CDEMA
CARIBBEAN DISASTER EMERGENCY MANAGEMENT AGENCY
Resilient States · Safer Lives

MULTI-HAZARD FRAMEWORK FOR RISK ASSESSMENT (MHFRA) IN THE CARIBBEAN

CDEMA
CARIBBEAN DISASTER EMERGENCY MANAGEMENT AGENCY
Resilient States · Safer Lives

WITH FINANACIAL CONTRIBUTION FROM THE EUROPEAN UNION

TARATUS EO4Multihazards esa

Contents

Summary for Decision-Makers

Background

There is a growing and urgent call for climate and disaster risk information to meaningfully inform decision-making for resilient and sustainable development across the 20 Participating States (PS) of the Caribbean Disaster Emergency Management Agency (CDEMA). With increasing exposure and projected escalations in disaster-related losses and damages due to climate change, these states, comprising primarily of Small Island Developing States (SIDS), and the land-locked and low-lying countries of Guyana, Suriname and Belize face heightened vulnerability. Comprehensive risk assessments are foundational to achieving the outcomes of the Caribbean Regional Comprehensive Disaster Management (CDM) Strategy and Results Framework (2014–2030). The strategy's overarching goal is "Safer, more resilient and sustainable CDEMA Participating States through Comprehensive Disaster Management."

Under **Priority Area 2** — *"Increased and sustained knowledge management and learning for CDM"* — the integration of risk information into development planning and sectoral programming, along with the establishment of integrated systems for evidence-based policymaking, is emphasized. To support implementation of this priority, tools like the **CDM Audit** and the **Multi-Hazard Early Warning System Checklist** establish standards for national and sectoral risk assessments. These include:

- Creation of centralised risk information repositories
- Availability of up-to-date hazard and risk data at appropriate spatial scales
- Capacity for hazard modelling
- Risk-informed decision-making in environmental monitoring, zoning, physical development, and macroeconomic planning

These priorities align with **Priority 1** of the **Sendai Framework for Disaster Risk Reduction 2015– 2030**: *"Understanding Disaster Risk"*, which highlights the importance of robust risk assessments as a basis for resilience-building.
CDM Audit Reports from across the Participating States indicate critical gaps, especially regarding the need for comprehensive, multi-hazard risk assessments, which are essential given the region's complex hazard landscape. The general practice in many countries, including the Caribbean, is to consider the impact of different hazards individually. However, in many scenarios, concurrently analysing two or more hazards becomes crucial but challenging due to their combined impact, due to the knock-on effect, where the impact of two events is larger than the summed-up impact of the individual events. Therefore, the analysis of compounding and cascading events is important for risk-informed decision-making.

Contextualizing Risk for the Caribbean

Developing **Caribbean-specific methodologies** is vital for accurately capturing vulnerabilities to external shocks and development impediments, especially when determining eligibility for Official Development Assistance (ODA). Conventional indicators like Gross National Income (GNI) per capita often fail to reflect the real risk landscape in the region. In response, SIDS advocated for the creation of

the **Multi-Dimensional Vulnerability Index (MVI)**. In 2024 the MVI was developed as a tool to better represent the vulnerability in developing countries. Additionally, the region faces challenges due to a lack of indicators tailored to its unique historical, cultural, social, and economic contexts, which can vary significantly even within island states (Drakes et al., 2020). This variation contributes to data uncertainties and can hinder effective resilience planning (Herron et al., 2016).

To support regional data access and decision-making, the **Caribbean Risk Information System (CRIS)**—

including the **virtual library** and **GEOCRIS**—were launched by the CDEMA Coordinating Unit (CU) in 2021. These platforms aim to host accessible risk management data and promote awareness, research, and evidence-based planning. A critical remaining challenge is the absence of minimum standards for conducting risk assessments that will be hosted on the CRIS. Establishing and applying such standards would enable the consistent creation or revision of national risk profiles, providing crucial input for preparedness, development planning and physical planning processes.

Regional Technical Working Group

To address this, the Regional Technical Working Group (RTWG) on Disaster Risk Assessment was established under the Physical and Environmental Planning Committee of the CDM Coordination and Harmonization Council. Comprising technical agencies with mandates in risk and development, the RTWG focuses on:

- Enhancing regional risk assessment capacities
- Developing standardised risk profiles for priority hazards
- Crafting and validating methodologies and tools
- Providing technical assistance for implementing and understanding risk assessments

The RTWG Members include the Caribbean Planners Association, University of Twente/ITC, Council of Caribbean Engineering Organisations, CDEMA, Caribbean Institute of Meteorology and Hydrology, UWI Climate Studies Group, Coastal Zone Management Unit (Barbados), Royal Institute of Chartered Surveyors, University of Technology, UWI Seismic Research Centre, and the World Bank.
At the 5th RTWG Meeting (February 27–28, 2024) in Barbados, held under the theme “Towards a Multi-Hazard Risk Assessment Framework for the Caribbean”, the group established a Core Group tasked with developing a regional Multi-Hazard Risk Assessment (MHRA) Framework. The framework will provide a suggested methodology for conducting MHRA in the Caribbean, accounting for:

- Differences in scale and governance
- Application purposes
- Data availability and quality
- Types of hazards and compound risks
- Anticipated changes due to climate and development trends

It was agreed that the methodology should be developed through a stepwise approach and will incorporate additional considerations raised during the meeting, for presentation at the Caribbean Comprehensive Disaster Management Conference, which was held in December 2–6, 2024, in St. Kitts and Nevis. This paper presents the outcome of the Core Group’s work under the RTWG and represents a major step towards a harmonised, evidence-based approach to disaster risk assessment in the Caribbean.

The context of the MHRAF

The Caribbean region is exposed to multiple hazards, which could either be hydrometeorological (hurricanes, droughts, floods), geophysical (e.g., landslides, earthquakes), environmental (e.g., loss of biodiversity, oil spills, salinisation, etc.) biological (e.g. viruses, pests and infectious diseases, sea algae), technological (transport accidents, fires) in nature. Increasingly, socio-natural hazards, such as climate change, which combine anthropogenic factors (e.g., greenhouse gas emissions) with natural factors, result in the intensification of hydrometeorological hazards and ecosystem degradation, disproportionately affecting the small island developing states (SIDS) and other countries in the region. Vulnerability to these hazards - likely exacerbated by a changing climate - is particularly high among SIDS and emerges from a combination of their small size, socio-economic conditions, dependence on coastal/blue economic activities (e.g., coastal tourism, etc,) and location of critical industrial, commercial and residential infrastructure within a few kilometres of the coastline, reliance on services from coastal ecosystems. Impacts are further intensified by simultaneous, cascading, consecutive, overlapping and compounding events and the relatively high level of population exposure due to unplanned urbanisation among other spatial planning challenges.

According to the UNDRR, Multi-hazard is defined as (1) the selection of multiple hazards that the country faces and (2) the specific contexts where hazardous events may occur simultaneously, cascadingly, or cumulatively over time, taking into account their potential interrelated effects (UNDRR). When communities are exposed to the risk of multiple hazards, management decisions must consider hazards and their interactions holistically. Multi-hazard risk assessment (MHRA) should identify all possible and relevant hazards and the valid comparison of their contributions to risk potential, including the contribution due to (i) the hazard interactions,(ii) the dynamic nature of exposure and vulnerability and (iii) capacity to adapt.

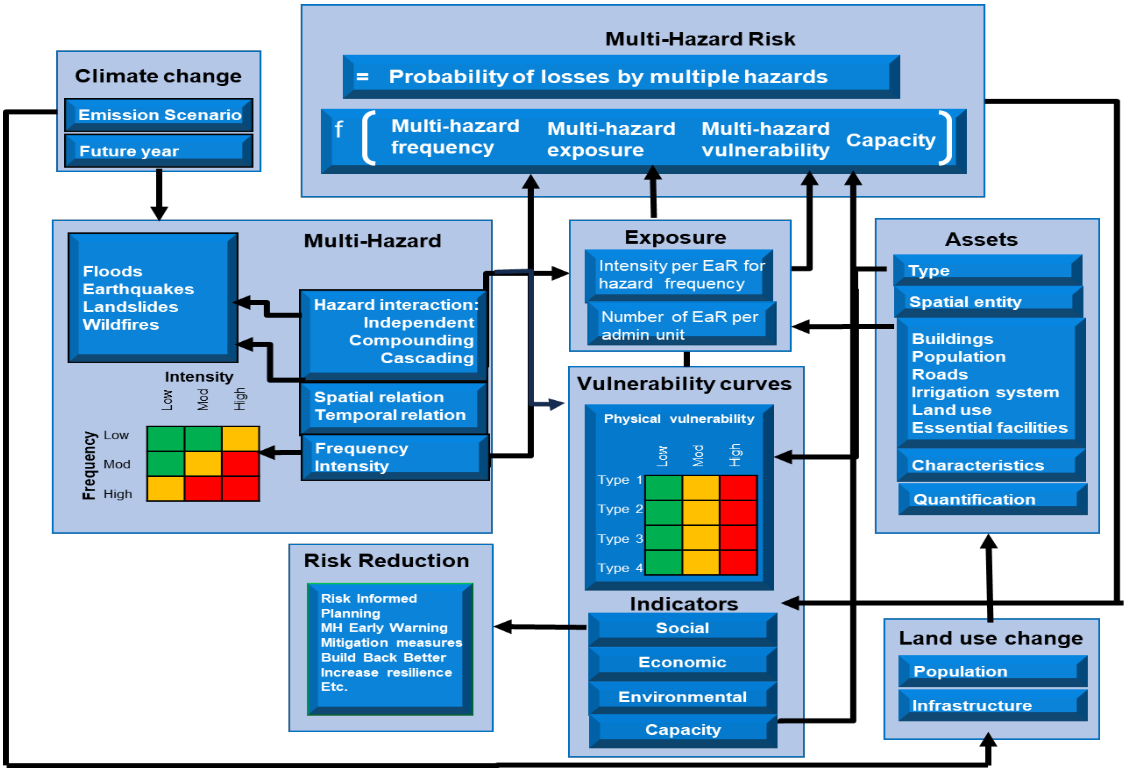


Figure 1: Conceptual framework of multi-hazard risk, with individual risk components of multi-hazards, assets exposure, vulnerability, and output leading to risk reduction planning

MHRA applies methodologies and approaches designed to evaluate and map the potential occurrence of various hazards within a designated geographic region. The general practice in many countries, including the Caribbean, is to consider the impact of different hazards individually. Therefore, the analysis of compounding and cascading events is important for risk-informed decision-making.

This framework for multi-hazard risk assessment in the Caribbean **aims** to enhance the understanding of the concept of multi-hazards, how these can be defined and conceptualized, and how the hazard and risk could be assessed. **A second aim is to guide/drive** the region towards a systematic generation of risk information at different spatial scales and mitigate limitations due to inadequate data management. This MHRA framework **provides** a general guideline that identifies the various approaches for MHRA that are suited for different levels of government, different applications, and different situations of data availability. It **serves** as a basis for the future development of detailed guidelines and capacity building (e.g., at the municipal level). It **addresses** the management policies and actions to **support** the cumulative building of knowledge in a sustainable and systematic way, highlighting important inter-institutional aspects of data management and sharing.

The framework for MHRA is developed in collaboration with CDEMA and other regional organizations. The framework (Figure 2) was developed after a series of meetings of the steering group and stakeholder consultations in the Caribbean. The international context of MHRA and its relevance to the Caribbean is considered by evaluating international literature on Multi- Hazard Risk Assessment and the relevant approaches that are developed at different levels in other countries, focusing specifically on countries with similar characteristics as the Caribbean. The proposed framework is consistent with the acts and policies on disaster and climate change of the Governments within the Caribbean, and it will serve as a guideline to generate risk information for disaster risk management and support the enhancement of Multi-hazard Early Warning Systems (MHEWS) and risk-sensitive development planning including infrastructure planning in various sectors like energy, health, education, transport etc.

