resource-constrained, and increasingly vulnerable to climate change, islands are highly stressed socio-metabolic systems. Examples of such studies include the Nicobar Islands, India (Singh et al., 2001; Singh & Grünbühel, 2003), Trinidad and Tobago (Krausmann et al., 2014), Samothraki, Greece (Noll et al., 2022), Grenada (Elgie et al., 2021; Symmes et al., 2020), Antigua and Barbuda (Bradshaw et al., 2020), and food security (Rahman et al., 2022) and e-waste (Mohammadi et al., 2021) in the Caribbean. These studies were foundational in identifying patterns SMR associated with island metabolism (Singh et. al. 2022).

Later, the SMR approach was explicitly applied to investigate resilience in the context of material flow analysis in the Bahamas (Martin del Campo et al., 2023a), mass-balance in Fiji (Thakur et al., 2026), water, energy, food nexus in the Caribbean (Martin del Campo et al., 2023b), food security in the Maldives (McHugh et al., in review) and flooding and infrastructure security in Mauritius (Rahman et al., in review).

Water systems are naturally cyclical and involve very closely interconnected societal and environmental systems. As a result, water has historically been left out of material flow analyses (Madrid-Lopez & Giampietro, 2015). More recently, the SMR concept was extended and operationalized to study climate resilience of water systems in Maldives, an approach referred to as "Hydro-socio-metabolic risk" (Hydro-SMR) (Voigt et al., in review). Hydro-SMR involves the analysis of water stocks and flows across space and time. Based on previous efforts to operationalize the concept of SMR, these flows are analysed to identify how they introduce or shape existing systemic risks. In the case of Hydro-SMR, these risks could include the interruption of critical water services, water shortage, degradation of water quality, occurrence of water-borne diseases and flooding. The structure of a water system may increase the likelihood or impact of these risks for example through limited redundancy in water resources, inadequate consideration of environmental protections or high reliance on imports.

Core Indicators to Operationalize Hydro-socio-metabolic risk (Hydro-SMR)

The Hydro-SMR framework examines systemic risks in water systems, focusing on indicators of water availability, consumption, self-sufficiency, access and stress. The definitions for each of these indicators are presented in Table 1.

Together, these indicators provide a way to measure Hydro-SMR by quantifying key patterns in water resource use. Availability is used to indicate the presence or absence of water resources. Consumption behaviours reveal resource quality, quantity, as well as how different socio-economic conditions shape resource use. Self-sufficiency is used to characterise external dependencies and access highlights the (in)equitable

distribution of costs and benefits within water systems. Water stress provides a measure of the sustainability of water withdrawal patterns given the amount of freshwater available.

Table 1: Hydro-SMR Indicators and their Definitions

Indicator	Description	Calculation
Availability [m3/capita/year]	Amount of freshwater per capita that is present in the region	Directly obtained from source as Total Internal Renewable Water Resources per Capita (FAO, 2026a)
Consumption [m3/capita/year]	Amount of water withdrawn per capita per year	Fresh water withdrawals plus desalinated water divided by population
Self-Sufficiency [%]	Percentage of water consumed that is domestically harvested or from desalination plants using local energy resources	100% minus Water Dependency Ratio and percentage of desalinated water produced using imported energy resources
Access [%]	Percentage of the population with access to safe drinking water	Directly obtained from source as Total Population with Access to Safe Drinking Water (FAO, 2026a)
Water Stress [%]	Freshwater withdrawals as a percentage of available freshwater resources, accounting for environmental flow requirements	Directly obtained from source as Water Stress (FAO, 2026a)

The Hydro-SMR framework is intended to extend traditional water accounting to address the social, environmental and political dimensions of water systems. Approaches such as the United Nations System of Environmental-Economic Accounting – Water (SEEA-Water) framework provide a critical quantitative assessment of water metabolism, including the flow of water into, within and out of systems. However, the availability of data required to assemble detailed economic and environmental water accounts is often limited in Caribbean SIDS (Janson et al., 2021). For this reason, the application presented here is focused only on the indicator framework and subsequent identification of SMR. Future applications of the Hydro-SMR framework are encouraged to first assemble longitudinal economic and environmental water accounts to quantify

resource use dynamics over time and across industries.

In addition to its indicator framework, the Hydro-SMR approach adds value through its conceptualisation of risk as emerging from historical system structures and patterns of water flow. Core components of the SMR concept can be explored in Hydro-SMR analysis without the need for completed water accounts including the scale, dynamics and equity of water systems. Integrating alternative data sources such as interviews, surveys, policy analysis and sub-national reports or datasets can support this analysis. For example, surveys can be used to generate data on consumer behaviours, and dimensions of access such as affordability and reliability. Expert interviews and reports can act as proxy data to determine trends in water systems over time.