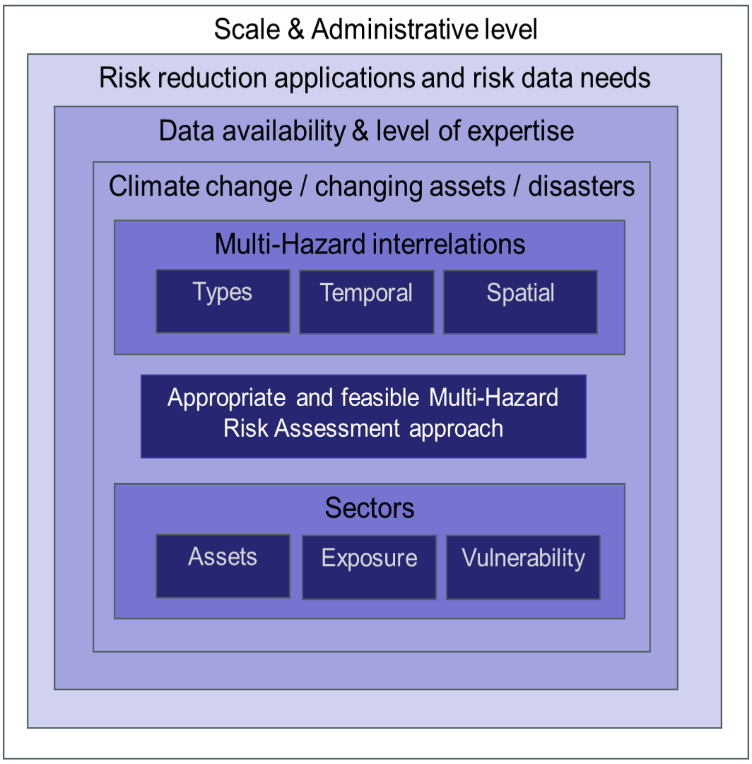


Figure 2: Illustrating the MHRA framework: what is the appropriate and feasible method for multi-hazard risk assessment in the Caribbean, given a range of conditions?

Legislative frameworks

One of the significant challenges in the legislative framework for multi-hazard risk assessment in the Caribbean is the absence of up-to-date laws or inconsistencies in implementing disaster management laws across different countries. Research indicates that while many Caribbean nations have enacted disaster management legislation, the effectiveness of these laws is often hampered by inadequate resources, lack of political will, and insufficient capacity at the local level. For example, a study on Trinidad and Tobago and Grenada highlighted operational deficiencies in implementing disaster risk management policies, which limited their effectiveness during emergencies. This challenge underscores the need to harmonize regional disaster management laws and practices to ensure a cohesive approach to multi- hazard risk assessment.

Furthermore, the legislative framework must also address the role of climate change in exacerbating disaster risks through increased vulnerability from climate-related impacts brought on by the increased frequency and intensity of natural hazards and the sub-seasonal, seasonal and decadal scales. Accordingly, integrating climate risk assessments into existing disaster management legislation is essential for understanding and mitigating the potential impacts of climate-related disasters on communities and infrastructure. This integration requires a paradigm shift in how disaster risk is conceptualized, moving from a hazard-centric approach to one considering the broader socio-economic and environmental contexts contributing to vulnerability. Further, this shift must be towards adaptive management strategies responsive to changing environmental conditions and emerging risks.

Policymakers must prioritise investments in climate resilience initiatives that enhance the capacity of communities to withstand and recover from the impacts of climate-related disasters. Legislative measures that promote climate adaptation strategies alongside disaster risk reduction efforts can enhance the overall resilience of Caribbean communities. Of several member-states in the Organization of Eastern Caribbean States (OECS), their disaster management agencies had not mainstreamed climate change in their routine operations. Notably, one critical limitation affecting the successful implementation of the legislative framework may be the reality that SIDS within the Caribbean do not have adequate access to climate finance, which will facilitate adaptation management strategies.

DRM activities that require risk information

Applications of multi-hazard risk assessment are diverse and crucial in various fields, including disaster risk management (DRM), land use planning, disaster response, and climate change adaptation. Leveraging advanced technologies and methodologies, these applications comprehensively evaluate potential risks from multiple hazards in isolation, composite, and compounding effects concurrently. As climate change intensifies hazards, multi-hazard risk assessments play a crucial role in adapting strategies to the changing climate and ensuring dynamic and responsive emergency plans.

There are many policy, planning, and management activities that require risk information (See Table 1), but the type of information and quality differ among these and at which administrative level these actions are taken. An illustrative list of the main responsibilities of the national and subnational organizations is presented in Table 1, which is subdivided according to the main disaster management phases and administrative units. The table indicates at which administrative levels the respective actions are most important. At the regional scale, supporting countries with resource allocation related to DRM is one of the primary tasks. Further, the management of information on hazard events, disaster losses, and damages, visualization of hazard, vulnerability, risk and capacity, multi-hazard early warning, and impact-based forecasting are important tasks supported by regional partners, such as CDEMA among others.

Multi-hazard risk assessments are a crucial foundation for multi-hazard early warning systems (MHEWS) in DRM. These assessments provide a holistic understanding of hazard, vulnerability, and exposure, which feeds into the first pillar of Risk Knowledge in MHEWS. The information gained from the assessments is essential for realistic monitoring and impact-based forecasting, which supports the second pillar of Detection, Monitoring, and Forecasting.

Data for Multi-Hazard Risk Assessment

For a successful MHRA, data should cover various aspects such as hazard frequency, intensity, exposure, and vulnerability at multiple scales. Reliable data, accessible through integrated platforms, support risk assessment efforts by enabling local governments, disaster management agencies, and communities to identify high-risk areas and prioritize investments in resilience-building and disaster preparedness. However, the availability of comprehensive and accurate data varies greatly across the region, creating a divide between data-rich and data-poor areas. This variability has significant implications for resilience-building efforts and the ability to respond effectively to threats like hurricanes, earthquakes, volcanic eruptions, flooding, and health risks such as infectious and non-communicable diseases.

Table 1: Overview of policy, planning, and management activities that require risk information and the main output requirements at national, provincial, and local levels. The green colored boxes show the most important combinations. The orange ones are less common, and the red ones are actually not done at that scale.

	Applications that require risk information	Implications for the risk assessment at different levels		
		Regional	National	Municipal / Parish
Prevention and Mitigation	Prioritization of admin units for investments by governments, NGO, and donor organizations	Relative classes of exposure, vulnerability, capacity, and risk for countries	Relative classes of exposure, vulnerability, and capacity for municipalities	Relative classes of exposure, vulnerability, and capacity for wards
Prevention and Mitigation	Environmental Assessment	Expected changes in multi-hazard exposure and losses under different future scenarios	Environmental Impact Assessments for large developments: multi-criteria, including multi-hazard and risk	EIA for specific municipal facilities. Multi-criteria, including multi-hazard and risk indicators that are derived quantitatively
Prevention and Mitigation	Risk informed planning	Prioritisation of cross-border activities (trade, tourism	Prioritisation of municipalities or watersheds (see above)	Exposure to multiple hazards and frequency
Prevention and Mitigation	Regulatory zoning and building regulations	Regional initiatives, Quantitative multi-hazard information	Quantitative multi-hazard information	Quantitative multi-hazard information
Prevention and Mitigation	Design of risk mitigation measures	This is not done at the regional scale. Prioritisation is done for resources (See above)	Monetary losses for Cost-Benefit analysis	Monetary loss for cost – Benefit analysis, population losses
Prevention and Mitigation	Planning critical infrastructure and essential facilities	Prioritization of provinces or watersheds (see above)	A general indication of frequency and expected losses of multi-hazards	Quantitative information at the local level for critical sections
Prevention and Mitigation	Risk financing instruments	Regional instruments, Probability of Monetary losses (AAL, PML) for the entire country)	Probability of Monetary losses (AAL, PML) for the entire country and per municipality)	Only for cities: the probability of Monetary losses (AAL, PML) for insured assets
Preparedness	Multi-Hazard Early warning	At regional level for linking with major triggering events (Hurricanes, Rainfall estimates, volcanoes etc.)	Overview of municipalities with vulnerability and population exposed to multi-hazard event scenarios for warning dissemination	Local EWS: detailed information on population exposure for different multi-hazard scenarios and time periods
Preparedness	Impact-based forecasting	Real-time expected exposed buildings, population, agriculture, roads to multi-hazards	Real-time expected exposed buildings, population, agriculture, and roads to multi-hazards	Identification of exposed and vulnerable locations and dissemination of information based on the likelihood of impact using spatial information.
Response & Recovery	Disaster response planning	Allocation of resources for disaster response, based on prioritisation (See above)	Allocation of resources for disaster response, often based on parish, using prioritisation (See above), provincial stockpiling and warehousing of relief facilities	Shelter planning allocation of emergency response resources based on multi-hazard scenarios, evacuation site planning, and evacuation route modeling
Response & Recovery	Recovery and reconstruction planning	Allocation of resources for disaster recovery, based on damage per country based on new loss estimations	Prioritisation of sites for reconstruction planning based on loss estimations of the new situation and possible changes in hazards, exposure, and vulnerability	Planning of safe sites for reconstruction planning based on loss estimations of the new situation and possible changes in hazards, exposure, and vulnerability. Multi-hazard risk-sensitive land use planning.

The Caribbean faces a number of challenges in data collection, management, and accessibility, which complicate efforts to build a robust MHRA framework:

Limited Technical Capacity: Many Caribbean nations lack the technical capacity and financial resources needed to gather, analyse, and manage MHRA data. Training, equipment, and specialised expertise are often limited, hindering data collection efforts, particularly for complex datasets like high-resolution hazard maps and vulnerability assessments. There is an urgent need for capacity-building initiatives that can empower local stakeholders to leverage these tools effectively.

Institutional Challenges. Many countries operate within fragmented governance structures, where responsibilities for disaster risk management are dispersed across multiple agencies. Establishing clear lines of communication and collaboration among relevant stakeholders is essential for overcoming these challenges and fostering a more integrated approach to multi-hazard risk assessment.

High Costs of Data Acquisition. Satellite imagery and remote sensing data are valuable for hazard assessments, but can be prohibitively expensive for smaller nations. Furthermore, maintaining up-to-date databases requires ongoing investment, which is challenging in regions with limited budgets.

Inconsistent Data Standards. The absence of standardised protocols for data collection and management across Caribbean countries leads to inconsistencies in data formats, quality, and accuracy. Many countries within the region rely on disparate data sources, which can lead to inconsistencies and gaps in the information available for risk assessment. The absence of a unified approach to data collection and sharing further complicates efforts to develop a cohesive understanding of multi-hazard risks across the Caribbean.

Limited Data Sharing and Access. Privacy concerns, intellectual property issues, and institutional policies can restrict access to important datasets. The lack of clear data-sharing agreements between national agencies and regional organisations also impedes collaborative efforts, leaving some areas underserved in terms of data availability.

Public-Private Partnerships. Initiatives aimed at enhancing regional data repositories and fostering partnerships between governments, academia, and the private sector have shown promise in addressing some of the existing data gaps. However, sustained efforts are needed to ensure that these initiatives translate into meaningful improvements in data availability and accessibility.

International Contribution. By aligning regional priorities with international funding opportunities, Caribbean nations can enhance their capacity to conduct comprehensive multi-hazard risk assessments that inform disaster risk reduction strategies.

Local Knowledge Integration. The integration of local knowledge and community-based approaches into multi-hazard risk assessments is a critical aspect of improving data availability in the Caribbean. Engaging communities in the data collection process and creating an enabling environment for citizen science not only fosters ownership and empowerment but also ensures that assessments are grounded in the realities faced by those most affected by hazards.

Regional Data Integration Platforms. Data integration platforms can serve as centralised repositories for MHRA data. By consolidating data from reliable sources, decision-makers can have access to regional data, supporting both national and cross-border risk assessments.

Leveraging Open-Source and Crowdsourced Data. Open-source platforms and crowdsourced data collection can provide valuable resources for MHRA at a low cost.

Expanding Use of Satellite and Remote Sensing. International space programmes provide access to satellite imagery, which can support many hazard assessments.

Promoting Data Sharing Agreements. Establishing formal data-sharing agreements within the Caribbean would enable better access to critical datasets and facilitate cross-country collaboration on MHRA. Standardising data collection methods and protocols would further enhance the compatibility of datasets.

Multi-Hazard Assessment

Multi-hazards were defined as “multiple major hazards that an area faces, and the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects”. Given the interrelationships among hazards, the cumulative effect of several hazardous events is expected to surpass that of each individual hazard. Therefore, it is essential that within the multi-hazard risk framework these interrelations are considered with respect to timing and their impact at varying spatial scales. Notwithstanding, it is important to understand the impacts associated with independent events to better appreciate the reality of the expected impact of simultaneous, cascading, consecutive, overlapping and compounding events.

The choice of appropriate multi-hazard risk assessment methods is governed by the interrelations between the hazardous events that should be considered. We are referring here to hazard interrelations, and not hazard interactions, because the hazards might not actually interact with each other while still having an important influence on the resulting impact. The hazard interrelation is determined by a combination of three components:

- Type interrelation: how different hazard types can have an influence on the expected losses.
- Spatial interrelations: how the spatial extents of hazards have influence.
- Temporal interrelations: how the timing of events relative to each other is important for losses.

It is important to consider this combination of the interrelation between the type of hazard, the temporal aspect, and the spatial aspect in order to select the best approach for multi-hazard and risk assessment. In order to simplify the above-mentioned classification for applicability in the Caribbean, we propose the following simplified classification (See Figure 3). This simplified classification is important because the different types of hazard interrelations impact how risks are assessed. Table 2 gives a summary of these considerations.