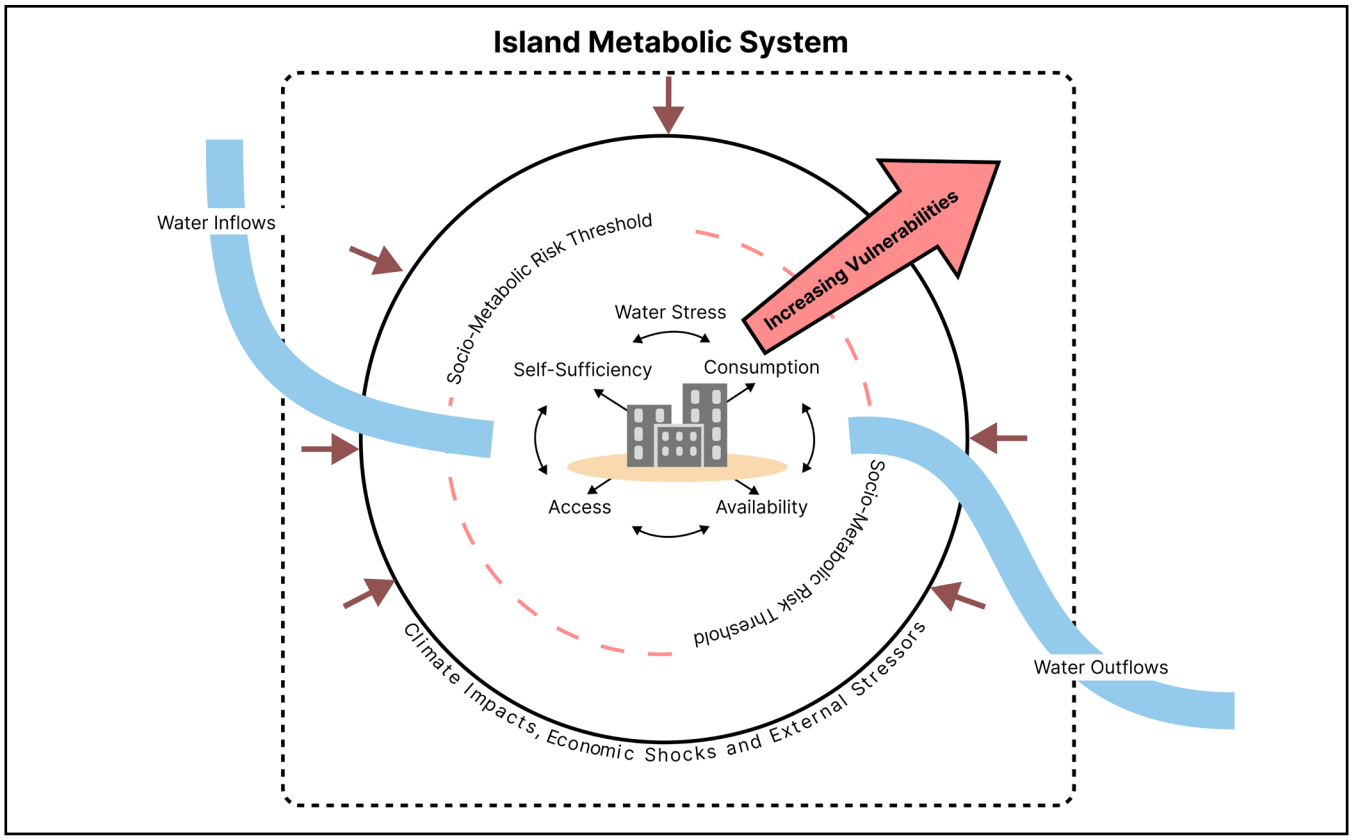


Figure 2: Conceptual figure of the Hydro-SMR framework (adapted from Martin del Campo et al., 2023b and Singh et al., 2022).

Figure 2 presents the Hydro-SMR framework visually, emphasising that systems operate within a SMR threshold. Many factors, including vulnerability, system structure and external stressors can bring the system closer to crossing this threshold and the subsequent occurrence of risks. The indicators of self-sufficiency, access, consumption and availability characterise system performance. Imbalance between the indicators, such as high consumption and low availability resulting in high water stress, can also bring the system closer to risk thresholds. When investigated over time, this analytical framework reveals system dynamics and trajectories that drive increased presence of SMR.

Application of a Hydro- socio-metabolic risk (SMR) Framework for Caribbean Small Island Developing States (SIDS)

For this technical brief, the Hydro- socio-metabolic risk (SMR) analysis framework is applied to a set of 17 Caribbean Small Island Developing States (SIDS): Antigua and Barbuda, Bahamas, Barbados, Belize, Cuba, Dominica, Dominican Republic, Grenada, Guyana, Haiti, Jamaica, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname and Trinidad and Tobago. These island nations were selected based on data availability in FAO AQUASTAT and adequately represent the diversity of the Caribbean region with over 90 per cent of the region's population and a variety of island sizes, governance structures, levels of development and climates included. Quantitative data on the indicators of availability, consumption, self-sufficiency, access and water stress was collected from FAO AQUASTAT. While this international database was used for the purpose of demonstrating the application of the Hydro-SMR framework, it is acknowledged that the quality of this data is variable and thus the results should be considered with a degree of caution (Dantas et al., 2021). Future Hydro-SMR assessments are encouraged to engage local water utilities and agencies to collect data directly or validate the use of proxy data where necessary. Building on this quantitative analysis, critical Hydro-SMR are identified along with opportunities for climate risk mitigation and adaptation. Below we present Hydro-SMR trends for the Caribbean based on the five indicators.

Availability

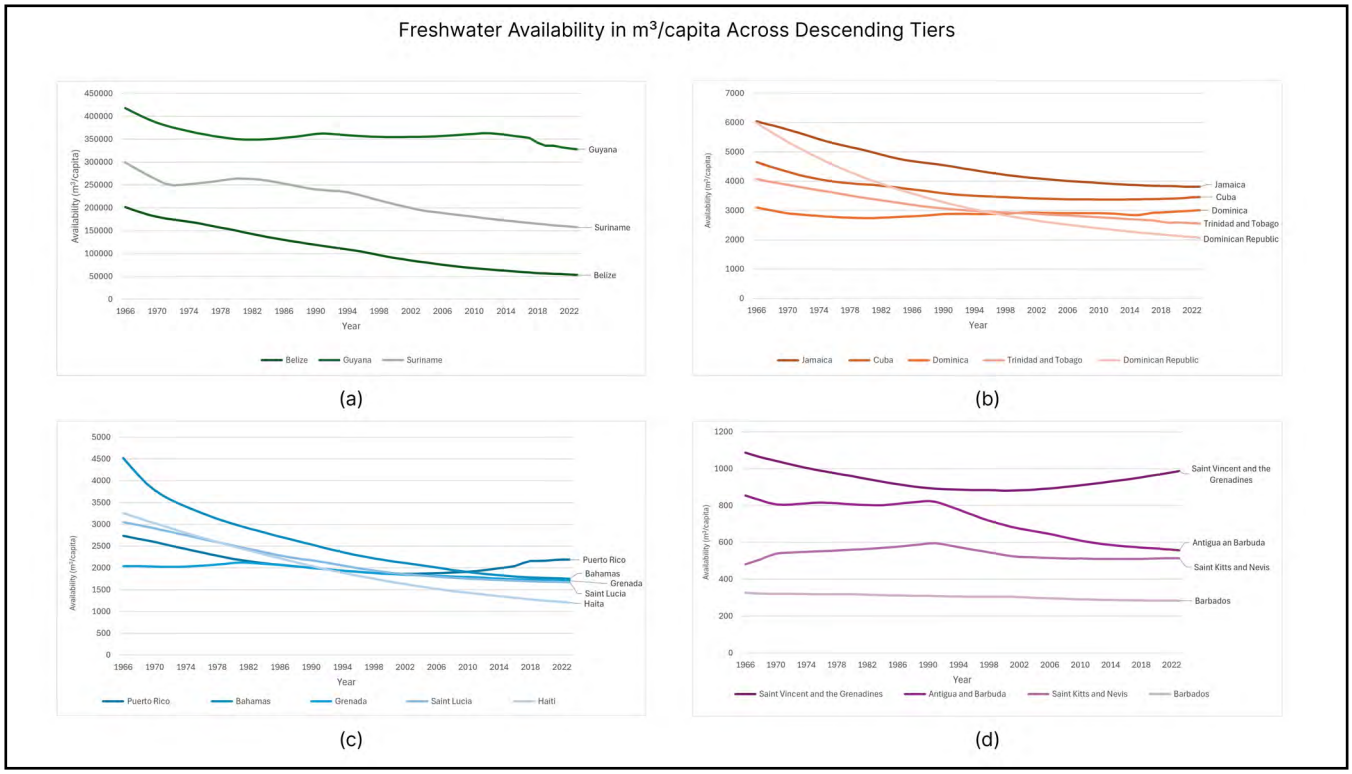


Figure 3: Freshwater availability (including surface and groundwater) in m3/capita grouped in descending order from (a) Highest to (d) Lowest. Source: FAO, 2026a

Limited availability of renewable freshwater resources is a critical threat to water security in the Caribbean with many countries including Aruba, Antigua and Barbuda, Saint Kitts and Nevis and Barbados below the Falkenmark water scarcity threshold of less than 1,000 m3/capita/year (Forde et al., 2024) (Figure 3). At the same time, many Caribbean countries also experience an abundance of freshwater resources such as in Guyana, Suriname and Belize which each had availability over 50,000 m3/capita in 2022. Spatial variation in availability also occurs within countries, particularly those with large land masses such as Belize, whose Northern areas receive significantly less rainfall than the South (Forde et al., 2024). Further, temporal variation in rainfall patterns impacts intra-annual availability via distinct wet (July to December) and dry (January to June) seasons (Cashman et al., 2014; Forde et al., 2024).