Multi-Hazard Exposure and Vulnerability Assessment

The impacted area of a hazardous event might vary considerably among different combinations of hazard type and element-at-risk type. Further, the directly impacted area, as obtained from the exposure analysis, might be much smaller than the area that is indirectly impacted, and this area might also change dynamically over time as the impacts of an event cascade over different sectors. The time that direct and indirect impacts take place may also be quite different, as indirect impacts may last a much longer time than direct impacts.
The expected changes in multi-hazard, exposure, vulnerability, and risk also determine the appropriate method for multi-hazard risk assessment. These changes can be related to:

Climate: Climate change affects the frequency, intensity, and interrelation of hazards. Extreme events might become more frequent, thereby increasing the number of consecutive events. They might also lead to higher intensities, which in turn lead to larger losses. Climate scenarios should be developed for specific future years, and their consequence in the hazard modelling should be analysed. Climate change might also change the interrelationships between hazard types (introducing new hazard combinations or intensifying existing ones).

Changing assets: future developments such as population changes, expanding urbanisation, globalisation, and infrastructure development may drastically change the exposure and vulnerability of assets. including our ever-increasing dependency on electricity and internet access, which should be considered in future multi-hazard risk assessments.

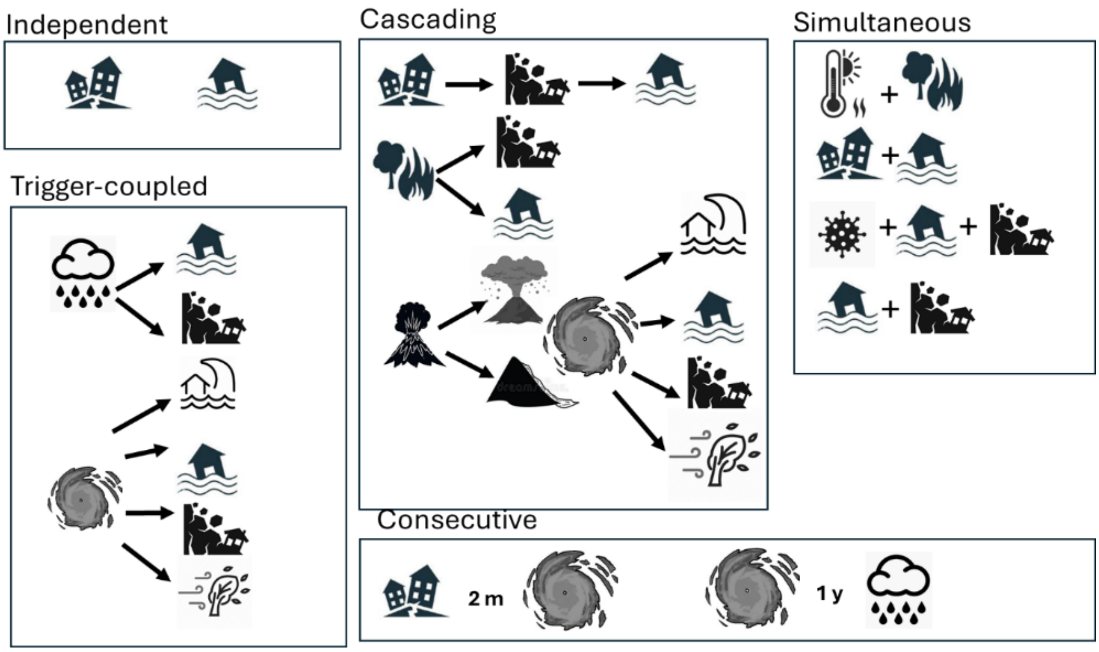


Figure 3: Simplified classification of hazard interactions.

Table 2: Consequences of hazard assessment approaches for multi-hazard interrelations.

Hazard interrelation	**Hazard Assessment**		**Remarks**
	Frequency assessment	**Intensity assessment**	
Independent events	Magnitude/ intensity / frequency relation for each hazard is modelled independently	Intensity of each hazard type for that return period is modelled separately.	This is the conventional single hazard modelling approach. Still relevant to assess risk of independent events
Simultaneous events	Determine scenarios of events, and determine the joint frequency of the individual, if possible	If the intensity of one event is influenced by the other, they should be modelled jointly , if possible. Otherwise, separate intensity models	There are many possible scenarios , and it will be difficult to consider all. A limited selection is made
Trigger coupled events	The return period of the main trigger is assessed and used for the coupled hazards	The intensity of the various hazard types should be modelled together, based on the magnitude of the trigger event.	Here the modelling of the joint events is easier because they are linked to the same magnitude trigger event.
Cascading events	After assessing the frequency of the main trigger, event trees are used to determine the probability of the cascading hazards	The intensity (& spatial extent) of one event depends on the outcome of the previous event. Thus, modelling should be done in sequence.	There are many scenarios possible, and the probability and intensity of the steps in the cascade are often difficult to model.
Consecutive events	The timing between two events is based on frequency assessment and seasonality. scenarios should also be generated here.	The intensity of the consecutive event might be amplified by the effect of the earlier event (e.g. conditions might have changed). This should be considered.	The most important consequence will be on vulnerability, exposure and loss assessment. Only when there is an amplifying effect the hazard is influenced.

Disaster occurrence: Disasters cause drastic changes in assets and hazards as well. The recovery time, the time needed for the environment to recover from a previous event (e.g., a forest fire), is important to the occurrence of pre-conditioning events (e.g., flash floods after extreme rainfall), and the longer the time between these events, the less likely that the second one will turn into a hazardous event. Further, the time needed for society to recover from the impact of a previous event is essential in determining the impact of consecutive events. The recovery, however, is very difficult to take into account in the multi- hazard risk assessment of consecutive events, as it depends on many factors that are difficult to predict beforehand, such as the specific impact of previous events, the pace of reconstruction, financial realities, and the risk governance. Although this concept is considered conceptual, hardly any studies have developed concrete examples.

To include the dynamic aspects of exposure and vulnerability within a multi-hazard risk assessment, it is very relevant to distinguish between an assessment that considers the current situation and the coming years (loss prediction), where any combination of hazardous events might take place, and situations where a particular disaster hazard event has already occurred. Many of the studies that illustrate the importance of multi-hazard risk assessment are based on historical event scenarios for which specific hazard interactions and timing between events were already known (forensic analysis).

Multi-Hazard Risk Assessment

Disaster risk assessment is defined as “a qualitative or quantitative approach to determine the nature and extent of disaster risk by analysing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment. It integrates the hazard, exposure, vulnerability and adaptive capacity components by first analysing the loss related to specific scenarios of hazard events, with their own frequency of occurrence, and integrating this into the risk assessment. When considering the multi-hazard risk, the most conventional approach is to consider the multilayer single hazard, in which the exposure and losses for each combination of individual hazard type, frequency, and element-at-risk are calculated separately and aggregated per administrative unit. The total risk is then analysed by integrating the losses into Average Annual Losses (AAL) and adding these for the individual hazard/element-at-risk combinations. Many methods for multi-hazard risk assessment have been outlined in the literature.

A comprehensive multi-hazard risk assessment (MHRA) is essential for enhancing resilience and reducing the socio-economic impacts of these disasters. Multi-hazard risk assessment identifies, analyses, and quantifies the risks posed by multiple hazards to a given area, infrastructure, or population. Unlike single-hazard assessments, MHRA considers the potential for simultaneous or cascading events, recognising that the impact of one hazard can exacerbate another. For example, hurricanes can trigger flooding, landslides, and coastal erosion, while volcanic eruptions can lead to tsunamis. MHRA is particularly important in the Caribbean, where overlapping hazards can cause compounding damage. Understanding the interactions between hazards and the vulnerability of various sectors, such as housing, infrastructure, and agriculture, is vital to developing effective disaster risk reduction (DRR) and climate change adaptation (CCA) strategies. CDEMA’s guidelines also stress the importance of regional collaboration.

Table 3 gives a summary of the recommended approaches for Multi-Hazard Risk Assessment for different scales and activities.

A robust MHRA framework typically includes the following core components:

Multi-Hazard Assessment: Determining the types of hazards that can impact a region, including their frequency, intensity, and duration. Hazard identification is based on indigenous knowledge, historical data analysis, monitoring, modelling and forecasting.

Exposure Assessment: Identifying the elements at risk, including people, buildings, infrastructure, and ecosystems, and determining their location relative to the hazard-prone areas.

Vulnerability Analysis: Analyzing the susceptibility of exposed elements to impacts. This involves understanding the socio-economic factors (e.g., poverty, age, disability) and physical factors (e.g., building quality) that contribute to vulnerability.

Scenario Analysis: Developing potential future disaster scenarios based on models, historical analogues and expected change in climate, hazards, assets, vulnerability and exposure.

Risk Calculation: Quantifying hazards' probability and potential impact on exposed elements. Risk is often expressed as a combination of hazard likelihood, exposure, vulnerability and adaptive capacity). This includes an uncertainty and sensitivity analysis: Addressing uncertainties in data, models, and future projections. This is particularly important in regions like the Caribbean, where climate alters the frequency and intensity of hazards.

Risk Evaluation: analyzing if the level of risk is acceptable or not. In the absence of risk acceptability standards for the Caribbean, compared with other types of risk. This supports risk ranking and the establishment of risk transfer mechanisms

Risk Reduction Alternatives: that help planners and policymakers prioritize areas of concern and prepare appropriate mitigation measures.

Early warning, early action

One of the most important applications of MHRA is for Multi-Hazard Early Warning Systems (MHEWS) and Impact-Based Forecasting (IBF). The Climate Risk Early Warning Systems (CREWS) initiative, supported by the World Meteorological Organisation (WMO), aims to improve early warning systems for multiple hazards in the Caribbean. CREWS provides technical assistance and capacity building to enhance hydrometeorological services, ensuring that risk assessments incorporate real-time data and impact-based warnings. CREWS promotes the use of multi-hazard early warning systems (MHEWS) that address a range of risks, including hurricanes, floods, and droughts. By improving the accuracy and timeliness of early warnings, CREWS enhances disaster preparedness and response capabilities across the Caribbean.

Impact-based forecasting is a near real-time estimation of expected impacts, considering the forecasted hazard trigger (e.g., tropical storms, rainfall, flooding and drought). The approach can be based on actual continuous modelling of hazards, exposure, vulnerability, and losses or based on machine learning approaches. The models should be fast enough to run in real time for process-based modelling. The method requires a direct coupling with real-time hazard forecasting.

Depending on the data availability, three different approaches for the MHRA component could be selected:

- Indicator-based approach, linked with a single scenario impact model
- Quantitative single impact model, linked with physically based modelling of hazard events.
- AI approach linked with a database of previously modelled events.
- AI approach based on a dataset of damage data.

Conclusion

While Caribbean nations have made significant progress in implementing multi-hazard risk assessments, several challenges remain. Nevertheless, despite these challenges, MHRA presents significant opportunities for improving resilience in the Caribbean. By integrating scientific data, community participation, capacity development and regional collaboration, Caribbean nations can better understand and mitigate the risks posed by multiple hazards.

Multi-hazard risk assessment is a vital tool for reducing disaster risks and building resilience in the Caribbean. The region's vulnerability to hurricanes, earthquakes, floods, and other hazards necessitates a comprehensive approach that considers the interactions among hazards, exposure, and vulnerability. Methodologies such as probabilistic risk assessment, deterministic scenario analysis, geospatial risk mapping, and community-based assessments provide valuable insights into the risks facing Caribbean nations.

Table 3: Recommended multi-hazard risk assessment approaches for DRM applications at different levels. Boxes shaded with horizontal lines are combinations of applications that are mostly done at another level.