Consumption

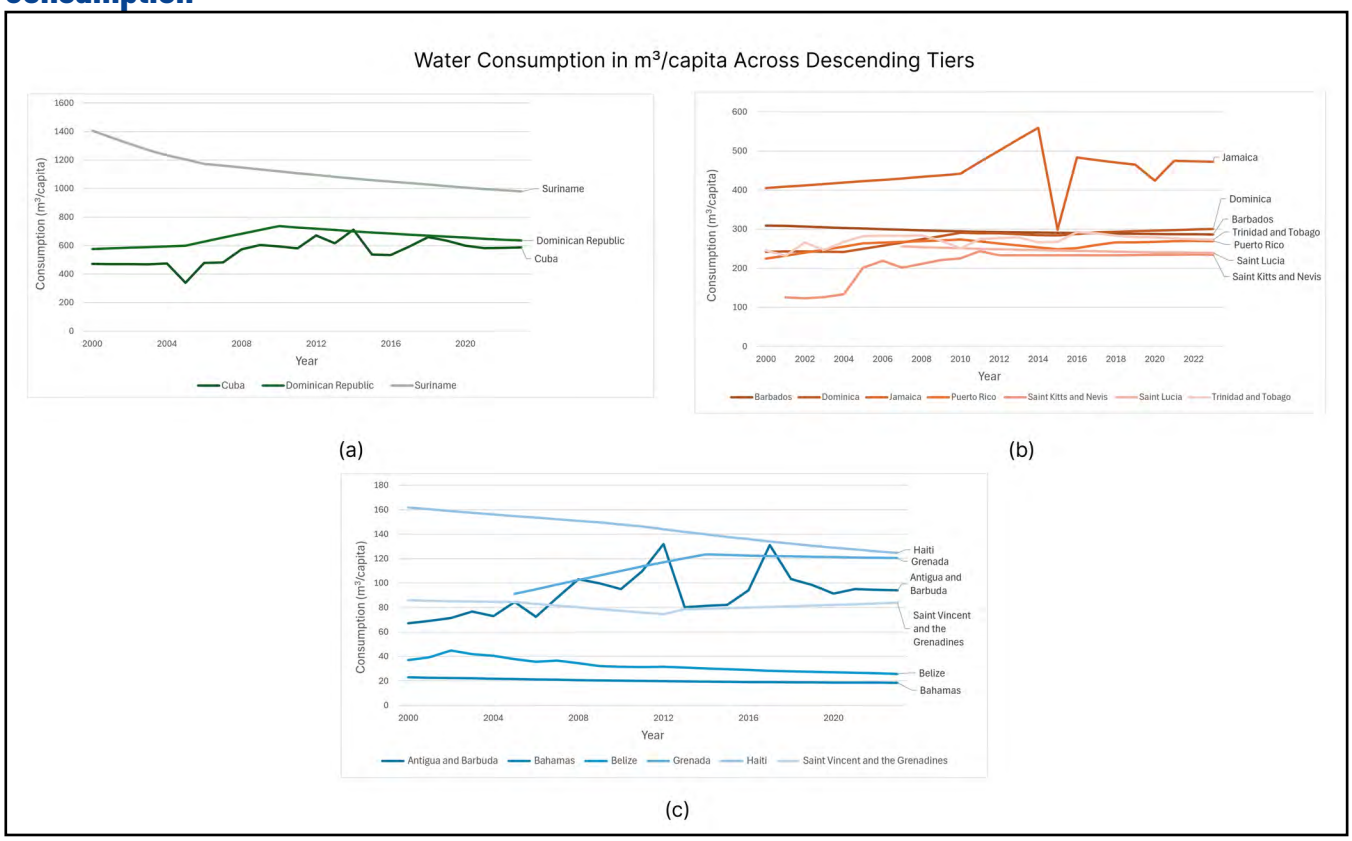


Figure 4: Consumption in m3/capita/year, grouped in descending order from (a) Highest to (c) Lowest. Source: FAO (2026).

In general, availability of renewable freshwater resources has been in decline over the past 50 years and can be expected to decline due to a variety of factors including population growth, growing water-intensive industries and increased evaporation because of climate change (Choudhury & Nibbs, 2025; CSGM 2022; Forde et al., 2024). In many Caribbean countries, water service providers are also responsible for water resource management and lack the capacity to address challenges affecting freshwater availability such as land use and climate changes (Cashman et al., 2014).

While per capita consumption values have remained moderately stable, water demand can nonetheless increase as populations grow (Figure 4). Industrial activities and irrigated agriculture drive water consumption in heavily industrialized islands such as Jamaica and Trinidad and Tobago (Forde et al., 2024). Tourism also drives high levels of water consumption from both increased population and the higher per capita water consumption of tourists (Crisman & Winters, 2023). The effects of this increased demand often compound challenges of water availability during the dry season, which coincides with peak tourist season (Crisman & Winters, 2023).

Water Stress

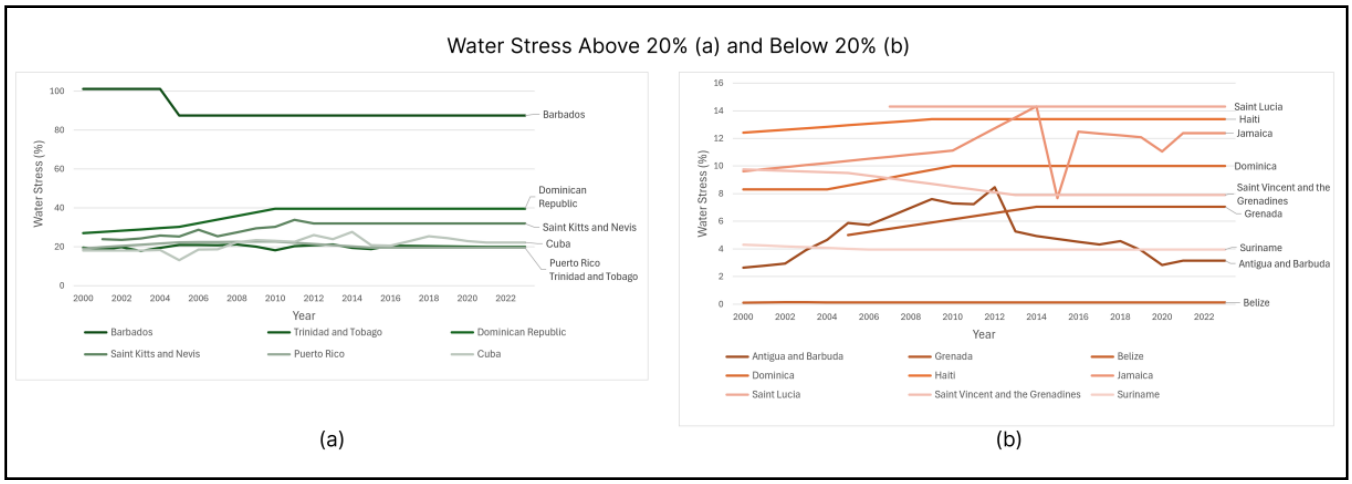


Figure 5: Water stress percentage for Caribbean countries presented across two groups, (a) at or above 20% and (b) below 20%. Note that Guyana and The Bahamas have not been included due to limited data. Source: FAO, 2026a.

Further, climate impacts such as droughts shape consumption patterns. This can be seen in Jamaica, where in 2015, consumption fell following three consecutive years of drought that resulted in recurrent daily water restrictions and severely reduced agricultural production (Neufville, 2015) (Figure 4). A large portion of distributed water volumes are lost in distribution networks as unaccounted or non-revenue water (NRW) which amount to around half of water produced by utilities on average (Burunciuc, 2026; Forde et al., 2024). These consumption patterns emphasize the importance of not only evaluating national consumption but also consumption across industries and user types.

Another critical consideration is the ratio of withdrawals to available freshwater resources, defined as the water stress index (UN, 2026). Water stress levels from 2000 to 2022 for the Caribbean SIDS under study are presented in Figure 5. A territory is considered "water-stressed" if it withdraws 25 per cent or more of its total renewable freshwater resources (UN-Water, 2024). Countries with abundant water availability may still face significant water stress as a result of high demands. This occurs in the Dominican Republic and Trinidad and Tobago which each required

over 20 per cent of available resources to meet demand in 2024 (Forde et al., 2024). Notably, Barbados experiences extremely high levels of water stress due to limited freshwater availability and must augment their supply with desalinated water (Forde et al., 2024). It is also possible for water stress to occur as a result of water supply deficits because of insufficient infrastructure, storage and institutional capacity to supply freshwater as opposed to a lack of available resources (Cashman et al., 2014).