Multi-Hazard Risk Assessment Methods and Applications				
	Applications	**Regional Level (< 1:100,000; Grid > 20 m)**	**National level (1:25,000-1:100,000; Grid 5-20 m)**	**Local / Ward level (>1:25.000, Grid< 5 m)**
Prevention & Mitigation	Prioritization DRR	Indicator Multi-Criteria Evaluation	Indicator Multi-Criteria Evaluation	Multi-Criteria &, Community-Based DRA
	Environment Assessment	Indicator Multi-Criteria Evaluation	Indicator Multi-Criteria Evaluation	Multi-Criteria &, Community-Based DRA
	Risk-informed planning	Not a suitable scale for this	Simplified QRA, Risk Matrix, Indicator Multi-Criteria Evaluation	Scenario-based risk assessment, Risk Matrix Approach
	Regulatory zoning and building regulations	Probabilistic risk analysis	Simplified QRA	Simplified QRA
	Design of risk mitigation measures	Not a suitable scale for this	Impact chains, Event-tree analysis, Simplified & Probabilistic risk analysis	Impact-chains, Community-Based, Simplified & Probabilistic risk assessment
	Planning critical infrastructure and essential facilities	Impact chains, Event-tree analysis, Simplified & Probabilistic risk analysis	Impact chains, Event-tree analysis, Simplified & Probabilistic risk analysis	Impact-chains, Community-Based, Simplified & Probabilistic risk assessment
	Risk financing instruments	Probabilistic risk analysis	Probabilistic risk assessment	Not a suitable scale for this
Preparedness	Multi-Hazard Early warning	Impact chain analysis Scenario-based analysis	Impact chain analysis Scenario-based analysis	Impact chains analysis, Community-Based DRA, Scenario-based analysis
	Impact based forecasting	Indicator-based & AI	Physical modelling & AI	
Response & Recovery	Disaster Response Planning	Impact chains Scenario-based analysis	Impact chains, Scenario-based analysis	Impact chains Community-based DRA scenario-based analysis
	Reconstruction planning for recovery	Impact chains, Scenario-based analysis, Multi-criteria evaluation	Impact chains, Scenario-based risk assessment, Multi-criteria evaluation, Risk Matrix approach	Impact chain analysis, Community-based DRA, Scenario-based risk assessment

Guidelines from regional and international organisations have been designed to ensure that MHRA is conducted using standardised, scientifically sound procedures. By leveraging these tools and guidelines, Caribbean nations can enhance their disaster preparedness, improve early warning systems, and build more resilient communities in the face of an increasingly uncertain climate future.

Recommendations

- **Enhance Regional Coordination and Centralise Data Management:** A more coordinated approach is critical to enhancing efficiencies among regional institutions in the Caribbean. The Caribbean Disaster Emergency Management Agency (CDEMA) should continue to advance its role as the central coordinating body for multi-hazard risk assessment in part through collaborations with regional organisations. Mainstreaming an interoperable system of systems to support the establishment of a regional hub for hazard data would improve information sharing across countries and institutions.
- **Invest in Capacity Building for National and Local Agencies:** Many Caribbean nations face challenges related to limited technical capacity, which hinders the effectiveness of their multi-hazard risk assessments. A concerted effort should be made to invest in human resources and continued professional development across national disaster management stakeholders. Specialized training in MHRA and related topics like Geographic Information Systems (GIS), remote sensing, environmental modelling, and hazard mapping is essential to build technical expertise.
- **Develop Standardised Protocols for Data Collection and Sharing:** One of the main challenges limiting the effectiveness of multi-hazard risk assessment in the Caribbean is the lack of standardised data formats and protocols for data sharing across institutions and countries. Developing a standardised protocol for hazard data collection, analysis, and dissemination would enhance the comparability and utility of hazard data. These protocols should address data resolution, time intervals, metadata standards, and quality control mechanisms.
- **Promote Public-Private Partnerships (PPPs) for Hazard Monitoring and Data Acquisition:** The private sector can play a crucial role in enhancing multi-hazard risk assessment capabilities in the Caribbean. Public-Private Partnerships (PPPs) can facilitate investments in advanced hazard monitoring technologies, such as high-resolution satellite imagery, early warning systems, and real-time monitoring networks. However, PPPs should be part of the concerted efforts in MHRA and not be limited to stand-alone initiatives.
- Additionally, **integrating community-based assessments** ensures that risk management strategies are grounded in local realities, making them more effective in building resilience. Implementing these recommendations will enhance the Caribbean's ability to cope with its unique vulnerability to natural hazards and the growing impacts of climate change.

Chapter 1. Introduction

1.1. Background

The Caribbean region is highly susceptible to hydro-meteorological and geological hazards (UNDRR 2022; Pinos and Quesada-Román 2021; Wilkinson *et al.* 2021). The region is highly vulnerable to climate change and disasters caused by natural hazards and faces both extreme and slow-onset climate-related hazards (Schultz et al., 2016). The Caribbean's climate vulnerabilities emerge from a combination of fragile mountainous island topography and ecosystems and highly variable hurricane-driven hydrology. The impacts of these hazards are further intensified by the high level of population and critical infrastructure exposure due to unplanned urbanization and high levels of vulnerabilities arising from socio-economic conditions (Aguilar and Guerrero 2022; Valero, Miranda, and Murisic 2021; Mycoo et al., 2022). Recent shocks include the 2024 Beryl hurricane, and 2017 and 2018 hurricane seasons (Irma and Maria), floods and frequent landslides, and the COVID-19 pandemic 2020. According to the Climate Risk Index (Eckstein et al., 2021), several Caribbean countries rank within the 20th most affected countries globally. Figure 1.1 provides some information on disaster impact (EMDAT, 2024)

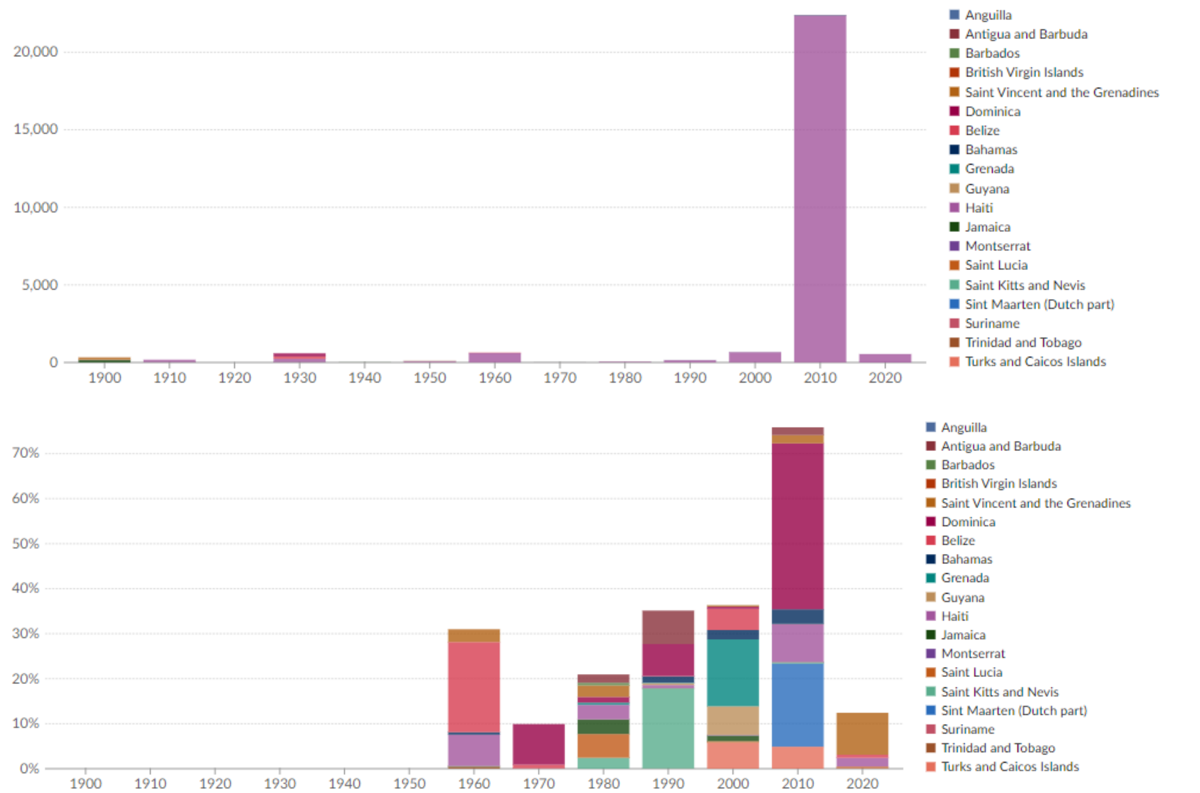


Figure 1.1: Above: Persons killed by natural disasters in the member states of CDEMA . Below: Decadal average: Annual economic damages from disasters as a share of GDP. Disasters include all geophysical, meteorological and climate events including earthquakes, volcanic activity, landslides, drought, wildfires, storms, and flooding. Decadal figures are measured as the annual average over the subsequent ten-year period (source: EMDAT, 2024).

Approximately 80 percent of its population is at risk from natural and climate-induced hazards, including hurricanes, volcanoes, drought, earthquakes, landslides, floods, forest fires, extreme heat stress, air pollution, etc.

Furthermore, disasters affect three of every ten people in the region (Gencer 2013). Vulnerable communities, mainly the poor living in remote areas and working in subsistence agriculture, face the highest risk, with exposure being spatially heterogeneous. Storms and associated flood and landside risk are the most damaging natural hazards. Figure 1.2 provides information on decadal economic damages as share of the GDP of the CDEMA member states.

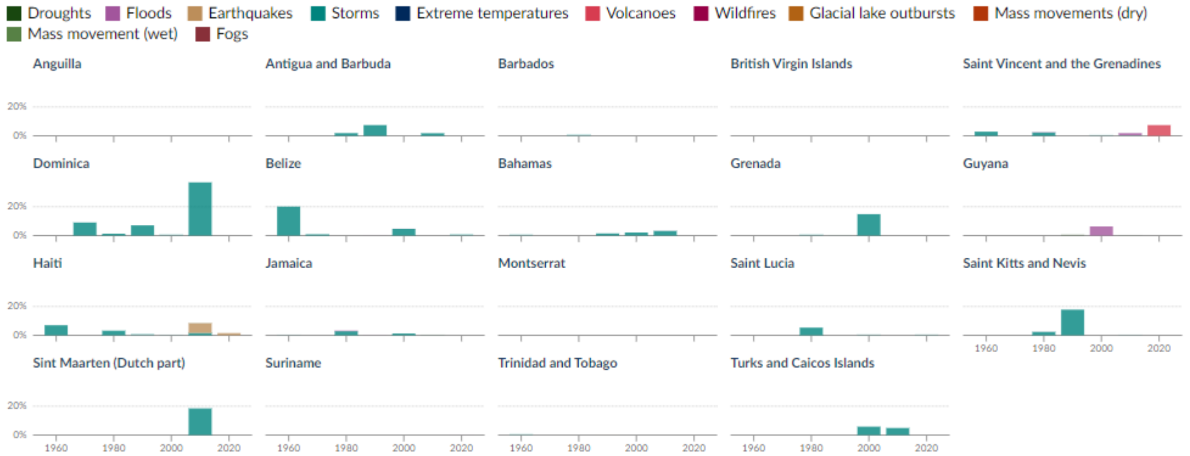


Figure 1.2. Decadal average: Economic damages from disasters as a share of GDP for different types of hazards per country for the past decades (Source: EMDAT, 2024).

In Latin America and the Caribbean, disasters have affected over 190 million people in the last 40 years (EMDAT 2024; Gencer 2013). In the Caribbean, for the last 20 years, average annual losses due to disasters have been estimated at US1.6 billion per year (Jones, Doughorty, and Brown 2022). The average annual economic loss from disasters is estimated at 17% of their GDP (at the current price) of FY 2018/19, even reaching a maximum value of 253% in Dominica in 2017 after Hurricane Maria (UNDP, 2024). Disasters are also a threat to development investments, mostly infrastructure and services. Since 1950, 324 disasters have occurred in the Caribbean, causing losses of over 250,000 lives and affecting over 24 million people (UNDP. 2024). While the number of flooding events has doubled in recent years, landslides, forest fires, storms, and soil erosion are also rising, damaging homes and infrastructure like roads, bridges, hydropower plants, and public buildings.

Recent developments in regional and national disaster risk management (DRM) policy in the Caribbean, which aim to manage disaster and climate risks, include the establishment of the Caribbean Disaster Emergency Management Agency (CDEMA), the development of national DRM policies and strategies, strengthening of preparedness and response capacities, and the formation of methodological documents to support mainstreaming of climate and disaster resilience in development planning at the national and regional local levels, such as the Caribbean Nationally Determined Contribution Finance Initiative (NDCFI), which aims to support Caribbean countries in implementing their commitments to reduce greenhouse gas emissions and adapt to the impacts of climate change, as outlined in their Nationally Determined Contributions (NDCs) under the Paris Agreement (NDCFI, 2024). To achieve effective risk-informed decision-making, it is important to have a shared vision of the Sustainable Development Goals (SDGs) and to integrate risk with economic development and environmental sustainability. Linking the strategy to SDGs and the Sendai Framework for Disaster Risk

Reduction 2015–2030 will facilitate the implementation of the strategy and provide added value to society (UNDRR, 2021).

1.2. Concept of Multi-Hazard Risk

The term *hazard* refers to potentially dangerous phenomena such as floods, landslides, forest fires, and earthquakes that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation (Lanlan *et al.* 2024; Ward *et al.* 2020). Each hazard is characterized by its type, location, magnitude (indicating the severity/energy of the event), intensity (indicating the spatial distribution of the damaging effects), the frequency of the events with the same magnitude/intensity, the time of onset, and duration (See Figure 1.3 and Annex 1). *Multi-hazard* is defined as multiple hazards that an area faces and the specific contexts where hazardous events may occur simultaneously, cascadingly, or cumulatively over time, taking into account the potential interrelated effect (Šakić Trogrlić *et al.* 2024; UNDRR 2016).*Multi-hazard Risk assessment* should identify all possible and relevant hazards and the valid comparison of their contributions to hazard potential, including the contribution to hazard potential from hazard interactions and spatial/temporal coincidence of hazards, while also taking into account the dynamic nature of vulnerability (Rusk *et al.* 2022; Ming *et al.* 2022; Gill and Malamud 2016; Gallina *et al.* 2016; Gill et al., 2022). The *multi-hazard risk assessment* entails the examination of various hazards within a specific context, considering their possible interactions and the resulting potential impacts arising from their compounding, concurrent, or cascading occurrences (Owolabi and Sajjad 2023; Choi *et al.* 2021).

Multi-hazard risk assessment applies methodologies and approaches designed to evaluate and map the potential occurrence of various hazards within a designated geographic region (Gill et al., 2022). The current practice in many countries, including the Caribbean, is to consider the impact of different hazards individually. However, in many scenarios, concurrently analyzing two or more hazards becomes crucial but challenging due to their combined impact due to the knock-on effect, where the impact of two events is larger than the summed-up impact of the individual events. Therefore, the analysis of compounding and cascading events is important for risk-informed decision-making. Typically, a community or settlement can be susceptible to diverse hazards arising from multiple triggers, which could be related to environmental (topography, geomorphology, geology, soils, etc.), climatic (heatwave, cold wave etc.), or human activities (deforestation, construction, tourism, vegetation burning etc.) or a combination of both, creating the complexities in assessment.

There are several key components in MHRA, as indicated in Figure 1.3 :

- **Multi-Hazard Identification/Analysis:** the recognition and categorization of various hazards that pose a risk to a community, and the assessment of their frequency. They may be coinciding with other hazards, or occur in a cascade.
- **Asset mapping and characterisation:** mapping/modelling the presence of people, buildings, infrastructure, and other assets that could be impacted by the hazards.
- **Exposure Assessment:** analysing the number of assets that might be affected by multi-hazard events, and quantifying the hazard intensity for these intersections;

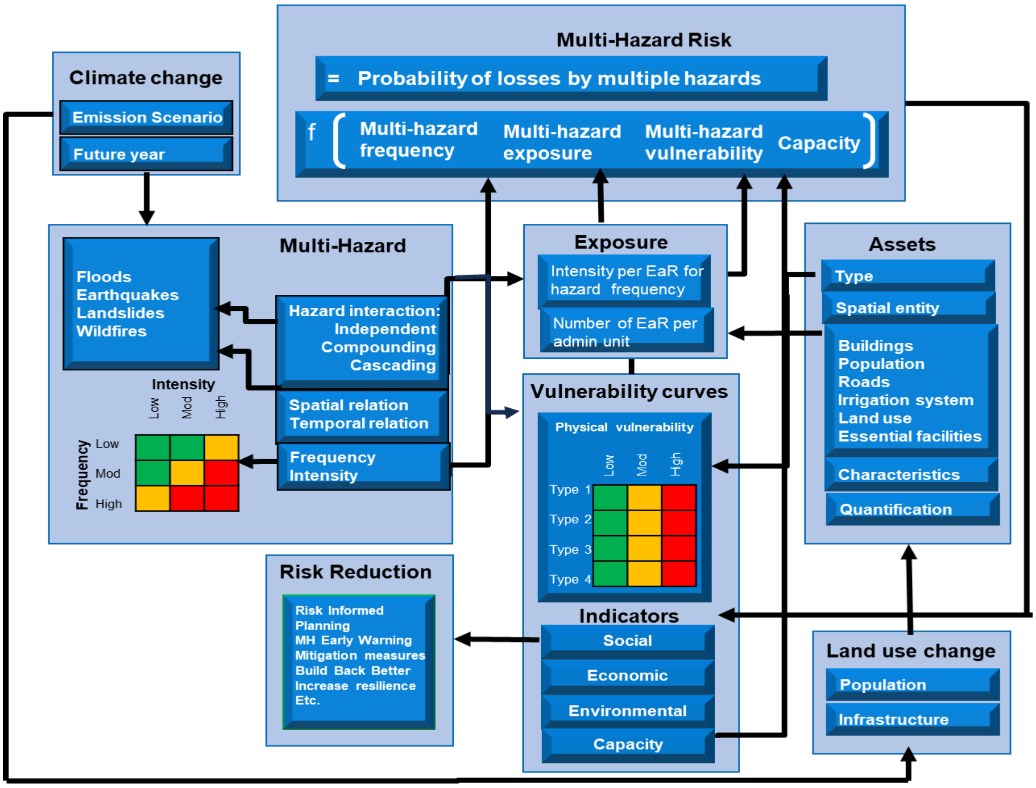


Figure 1.3: Conceptual framework of multi-hazard risk, with individual risk components of multi-hazards, assets exposure, vulnerability, and output leading to risk reduction planning (Van Westen, et al., 2011)

- **Vulnerability Assessment**: evaluating the susceptibility to damage, either in the form of physical vulnerability curves, or socio-economic indicators;
- **Risk Analysis**: the analytical step that assesses the likelihood of impacts on vulnerable populations and infrastructure. This combines the hazard, exposure and vulnerability data for the creation of risk maps.
- **Risk Assessment:** the evaluation of the level of risk and the decision whether this is acceptable or not, and whether risk reduction measures are needed;
- **Risk Reduction Strategies**: developing actionable measures to mitigate identified risks, including community preparedness initiatives, early warning, infrastructure improvements, and policy recommendations.
- **Scenario development**: evaluate possible future scenarios related to climate, population, economic and land use changes, that may change multi-hazard risk in future. .

In a multi-hazard context, vulnerability and exposure assessment encompasses a range of dimensions, including social, environmental, economic, and physical aspects (; de Ruiter and van Loon 2022). Vulnerability and exposure are also dynamic and change over time (with time scales ranging from hourly to decades) as a result of previous disaster impacts (Rasool, Rana, and Waseem 2024). Capturing these dynamics is a major challenge in MHRA. Vulnerabilities translate into reduced access to entitlements and opportunities, impairing capabilities and potentially contributing to fatality, livelihood disruption, or displacement in a hazardous event. The brunt of these impacts is disproportionately borne by the most marginalized communities, intensifying inequality and perpetuating poverty. Comprehending the risk landscape and the interplay of social, environmental, and economic systems and their resulting vulnerability remains a cornerstone of multi-hazard risk assessment.

1.3 International Concepts of MHRA

The Sendai Framework on Disaster Risk Reduction emphasizes a so-called all-hazards approach "to strengthen technical and scientific capacity to capitalize on and consolidate existing knowledge and to develop and apply methodologies and models to assess disaster risks, vulnerabilities and exposure to all hazards" (UNDRR, 2016). This multi-hazard risk assessment is not simply the combination of the probability of expected losses from individual hazards. It is crucial to consider the interrelationships among the different hazards and the interrelationships between the hazards and vulnerabilities, which is also referred to as multi-risk (Zschau, 2017). A very useful definition of multi-hazard risk was given by Gill and Malamud (2014 (See Annex 1). Figure 1.4 provides an overview of MHRA approach for National Scale Risk Assessment.

Figure 1.4: Framework for National Disaster Risk Assessment (UNISDR, 2017)

Several international concepts on Multi-Hazard Risk Assessment are relevant to consider. Over the past decade, a large number of scientific publications has been devoted to better understanding and quantifying multi-hazard events (Marzocchi et al., 2009, 2012; Gill and Malamud, 2014; Gallina et al., 2016; Gill et al., 2022; Hochrainer-Stigler et al., 2023; Owolabi & Sajjad, 2023). Pescaroli and Alexander (2018) and Alexander and Pescaroli (2019) provide a holistic framework for better understanding the terms used.

The term compound risk came from the climate risk community and was used in IPCC reports as "a special category of climate extremes, which result from the combination of two or more events, and which are again 'extreme' either from a statistical perspective or associated with a specific threshold" (IPCC, 2018). These could be two or more simultaneous or successive extremes or events that combine to become an extreme event. Although initially used to describe specific combinations of weather and climate events that contribute to risk (Zscheischler et al., 2020). Several terms are used in this context , such as compounding risk, cascading risk, interacting risk, interconnected risk , systemic risk, and emerging risk (See Annex 1)

The topic has received considerable attention in the international research agenda, as evidenced by the wide range of projects funded by the EU (CORDIS, 2024). Annex 2 gives some recent EU projects that are relevant in this context.

1.4 Objectives and scopes

The framework for multi-hazard risk assessment in the Caribbean aims to address the lack of understanding of the concept of multi-hazards, how these can be defined and conceptualized, and how the hazard and risk could be assessed. The framework for multi-hazard risk assessment in the Caribbean is aimed to drive the Caribbean towards a systematic generation of risk information at different geographic scales, data availability, and required resolutions. This MHRA framework provides a general guideline that identifies the various approaches for multi- hazard risk assessment that are suited for different levels of government, different applications, and different situations of data availability. It serves as a basis for the future development of detailed guidelines and capacity building (e.g., at the municipal level). It addresses the management policies and actions to support the cumulative building of knowledge sustainably and systematically, highlighting important inter-institutional aspects of data management and sharing. The framework for MHRA is developed in collaboration with CDEMA and other regional organisations. The framework (See Figure 1.4) was developed after a series of meetings of the steering group and stakeholder consultations in the Caribbean.

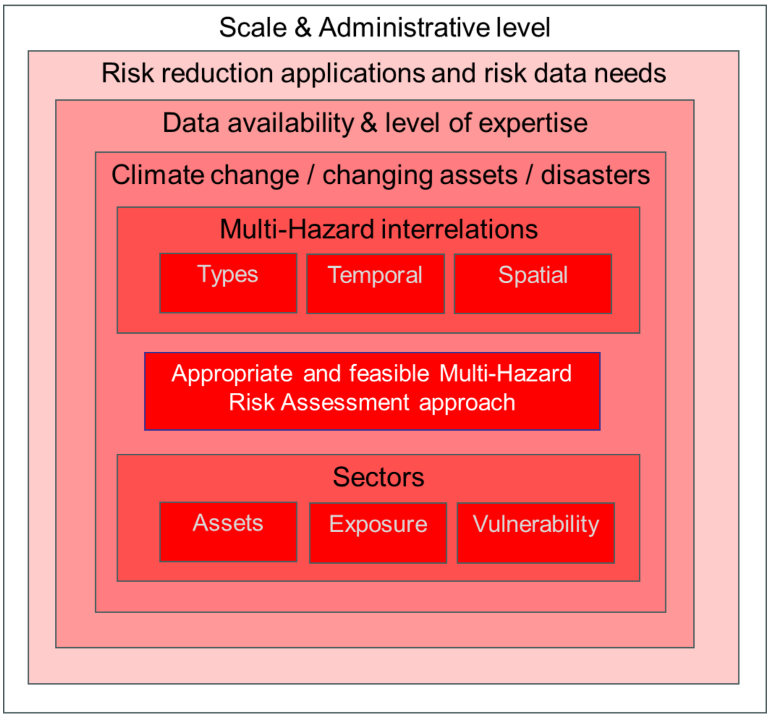


Figure 1.4: Illustrating the MHRA framework: what is the appropriate and feasible method for multi-hazard risk assessment in the Caribbean, given a range of conditions.

The approach was presented at the Caribbean Disaster Management conference in Saint Kitts and Nevis on 5 December 2024. Stakeholders were invited to fill out a survey and a series of stakeholder interviews were conducted. The international context of MHRA and its relevance to the Caribbean is considered by evaluating international literature on Multi-Hazard Risk Assessment and the relevant approaches that are developed at different levels in other countries, focusing specifically on countries with similar characteristics as the Caribbean. In the context of Disaster Risk Management (DRM) in the Caribbean, the proposed framework is consistent with the Acts and policies on disaster and climate change of the Governments within the Caribbean, and it will serve as a guideline to generate risk information for disaster risk management through the establishment of MHEWS and risk-sensitive development planning including infrastructure planning in various sectors like health, education, transport etc.