Access

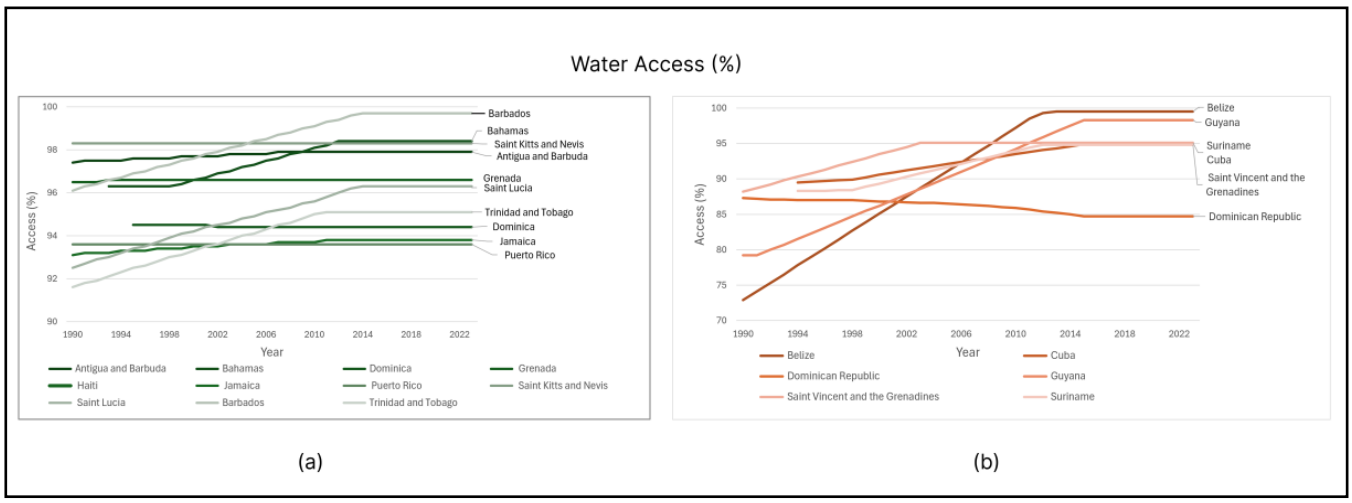


Figure 6: Percentage of population with access to safe drinking water sources, grouped by initial value with (a) above 90% and (b) below 90%. Source: FAO (2026).

Access to safe drinking water sources is high across the Caribbean, with all countries included in this review having access levels over 91 per cent as of 2022, excluding the Dominican Republic. The countries can be seen to follow two distinct patterns, those that maintained access above 90 per cent for the duration of the period and those that rapidly improved access levels from below 90 per cent to above throughout the 1990s (Figure 6). This improvement was likely driven by a strong social welfare focus from governments following independence (Cashman et al, 2014). To increase access to essential services, governments implemented programs to expand the provision of water, sanitation, health care and education (Cashman et al., 2014). Water access challenges may not always be visible at the national level, and many communities continue to face issues with water supply reliability and quality despite high national access levels (Caribbean Development Bank, 2024; Pena & Cashman, 2025).

Affordability should also be considered as an important dimension of access. In the Caribbean, water tariffs vary significantly with the types of source water used. For example, monthly household water costs in the Bahamas, which is heavily reliant on desalinated water, were estimated to be 37.21 USD for 15 m3 of water (Janson et al., 2021). The same amount of water was estimated to cost 4.42 USD in Trinidad and Tobago, whose water is largely sourced from surface and groundwater (FAO, 2015; Janson et al., 2021).

Self-Sufficiency

A country's self-sufficiency may be drawn down by dependence on freshwater sources outside of their national boundaries or by using import dependent water sources such as diesel-powered desalination. While many countries remain entirely self-sufficient there are an increasing number turning to desalination to supplement freshwater resources and meet rising demand (Forde et al., 2024; UNESCO, 2006). Notably, 10 of the 17 islands included in this case study use desalinated water to supplement their supply. This reliance can be significant, ranging from 85 to 100 per cent of supply in northern Caribbean countries including Antigua and Barbuda and the Bahamas (Forde et al., 2024). Without the use of local renewable energy sources, increasing reliance on desalination can draw down self-sufficiency, bringing many countries towards 0 per cent. In Aruba, almost 100 per cent of water demand is met using desalination (Martin del Campo et al., 2023b). As a result of expanding renewable energy capacity of the national grid, the self-sufficiency of Aruba's water system has increased from 0 per cent in 2008 to 15.6 per cent in 2026 (WEB Aruba, 2026). However, it is also possible for desalination plants to operate independently from the national grid, requiring water providers to install their own renewable energy capacity to increase self-sufficiency. Without concurrent expansion of local and renewable energy supplies, reliance on desalination locks in external dependencies and leaves countries vulnerable to shocks such as global fuel crises, geopolitical conflict and supply chain disruptions.

Hydro-socio-metabolic risk (SMR) in the Caribbean

Analysed over time, the indicators outlined in this brief demonstrate a shifting metabolic pattern across Caribbean Small Island Developing States (SIDS) that features worsening demand-supply gaps, persistent challenges in accessing reliable and high-quality water sources and increasing dependence on imported fuels for desalination. These systems experience Hydro- socio-metabolic risk (SMR) related to the availability of water, self-sufficiency, ageing infrastructure and equity which are further outlined below.

Risks to Water Availability

Significant Hydro-SMR dynamics persist across the Caribbean related to the availability of water resources, particularly their spatial and temporal fluctuations. Climate projections suggest longer dry periods and more frequent drought conditions across the Caribbean (Cashman et al., 2010; CSGM 2022; Taylor et al., 2018). Compounding these climatic changes is a rising demand for water, resulting in increasing demand-supply gaps and heightened vulnerability to changing rainfall patterns (Forde et al., 2024). The Caribbean has faced serious drought conditions at the regional level, in 2009-2010 and 2014-2016, and frequent droughts also occur at the sub-regional level (Trotman et al., 2021). Water storage plays a critical role in ensuring water is available

in the right quantities at the right time. However, historically, storage infrastructure has not had sufficient capacity to meet these needs (Cashman et al., 2010).