Chapter 2. The Caribbean Context

This chapter provides a short overview of relevant context for MHRA in the Caribbean, structured into the following sections:

- MHRA initiatives in the Caribbean
- Legal frameworks and Stekholders for MHRA in the Caribbean
- Decisions that require risk information
- Data availability

2.1. MHRA Initiatives in the Region

In the Caribbean, there are numerous organizations and studies that have contributed significantly to advancing MHRA methodologies and best practices. The Caribbean Community (CARICOM) through the Caribbean Disaster Emergency Management Agency (CDEMA) have spearheaded initiatives to improve regional disaster resilience.
Some notable initiatives are:

- **CDEMA's Comprehensive Disaster Management Strategy**: Launched in 2007, this strategy aims to integrate disaster risk reduction into development planning across member states. It emphasizes the importance of data-driven decision-making and the adoption of MHRA approaches to manage risks associated with multiple hazards.
- **The Caribbean Risk Atlas**: This regional initiative serves as a platform for mapping and analyzing vulnerabilities across Caribbean nations. The Risk Atlas should provide critical data and assessments that help inform policy decisions and resource allocations, highlighting the interconnected nature of risks across the region.
- **The CHARIM (Caribbean Handbook on Risk Management)** initiative (CHARIM, 2017) and the **Caribbean Risk Information System (CRIS)** have been developed in collaboration with the World Bank with financial support from the European Union (EU) in the framework of the ACP-EU Natural Disaster Risk Reduction Program, managed by the Global Facility for Disaster Reduction and Recovery (CRIS, 2024) .
- The **Caribbean Coastal Resilience Decision Support Tool** allows users to assess coastal protection benefits of reefs and mangroves, and better understand vulnerability to flood exposure (Nature Conservancy, 2023)
- The **NASA Caribbean Geoportal** (NASA, 2024) provides real-time satellite based information related to natural disaster in the Caribbean.
- The **Caribbean Climate Online Risk and Adaptation tool** (CCORAL) is an online support system for climate-resilient decision-making. It takes a pragmatic approach, promoting the right tools and techniques to fit the context of Caribbean decision-making, available time and resources, and uncertainty about climate variability and change. Users are encouraged to prioritise their efforts and use components of CCORAL of the most value to them (CCCCC, 2024) .
- The Inter-American Development Bank (IDB) Environmental Safeguards Unit (ESG) launched a guideline to address the **Climate Change Data and Risk Assessment Methodologies for the Caribbean** to better understand how to assess and address climate change related risks (Herron et al., 2016)

Despite these initiatives, the Caribbean faces unique challenges in implementing effective MHRA. Regional efforts have laid a foundation for enhancing MHRA, but continued investment in capacity building and data infrastructure is essential for future progress.

Specific challenges to effective regional approaches to MHRA include:

- **Geographical Diversity**: The region's islands exhibit significant variations in exposure to different hazards, necessitating tailored risk assessment approaches.
- **Resource Limitations**: Many Caribbean nations experience constraints in financial and human resources, which can hinder the ability to conduct comprehensive and regular risk assessments. MHRA is still not an integral part of annual fiscal budget allocations. Overall, individual countries in the Caribbean are taking significant steps toward integrating MHRA into their disaster management frameworks. However, disparities in resources and data availability remain challenges.

Annex 3 presents some examples of MHRA work done in individual countries

2.2. Legal Frameworks and stakeholders for MHRA in the Caribbean

A MHRA framework encompasses legislative measures, the roles of regional and national agencies, and collaborations with international organizations. This section explores these dimensions, focusing on legislative frameworks, the Caribbean Disaster Emergency Management Agency (CDEMA) and national disaster management authorities, relevant agencies for multi-hazard risk assessment (MHRA), and the role of international organizations.

Legislative frameworks in the Caribbean are critical for establishing the legal basis for disaster management and ensuring a coordinated response to disasters (Jones, Doughorty, and Brown 2022). Many Caribbean nations have enacted specific disaster management laws outlining government agencies' responsibilities, citizens' rights, and disaster response and recovery procedures. For instance, various Caribbean countries have disaster management acts that mandate the establishment of national disaster management offices, which are responsible for coordinating disaster preparedness and response efforts (See Annex 4) (Murray and Watson 2022). Legislation is crucial because it:

- shifts the focus from reactive measures to proactive risk management strategies, fostering a preparedness culture;
- provides the legal obligation for government agencies to collaborate and engage with local communities;
- addresses all phases of the disaster management cycle;
- stresses the integration of disaster risk reduction into national development plans;
- facilitates collaboration between governmental and non-governmental organizations,

There is the International Disaster Response Law (IDRL), a set of recommendations to governments about preparing their disaster laws and plans to mitigate the common regulatory problems in international disaster response. The IDRL has been implemented in several Caribbean states. For example, Jamaica, St. Vincent and the Grenadines, and Grenada implemented this law in 2013, 2017, and 2018, respectively. Despite their non-binding nature, these Guidelines and the efforts to encourage their use have led to the development of best practices in the regulation of international disaster relief, and have facilitated changes at the domestic level, and benefited disaster response processes and mechanisms at the national and regional levels (Nicholson 2017; Picard 2017; Clement 2014).

In addition to national laws, regional agreements significantly shape disaster risk management policies in the Caribbean. CARICOM and OECS have established regional disaster management frameworks that align with international agreements such as the Sendai Framework for Disaster Risk Reduction (2015-2030) (Maini *et al.* 2017).

One of the significant challenges in the legislative framework for multi-hazard risk assessment in the Caribbean is the inconsistency in implementing disaster management laws across different countries (UNDRR 2023; UNDRR & WMO 2023). While many Caribbean nations have enacted disaster management legislation, the effectiveness of these laws is often hampered by inadequate resources, lack of political will, and insufficient capacity at the local level (Murray and Watson 2022).

The legislative framework must also address the role of climate change in exacerbating disaster risks through increased vulnerability from climate impacts brought on by the increased frequency and intensity of natural hazards (Shultz et al., 2016). Legislative measures that promote climate adaptation strategies alongside disaster risk reduction efforts can enhance the overall resilience of Caribbean communities.

Stakeholders

The Caribbean Disaster Emergency Management Agency (CDEMA) plays a pivotal role in the Caribbean Community (CARICOM) disaster management framework. CDEMA plays a central role in harmonizing disaster management practices across the Caribbean, encouraging the adoption of international standards such as the Sendai Framework for Disaster Risk Reduction. Furthermore, it fosters regional collaboration in disaster management by maintaining the Caribbean Risk Information System (CRIS), which facilitates data sharing among Caribbean countries (CDEMA 2014).

Each Caribbean country has national disaster management authorities (NDMAs), which are guided by national disaster management acts or legislation outlining their responsibilities and the relationship between national and local disaster management bodies. These authorities work closely with CDEMA to develop national disaster risk management plans, conduct training exercises, and facilitate community engagement initiatives (Filimonau and De Coteau 2020).

The role of local non-institutionalized communities in disaster management cannot be overstated. Their engagement and participation are critical components of effective disaster risk reduction strategies. Establishing community-based disaster management committees can facilitate local-level decision-making and enhance the overall effectiveness of disaster response efforts. By gathering feedback from various sectors like government agencies, businesses, civil society organizations, and vulnerable communities, policymakers can develop legislation that addresses the specific needs and priorities of the region (Šakić Trogrlić *et al.* 2024a)

Multi-hazard risk assessment (MHRA) is a critical component of disaster risk management in the Caribbean. Various regional and national agencies are conducting MHRA to identify vulnerabilities and assess the potential impacts of multiple hazards. Agencies such as CDEMA, the Caribbean Institute for Meteorology and Hydrology (CIMH), and national meteorological services play significant roles in collecting and analysing data related to climate and weather patterns (Dookie and Spence-Hemmings 2022).

Other agencies, such as the Caribbean Development Bank (CDB) and the Caribbean Regional Organisation for Standards and Quality (CROSQ), have contributed to the regional risk assessment initiatives. Regional institutions, such as the University of the West Indies (UWI), The Caribbean Agricultural Research and Development Institute, Caribbean Tourism Organisation

(CTO), Caribbean Public Health Agency (CARPHA), CIMH, and CDEMA engage in MHRA on regional and national levels in support of their member-states priorities (WMO 2024; UNDRR 2022b; CTO 2020; Glas *et al.* 2017; Jonckheere et al. 2015).

International organizations play a significant role in supporting disaster management efforts in the Caribbean. Agencies such as the United Nations Office for Disaster Risk Reduction (UNDRR) and the Pan American Health Organization (PAHO) provide technical assistance, funding, and expertise to enhance the region's disaster resilience (Hamer *et al.* 2019). These organizations often collaborate with regional bodies like CDEMA to implement disaster risk reduction initiatives and facilitate knowledge sharing among member states. Additionally, international partnerships are crucial for mobilizing resources during disaster response efforts. For example, international organizations coordinate with local authorities during significant disasters to provide humanitarian assistance and support recovery efforts (Mike *et al.* 2021). Several other international agencies have boosted MHRA in the Caribbean. For example, the UNDRR has been a key international partner in the Caribbean, guiding global best practices for disaster risk management and MHRA. The UNDP is also a long-standing partner in disaster risk reduction initiatives across the Caribbean. The agency supports national governments in conducting risk assessments, strengthening institutional capacities, and integrating DRR into national policies. Likewise, the World Bank and its GFDRR provide financial and technical support to Caribbean countries for disaster resilience initiatives. The International Federation of Red Cross and Red Crescent Societies (IFRC) not only provides humanitarian assistance to Caribbean nations in the aftermath of disasters, they also work with national governments to ensure that legal frameworks are in place for comprehensive disaster risk management, including MHRAs (Hollis 2014). Similarly, The European Union (EU) has been a key partner in building Caribbean resilience through its European Development Fund (EDF). The Inter-American Development Bank (IDB) also collaborates with Caribbean countries to strengthen institutional capacities for disaster risk reduction, focusing on integrating climate change and MHRA into development planning and supporting data collection and risk modelling to promote resilient urban development (IDB 2024).

2.3 DRR activities that require risk information

Applications of multi-hazard risk assessment are diverse and crucial in various fields, including disaster risk management (DRM), land use planning, disaster response, and climate change adaptation. Leveraging advanced technologies and methodologies, these applications comprehensively evaluate potential risks from multiple hazards in isolation, composite, and compounding effects concurrently. As climate change intensifies hazards, multi-hazard risk assessments play a crucial role in adapting strategies to the changing climate and ensuring dynamic and responsive emergency plans.

There are many policy, planning, and management activities that require risk information, but the type of information and quality differ among these and at which administrative level these actions are taken. An illustrative list of the main responsibilities of the national and subnational organizations is presented in Table 2.1, subdivided according to the main disaster management phases and administrative units.

- Multi-Hazard Early Warning System.
- Prioritization of administrative units for investments.
- Risk-informed planning.

- Environmental Assessment.
- Regulatory zoning and building regulations.
- Planning critical infrastructure and essential facilities.
- Design of risk mitigation measures.
- Risk financing instruments.
- Impact-based forecasting.
- Disaster response planning.
- Recovery and reconstruction planning.

The table indicates at which administrative levels the respective actions are most important. At the regional scale, prioritizing countries for resource allocation related to DRM is one of the primary tasks. Further, the management of information on hazard events, disaster losses, and damages, visualization of hazard, vulnerability, risk and capacity, multi-hazard early warning, and impact-based forecasting are important tasks supported by regional partners, such as CDEMA.

Multi-hazard risk assessments are a crucial foundation for multi-hazard early warning systems (MHEWS) in DRM. These assessments provide a holistic understanding of hazard, vulnerability, and exposure, which feeds into the first pillar of Risk Knowledge in MHEWS. The information gained from the assessments is essential for realistic monitoring and impact-based forecasting, which supports the second pillar of Detection, Monitoring, and Forecasting. By offering data and insights, responders can allocate resources quickly, plan evacuation routes, and respond effectively to various hazards. The strategic allocation of resources ensures timely and efficient response efforts. Multi-hazard risk assessments also contribute to effective evacuation planning, guiding responders in organizing routes, shelters, and transportation logistics.

In land use planning, multi-hazard risk assessments inform the development of regulations, guidelines, and standards to address challenges posed by different hazards. These assessments contribute to zoning regulations and infrastructure plans, ensuring resilience to interconnected risks associated with climate change. MHRA supports comprehensive risk assessments, considering a range of hazards such as earthquakes, floods, landslides, forest fires, and other potential risks due to their interaction. This holistic approach allows for a thorough understanding of the complex risk landscape. The data assists in identifying the exposure and differential vulnerabilities of communities and critical infrastructure to withstand various hazards.

MHRA plays a crucial role in the insurance and financial sectors. They aid in developing risk models that assess the potential economic impacts of multi-hazard scenarios. This information is vital for creating insurance policies, risk financing strategies, and establishing contingency funds to mitigate the financial fallout from simultaneous occurrences of different hazards.

Table 2.1: Overview of policy, planning, and management activities that require risk information and the main output requirements at national, provincial, and local levels. The green olored boxes show the most important combinations. The orange ones are less common, and the red ones are actually done at that scale.

	Applications that require risk information	Implications for the risk assessment at different levels		
		Regional	National	Municipal /Parish
Prevention and Mitigation	Prioritization of admin units for investments by governments, NGO, and donor organizations	Relative classes of exposure, vulnerability, capacity, and risk for countries	Relative classes of exposure, vulnerability, and capacity for municipalities	Relative classes of exposure, vulnerability, and capacity for wards
	Environmental Assessment	Expected changes in multi-hazard exposure and losses under different future scenarios	Environmental Impact Assessments for large developments: multi-criteria, including multi-hazard and risk	EIA for specific municipal facilities. Multi-criteria, including multi-hazard and risk indicators that are derived quantitatively
	Risk informed planning	Prioritisation of cross-border activities (trade, tourism	Prioritisation of municipalities or watersheds (see above)	Exposure to multiple hazards and frequency
	Regulatory zoning and building regulations	Regional initiatives, Quantitative multi-hazard information	Quantitative multi-hazard information	Quantitative multi-hazard information
	Design of risk mitigation measures	This is not done at the regional scale. Prioritisation is done for resources (See above)	Monetary losses for Cost-Benefit analysis	Monetary loss for cost – Benefit analysis, population losses
	Planning critical infrastructure and essential facilities	Prioritization of provinces or watersheds (see above)	A general indication of frequency and expected losses of multi-hazards	Quantitative information at the local level for critical sections
	Risk financing instruments	Regional instruments, Probability of Monetary losses (AAL, PML) for the entire country)	Probability of Monetary losses (AAL, PML) for the entire country and per municipality)	Only for cities: the probability of Monetary losses (AAL, PML) for insured assets
Preparedness	Multi-Hazard Early warning	At regional level for linking with major triggering events (Hurricanes, Rainfall estimates, volcanoes etc.)	Overview of municipalities with vulnerability and population exposed to multi-hazard event scenarios for warning dissemination	Local EWS: detailed information on population exposure for different multi-hazard scenarios and time periods
	Impact-based forecasting	Real-time expected exposed buildings, population, agriculture, roads to multi-hazards	Real-time expected exposed buildings, population, agriculture, and roads to multi-hazards	Identification of exposed and vulnerable locations and dissemination of information based on the likelihood of impact using spatial information.
Response and Recovery	Disaster response planning	Allocation of resources for disaster response, based on prioritisation (See above)	Allocation of resources for disaster response, often based on parish, using prioritisation (See above), provincial stockpiling and warehousing of relief facilities	Shelter planning allocation of emergency response resources based on multi-hazard scenarios, evacuation site planning, and evacuation route modeling
	Recovery and reconstruction planning	Allocation of resources for disaster recovery, based on damage per country based on new loss estimations	Prioritisation of sites for reconstruction planning based on loss estimations of the new situation and possible changes in hazards, exposure, and vulnerability	Planning of safe sites for reconstruction planning based on loss estimations of the new situation and possible changes in hazards, exposure, and vulnerability. Multi-hazard risk-sensitive land use planning.

This information is vital for insurance companies, developers, and policymakers to determine the feasibility and cost-effectiveness of projects in specific areas. In disaster risk financing strategies, MHRA aids in formulating risk financing mechanisms, including catastrophe bonds and contingency funds, designed to mitigate the financial fallout from complex disaster scenarios. By understanding interconnected risks, disaster risk financing strategies can be tailored to address the unique challenges posed by multi-hazard events, ensuring timely and adequate financial resources for response and recovery efforts.

2.4 Data availability

This section examines the current state of MHRA data at the national and regional levels in the Caribbean, underscoring the disparities between data-rich and data-poor areas and the implications for disaster risk management. Some Caribbean nations have made significant strides in collecting and managing data for multi-hazard risk assessment. For instance, Puerto Rico and the U.S. Virgin Islands benefit from extensive data collection efforts supported by the United States government and various international organizations. These territories have access to high-resolution satellite imagery, detailed topographic maps, and comprehensive meteorological data (NOAA, 2015). In Puerto Rico, the Caribbean Coastal Ocean Observing System (CariCOOS) provides real-time data on oceanographic and meteorological conditions, which are crucial for assessing risks related to hurricanes and coastal flooding (NOAA, 2015). Additionally, the Puerto Rico Seismic Network (PRSN) offers detailed seismic data, enhancing the region's ability to assess earthquake risks (NOAA, 2015). Similarly, the Dominican Republic has developed robust data collection systems, particularly for hurricane and flood risk assessment. The country has implemented advanced meteorological monitoring systems and has access to detailed hydrological data, which are essential for predicting and managing flood risks.

In contrast, several Caribbean nations face significant challenges in data collection and management. Small island developing states (SIDS) such as Dominica, Saint Vincent and the Grenadines, and Grenada often lack the resources and infrastructure needed to gather comprehensive data for multi-hazard risk assessment (UNDRR, 2022). These countries typically rely on outdated maps, limited meteorological data, and sparse seismic monitoring networks.

Annex 5 provides and overview of the data availability for MHRA in the Caribbean. While the Caribbean region has access to various hazard-related datasets, significant gaps remain in other crucial areas of MHRA. These gaps hinder the ability of governments and organizations to perform accurate and comprehensive risk assessments.

- **Hazard Data Gaps:** For hazards such as floods and landslides, data availability is limited. Flood hazard mapping is inconsistent across Caribbean nations, and while some countries have developed national flood maps, they often lack the necessary resolution for effective local planning. Landslide data are even scarcer, with limited records on slope instability and past landslide events in the region (Van Westen, 2016b).
- **Exposure Data Gaps:** There is a pressing need for region-wide, standardized infrastructure datasets. The lack of detailed data on critical infrastructure locations, conditions, and vulnerabilities impedes accurate MHRA. Additionally, demographic data are often outdated, limiting the accuracy of exposure assessments for rapidly changing populations and urban areas (Jones, 2024; ECLAC, 2024).
- **Vulnerability Data Gaps:** Socio-economic vulnerability data are often aggregated at broad geographic scales, masking localized disparities. Detailed information on household income, access to healthcare, and educational attainment at the community level would enhance vulnerability assessments. Additionally, environmental vulnerability

data for ecosystems like wetlands, coastal zones, and forests require updates to capture changes driven by climate impacts (Abdulkadri, 2016; Weiskopf et al., 2020).

Challenges in Data Collection and Management

Despite the existence of various data sources, the Caribbean still faces significant challenges in harmonizing and integrating these datasets for comprehensive risk assessments (Rölfer et al., 2020). The lack of standardized methodologies for data collection and analysis often leads to inconsistencies and gaps in the available information. This is particularly evident in the context of climate change, where projections of future hazards require robust data to inform adaptation strategies. This is due to:

- **Limited Resources**: one of the primary challenges in data collection and management in the Caribbean is the limited availability of financial and technical resources. Many small island nations lack the funding and expertise needed to establish and maintain comprehensive data collection systems. This limitation affects their ability to gather accurate and timely data for multi-hazard risk assessment. Acquiring high-quality data, particularly geospatial data, is costly. Satellite imagery and remote sensing data are valuable for hazard assessments but can be prohibitively expensive for smaller nations. Furthermore, maintaining up-to-date databases requires ongoing investment, which is challenging in regions with limited budgets like the Caribbean. Training, equipment, and specialized expertise are often limited, hindering data collection efforts, particularly for complex datasets like high-resolution hazard maps and vulnerability assessments (UNDRR, 2022). Technological advancements, particularly in the fields of remote sensing and geographic information systems (GIS), have the potential to enhance data availability and facilitate multi-hazard risk assessments in the Caribbean.
- **Infrastructure Constraints: the** Caribbean region is prone to infrastructure damage from disasters, which can disrupt data collection efforts (de Beurs et al., 2019). For example, hurricanes can damage weather stations, seismometers, and other monitoring equipment, leading to gaps in data availability. Additionally, the rugged terrain of many Caribbean islands makes it difficult to install and maintain monitoring equipment in remote areas (Fobert et al., 2021).
- **Inconsistent Data Standards:** The absence of standardized protocols for data collection and management across Caribbean countries leads to inconsistencies in data formats, quality, and accuracy. This lack of standardization complicates data integration and sharing between organizations, making it difficult to conduct region-wide risk assessments (Dubrie et al., 2023). Many countries within the region rely on disparate data sources, which can lead to inconsistencies and gaps in the information available for risk assessment. The absence of a unified approach to data collection and sharing further complicates efforts to develop a cohesive understanding of multi-hazard risks across the Caribbean.
- **Accuracy of datasets:** Moreover, the integration of various data types—such as socio-economic, environmental, and infrastructural data—is essential for a holistic multi-hazard risk assessment. The interplay between these factors can significantly influence a community's resilience to hazards. For example, areas with high poverty rates may be more susceptible to the impacts of natural disasters due to inadequate infrastructure and limited access to resources (Scolobig et al., 2017). Therefore, the availability of comprehensive datasets that encompass these diverse dimensions is crucial for effective risk assessment and management.
- **Data Sharing and Coordination:** Effective multi-hazard risk assessment requires coordination and data sharing among various stakeholders, including government agencies, international organizations, and local communities. However, data sharing practices in the

Caribbean are often hindered by institutional barriers and a lack of standardized protocols.

- **Institutional Challenges:** In addition to technological barriers, institutional challenges also play a significant role in shaping the landscape of multi-hazard risk assessment data availability in the Caribbean. Many countries operate within fragmented governance structures, where responsibilities for disaster risk management are dispersed across multiple agencies. This fragmentation can lead to inefficiencies in data sharing and collaboration, ultimately impeding the development of comprehensive risk assessments. Establishing clear lines of communication and collaboration among relevant stakeholders is essential for overcoming these challenges and fostering a more integrated approach to multi-hazard risk assessment.

Opportunities for Improving MHRA Data Availability

As the Caribbean continues to grapple with the impacts of climate change and increasing hazard frequency, the need for comprehensive multi-hazard risk assessments becomes ever more pressing. The availability of high-quality data is paramount to informing effective disaster risk reduction strategies and enhancing community resilience. While significant challenges remain, there are also numerous opportunities for improving data availability through technological innovation, regional collaboration, and community engagement.

- **Public-Private Partnerships:** The Caribbean region has made strides in recent years toward improving data availability for multi-hazard risk assessments. Regional organizations, such as the Caribbean Disaster Emergency Management Agency (CDEMA), have been instrumental in promoting data sharing and collaboration among Participating States (Docherty et al., 2020; Ming et al.,2014). Initiatives aimed at enhancing regional data repositories and fostering partnerships between governments, academia, and the private sector have shown promise in addressing some of the existing data gaps. However, sustained efforts are needed to ensure that these initiatives translate into meaningful improvements in data availability and accessibility.
- **International Contribution:** Furthermore, the role of international organizations and funding agencies cannot be overlooked in the context of multi-hazard risk assessment data availability. Collaborative efforts with entities such as the United Nations and the World Bank can provide the necessary financial and technical support to bolster data collection and analysis capabilities in the Caribbean. By aligning regional priorities with international funding opportunities, Caribbean nations can enhance their capacity to conduct comprehensive multi-hazard risk assessments that inform disaster risk reduction strategies.
- **Local Knowledge Integration:** The integration of local knowledge and community-based approaches into multi-hazard risk assessments is another critical aspect of improving data availability in the Caribbean. Local communities possess valuable insights into their vulnerabilities and capacities, which can complement existing data sources and enhance the overall understanding of multi-hazard risks. Engaging communities in the data collection process not only fosters ownership and empowerment but also ensures that assessments are grounded in the realities faced by those most affected by hazards.
- **Regional Data Integration :** Platforms like the Caribbean Disaster Emergency Management Agency (CDEMA) can serve as centralized repositories for MHRA data. By consolidating data from various sources, CDEMA can facilitate easier access to regional hazard, exposure, and vulnerability data, supporting both national and cross-border risk assessments .
- **Leveraging Open-Source and Crowdsourced Data:** Open-source platforms and crowdsourced data collection can provide valuable resources for MHRA at a low cost. Tools like OpenStreetMap allow local communities to contribute spatial data, which is particularly

useful in rural and remote areas where formal datasets may be lacking (Bertolotto et al., 2020; Herfort et al., 2021; Goldblatt et al, 2020).

- **Expanding Use of Satellite and Remote Sensing :**International organizations such as NASA and the European Space Agency (ESA) provide free access to satellite imagery, which can support flood mapping, coastal erosion monitoring, and other hazard assessments. Leveraging these resources can help Caribbean countries access high-resolution geospatial data without incurring significant costs (Mathieu et al., 2017).
- **Promoting Data Sharing Agreements:** Establishing formal data-sharing agreements within the Caribbean would enable better access to critical datasets and facilitate cross-country collaboration on MHRA. Standardizing data collection methods and protocols would further enhance the compatibility of datasets across the region (ECLAC, 2020). For example, the Seismic Research Centre at the University of the West Indies, Trinidad is the official source of information on earthquakes and volcanoes in the English-speaking Eastern Caribbean. The unit observes, collects and archives seismic and volcanic activity data, and through a data-sharing agreement with other relevant stakeholders, makes the data and information available to the public (UWISeismic, 2024).

Chapter 3. Multi-hazard Exposure and Vulnerability

This chapter focuses on the approaches for classification of multi-hazard interrelations and the consequences for modelling the hazards, exposure and vulnerability.