Water availability is also threatened by hurricanes and extreme rainfall events which damage water treatment and supply infrastructure (Medina et al., 2021). Extreme weather events can also disrupt water availability by degrading the quality of water resources through increased saline intrusion and sediment loads (Gheuens et al., 2019; Medina et al., 2021). Climate change is expected to increase the frequency and intensity of extreme weather events in the Caribbean, further worsening existing vulnerabilities in water infrastructure and service delivery systems (Taylor et al., 2018).

Risks from Increasing Complexity as a Result of Desalination

To address these availability challenges, many Caribbean countries turn to desalination as a more reliable source for water. Desalination allows countries to become more resilient to seasonal shortages and can serve as a necessary adaptation to address inadequate freshwater supplies (Forde et al., 2024). However, this technology can introduce a lock-in effect for future Hydro-SMR patterns that may further threaten the resilience of water systems. Desalination increases operational costs, threatens environmental systems through brine disposal and is often reliant on imported fuels (Williams, 2022). For SIDS already heavily reliant on imports (UNDP, 2024), increasing reliance on desalination deepens vulnerabilities to external supply chain and geopolitical shocks.

Symptomatic and reactive approaches to water scarcity, such as desalination, are known to leave underlying systemic challenges unaddressed (Velásquez & Wachtendorf, 2023). Climate adaptation decisions, such as desalination, create path dependencies that shape and lock-in future social and institutional trajectories (Williams, 2022). This pattern has the potential to lead systems into a "socio-metabolic trap" (Singh et al. 2022), resulting in future water systems, shaped by current management decisions, becoming increasingly vulnerable to external shocks and higher costs for consumers. Desalination has an obvious role to play in achieving water security under a changing climate. However, efforts should be made to maintain the self-sufficiency of these systems to avoid locking-in vulnerabilities.

Infrastructure Risks

The Caribbean has aging and corroding water infrastructure that is failing at various levels of the distribution supply system. Corrosion of steel pipes from age and high salinity in the air creates weakness and leaks in the system. Low tariffs that have not been updated in decades leaves no opportunity to set aside capital to improve and invest in existing infrastructure. As such, insufficient maintenance of critical infrastructure also exacerbates SMR in the Caribbean, particularly in the form

of system losses or non-revenue water (NRW). A study of 11 utilities across the Caribbean found that 20 to 75 per cent of water supply was lost as NRW, with an average of 46 per cent (Janson et al., 2021). NRW is a pervasive challenge across the Caribbean which also allows it to be a key leverage point through which systemic risk can be reduced. Reductions in NRW help improve supply efficiency, quality of service and financial performance for utilities and offers benefits for multiple stakeholders including utilities, consumers and government (Janson et al., 2021). For example, the Water and Sewerage Corporation of the Bahamas began a NRW management project in 2012 that was able to reduce NRW by 40 per cent in its first year, effectively increasing water supply with no increase in water abstractions (Janson et al., 2021).

It is critical that efforts to address NRW challenges also address the underlying conditions driving the issue of inadequate infrastructure maintenance. Caribbean SIDS face a cycle of repeated and intensifying climate disasters which drive unsustainable debt (Choudhury et al., 2025). Following the significant economic cost of disasters, SIDS are faced with reduced capacities to invest in climate adaptation and resilience building, such as the maintenance of critical infrastructure (Choudhury et al., 2025). This creates a negative feedback loop as the frequency and intensity of climate disasters increase. With 70 per cent of SIDS facing debt-to-GDP ratios which exceed the sustainability threshold of 40 per cent, there is a critical need for support programs that allow SIDS to escape this cycle and invest in infrastructure development and long-term climate resilience (Bharadwaj, 2024).

Risks Introduced by Systemic Inequities

While access to piped water is high across the Caribbean, its reliability and quality remain concerns, with households facing intermittent or low water supply and poor water quality (Mycoo, 2018). Based on a 2019 survey conducted for Latin America and the Caribbean, 41 per cent of households with access to piped water reported intermittent access and 34 per cent reported relying on bottled water for drinking (Libra & Baquero, 2022). In general, limited data is available on water utility service quality, suggesting insufficient attention to service continuity and water quality (Janson et al., 2021). Rural populations are the most vulnerable to these challenges and often have lower coverage of potable water systems than urban areas (CAF, 2023; Janson et al., 2021). Equity challenges also exist within urban areas, which are home to 72 per cent of the region's population, a value projected to increase to 80 per cent by 2050 (Mycoo, 2022). Internal migration has been identified as the main driver of this urban growth (Busso et al., 2024). While the motivation for such migration is often complex, there is evidence that hydrologic extremes including a lack of water during droughts or abundance of water during extreme weather events can drive households to migrate internally (UN, 2023). Within growing urban areas, housing deficits and high costs drive a significant portion of the population to live in squatter settlements. At the same time, environmental risk from pollution (solid and liquid)

leaching into ground water is a risk worth noting. The toxic and hazardous pollution leaches from waste dumps, illegal dumping and landfills impact poorer neighborhoods in particular, due to their habitation proximity. Together with the lack of critical infrastructure, including water and sewerage within these settlements, threatens the health and safety of inhabitants (Mycoo, 2022). Ultimately, high access metrics mask persistent equity challenges in Caribbean water systems.

Conclusion

Achieving long-term water security in the Caribbean will require a transition from reactive, infrastructure-centred responses towards proactive, integrated systems-based approaches that recognise the interdependence of natural ecosystems, infrastructure, governance, energy systems, water pricing, water use hierarchy, and social equity. For example, interventions such as rainwater harvesting, managed aquifer recharge, watershed restoration, demand management, distributed water storage, wastewater reclamation and reuse and non-revenue water reduction should be considered to improve the flexibility and robustness of water systems while reducing exposure to climatic variability and economic shocks (Cashman, 2014; Cole & Cashman, 2021; Janson et al., 2021). Alongside, investments in capacity strengthening of utility workers in climate risks and emerging technologies for adaptation is crucial for achieving water security, an area of intervention championed by the Caribbean Water and Sewerage Association (CAWASA).

It is important to highlight the limitations of the indicators and international statistics used in this brief. For example, Total Internal Renewable Resources does not necessarily indicate the volume of freshwater that is exploitable as the availability of this water is limited by environmental flow requirements and the socio-economic resources required to utilize natural water resources (FAO, 2026b). As well, consumption, defined as total freshwater withdrawals, also includes flows that are eventually returned to the environment or lost, not only consumptive water uses. For high level regional analysis, the approach applied here offers a strong screening tool to identify water security risks. More in depth local analysis using a Hydro-socio-metabolic risk (SMR) approach should also include water accounting to trace water distribution among specific users and determine exploitable water volumes where possible.

Ultimately, the Hydro-SMR framework provides a practical mechanism for identifying interactions between environmental, economic, social, infrastructure and governance systems and understanding how current resource-use patterns shape future resilience. This could inform policy makers to help rebuild, maintain and renew Caribbean water infrastructure, along with capacity strengthening of utility workers. A new financing framework of policy instruments and governance shifting responsibility of planning to

corporate end-users would be beneficial. Updating legislation, developing a hierarchical water pricing model with funding from various sources for water production and distribution systems would be beneficial.

In conclusion, the framework generates meaningful insights on water system dynamics valuable for data-driven policy decisions that mitigate Hydro-SMR and promote resilience to climate risks. Applying this framework requires strong local partnerships to enable data sharing and analysis of challenges across spatial and temporal scales as well as to ensure local relevance and applicability of solutions. Future applications at national and sub-national levels have the potential to strengthen water governance, improve water resource data collection and management, identify systemic risks and develop locally relevant strategies to reconfigure resource use patterns towards increased sustainability and equity.

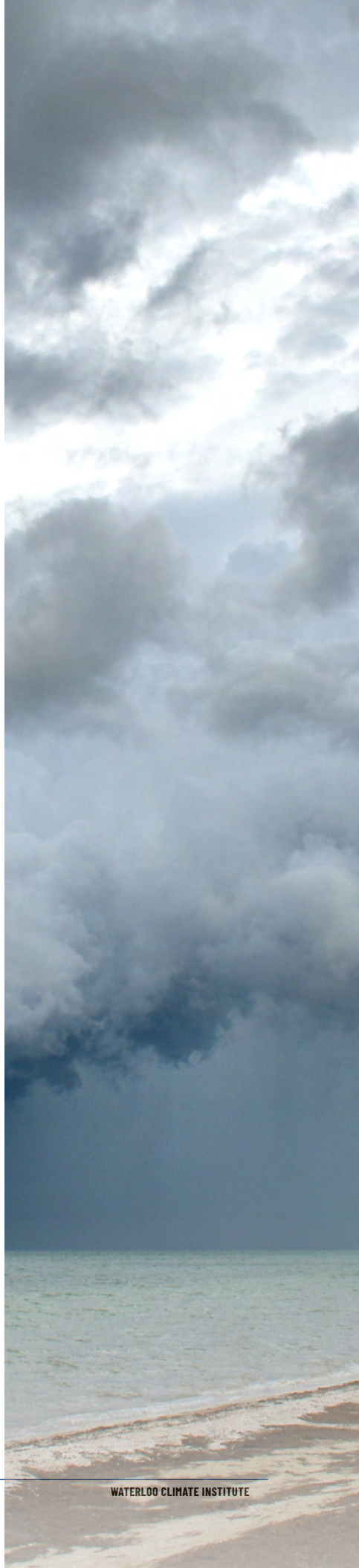
Data Availability

All data used in the analysis was sourced from FAO AQUASTAT. The compiled dataset is available through the Metabolism of Islands (MOI) website: Caribbean Hydro-SMR Indicators.xlsx

Note: The Caribbean Drought and Precipitation Network produces the "Caribbean Drought Bulletin". Visit: https://rcc.cimh.edu.bb/climate-monitoring/caribbean-drought-and-precipitation-monitoring-network/

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