3.1 Hazard assessment

Hazards are classified in different types, and there has been confusion on the classification methods, for example, between EM-DAT (2024) and DesInventar (2024), two of the main types of disaster databases. A recent publication by UNDRR & ISC (2020) differentiates a total of 302 hazard types, ordered into eight groups . These are further described and characterised in specific hazard information profiles in Murray et al. (2021) (See Figure 3.1). However, the Hazard Information Profiles do not consider multi-hazard relations in an exhaustive manner yet. Annex 5.1 points out some of the main characteristics of hazards that are relevant to consider in doing a hazard assessment.

Figure 3.1 Classification of 302 hazard types in 8 groups (Source: UNDRR, 2021)

The Caribbean's unique vulnerability to multi-hazards stems from its small island geography, high exposure to climate change, and limited resources for recovery. Multi-hazards refer to situations where multiple hazards (e.g., hurricanes, floods, earthquakes) occur simultaneously, in sequence, or cumulatively, leading to compounded impacts.

Given the interrelationships among hazards, the effect of several hazardous events is expected to surpass that of each individual one. Therefore, it is essential that within the multi-hazard risk framework these interrelations are considered with respect to timing and their impact at varying spatial scales. Notwithstanding, it is important to understand the impacts associated with independent events to better appreciate the reality of the expected impact of simultaneous, cascading, consecutive, overlapping and compounding events**.**

The choice of appropriate multi-hazard risk assessment methods is governed by the interrelations between the hazardous events that should be considered. We are referring here to hazard interrelations, and not hazard interactions, because the hazards might not actually interact with each other while still having an important influence on the resulting impact. The hazard interrelation is determined by a combination of three components:

- Type interrelation: how different hazard types can have an influence on the expected losses.
- Spatial interrelations: how the spatial extents of hazards have influence.
- Temporal interrelations: how the timing of events relative to each other is important for losses.

Annex 7 provides an overview of the interrelations between different **hazard types**. **Independen***t* hazards are those that do not have the same trigger and where the occurrence of a hazard is not related to the occurrence of the other hazards. The **triggering** relationship considers if the hazards are caused by the same external triggering event (e.g., precipitation and/or temperature extremes, earthquakes). The cascading relationship considers whether one hazard causes other hazards in a cascading relationship, where primary hazard events generate secondary hazard events. The **conditioning** (or **amplifying**) relationship considers if the occurrence of one hazard could amplify the frequency or intensity of a second hazard. The conditioning relationship determines whether the occurrence of one hazard might modify the conditions that make the occurrence of a second hazard more likely. Note that we do not consider the term compounding here as a separate class because this term is a general term that indicates that multi-hazard events might lead to larger losses than if we consider individual events.

Annex 7 also shows different **spatial relationships**, which considers if the hazards occur in the same area, adjacent areas, or far away. **Overlapping** events have areas that (partly) overlap and where two or more hazard types have an impact. The **source and spread** events relate to those multi-hazards where one event is the source, and another event is the area from which a hazard spreads out (e.g., a glacial collapse leading to a flood downstream). The **cross-boundary** relationship is relevant for hazards that cross administrative boundaries, where the information might not be shared, or where two or more authorities need to act and coordinate efforts.

Annex 7 shows also examples of the **temporal relationship**, which considers how the events occur in time, which could be **simultaneous** or **concurrent**, close to each other, or a long time after each other. **Consecutive** disasters are two or more disasters that occur in succession– it should be noted that these could also be two events of the same hazard type. Hazardous events may be slow-onset events such as droughts or pandemics, which may cover months or years, or fast-onset events such as earthquakes, storms, or flash floods.

It is important to consider this combination of the interrelation between the type of hazard, the temporal aspect, and the spatial aspect in order to select the best approach for multi-hazard and risk assessment. In order to simplify the above-mentioned classification for applicability in the Caribbean, we propose the following simplified classification (See Figure 3.2).

This simplified classification is important because the different types of hazard interrelations have consequences with respect to the way the hazard is assessed, and also later in the way the vulnerability, exposure and loss are assessed. Table 3.1 gives a summary of these consequences.

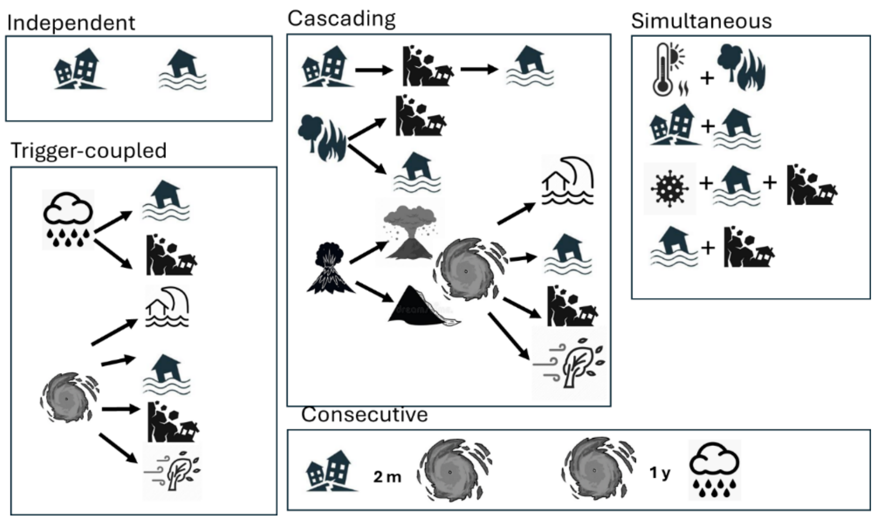


Figure 3.2: Simplified classification of hazard interactions in independent, compounding, and cascading events.

Table 3.1: Consequences of hazard assessment approaches for the different types of multi-hazard interrelations.

Hazard interrelation	Hazard Assessment		Remarks
	Frequency assessment	**Intensity assessment**	
Independent events	Magnitude/ intensity / frequency relation for each hazard is modelled independently	Intensity of each hazard type for that return period is modelled separately.	This is the conventional single hazard modelling approach. Still relevant to assess risk of independent events
Simultaneous events	Determine scenarios of events, and determine the joint frequency of the individual, if possible	If the intensity of one event is influenced by the other, they should be modelled jointly , if possible. Otherwise, separate intensity models	There are many possible scenarios , and it will be difficult to consider all. A limited selection is made
Trigger coupled events	The return period of the main trigger is assessed and used for the coupled hazards	The intensity of the various hazard types should be modelled together, based on the magnitude of the trigger event.	Here the modelling of the joint events is easier because they are linked to the same magnitude trigger event.
Cascading events	After assessing the frequency of the main trigger, event trees are used to determine the probability of the cascading hazards	The intensity (& spatial extent) of one event depends on the outcome of the previous event. Thus, modelling should be done in sequence.	There are many scenarios possible, and the probability and intensity of the steps in the cascade are often difficult to model.
Consecutive events	The timing between two events is based on frequency assessment and seasonality. scenarios should also be generated here.	The intensity of the consecutive event might be amplified by the effect of the earlier event (e.g. conditions might have changed). This should be considered.	The most important consequence will be on vulnerability, exposure and loss assessment. Only when there is an amplifying effect the hazard is influenced.

For a number of the hazard interrelations it is better to work with a limited number of possible multi-hazard scenarios, using so-called **deterministic approaches**, whereas for others it is also possible to analyze all possible scenarios using a **probabilistic approach**. A probabilistic approach may generate an ensemble of possible hazard scenarios to estimate occurrence probabilities or potential impact projections. These scenarios can be linked to damage/loss models to quantify the level of risk exposure based on the expected probabilities of occurrence. Hazard assessment methods can be subdivided in:

- **Inventory-based methods**, which are based on large inventories of past events (e.g. hurricane tracks), which are used to model possible future ones.
- **Community-based methods,** which are based on the local knowledge of past events
- **Expert-based methods**, where the susceptibility (relative hazard degree) is determined by experts, either based on direct or indirect mapping (e.g. using Spatial Multicriteria Evaluation). Experts can be from regional institutions (e.g. UWI Seismic Research Centre, or CIMH), academic institutions or consultants.
- **Data-driven methods**, where the hazard degree is analysis using statistical methods, machine learning or deep learning AI methods, based on a set of training data. This requires a sufficient large and reliable set of training data is available
- **Physically-based methods**, where hazardous processes are modelled using their physical laws which simulate the actual events.

In Annex 8 examples are given of multi-hazard modelling for different types of hazards:

- Hurricane-related hazards (strong winds, storm surge, extreme rainfall, landslides, floods);
- Coastal related hazards (coastal flooding, coastal erosion);
- Drough-related hazards (meteorological drought, hydrological drought, agricultural drought)
- Geological hazards (earthquakes, tsunamis, volcanic eruptions)
- Environmental and health hazards (pollution, vector-borne diseases)
- Anthropogenic hazards (accidents)

Hazards under climate change

The Intergovernmental Panel on Climate Change (IPCC) identifies the Caribbean as a hotspot for climate change impacts due to its geographical location, high dependency on natural resources, and socio-economic vulnerabilities (UN 2022; Masson-Delmotte *et al.* 2021). For the Caribbean region, several studies have identified the main impacts (Climate Studies Group Mona, 2020; Bloemendaal et al. 2023; Jagessar, 2023). Climate change affects natural hazards in many ways, including:

- **Extreme weather events**: Climate change increases the intensity and frequency of extreme weather events like hurricanes, heat waves, droughts, floods, and wildfires (McClanahan and Cinner 2012).
- **Sea level rise**: Rising sea levels expose more areas to erosion and flooding (Mimura 2013; Carbognin *et al.* 2010).
- **Droughts**: Warmer temperatures lead to more droughts in places like the Mediterranean, Central America, Brazil, South Africa, and Australia (IPCC, 2018).

- **Storms**: More atmospheric water vapour fuels more powerful storms (Knutson *et al.* 2021; Harvey *et al.* 2020).
- **Wind speeds**: Warmer ocean temperatures and more atmospheric heat lead to increased wind speeds in tropical storms (Lau *et al.* 2022; Knutson *et al.* 2021).
- **River flooding**: Warmer temperatures increase the risk of river flooding as more precipitation occurs in the water source areas (Mandal *et al.* 2022).

Climate change also influences regional hazards by altering temperature and precipitation (Lachaud et al., 2022; Mohan et al., 2020). Annex 9 summarizes how climate change affects specific Caribbean hazards.

Assessing hazards under climate change in the Caribbean requires a combination of traditional and advanced methodologies. The following methods are crucial for hazard assessment in a changing climate.

- **Climate Modelling:** Climate models are essential for predicting how climate change will affect hazard frequency and intensity in the Caribbean (Herron *et al.* 2016). Global climate models (GCMs) and regional climate models (RCMs) simulate future temperature, precipitation, and sea-level rise under different greenhouse gas emission scenarios. These models are used to project the future behaviour of hurricanes, rainfall patterns, and droughts and assess long-term risks from sea-level rise. However, due to the small landmasses and unique climate systems in the Caribbean, downscaling global models to the regional and local levels is necessary to improve the accuracy of predictions (Taylor et al., 2012).
- **Remote Sensing and GIS:** Remote sensing technologies like satellites are critical in hazard assessment by providing real-time data on weather patterns, sea levels, land use, and environmental changes (Yang *et al.* 2013). This data is often integrated with GIS to map vulnerabilities, monitor shoreline erosion, and assess flood risks. Remote sensing also helps track changes in forest cover, coral reefs, and wetlands, critical ecosystems for disaster risk reduction (Thomas *et al.* 2019). For example, the Caribbean Disaster Emergency Management Agency (CDEMA) uses GIS and satellite data to monitor hazards and assess regional disaster impacts (CDEMA 2022). These tools are also instrumental in creating disaster risk maps that guide policy and decision-making processes.
- **Participatory Approaches:** In addition to technological methods, participatory approaches involving local communities are essential for hazard assessment in the Caribbean (Roopnarine *et al.* 2021). Engaging communities in data collection, vulnerability mapping, and disaster preparedness builds local resilience and ensures that assessments reflect different populations' specific needs and vulnerabilities (Pelling and Uitto 2001). Participatory approaches can also help identify areas where traditional knowledge and practices can complement scientific assessments.

3.2 Multi-Hazard Exposure assessment

Assets (also indicated as elements-at-risk) refer to "the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas" (UNDRR, 2017). In other words, all the objects, people, activities, values, animals, ecosystems etc. that could be impacted by single or multi-hazard events. Table 3.2 gives a classification of the assets that are most frequently used in (multi-hazard) risk assessment.

Table 3.2: Classification of assets and indications of their importance.

Type	Description	Importance
Buildings	Occupancy type (use), construction types, height, age, total floor space, and replacement costs. Monuments and cultural heritage	Buildings are the most used asset type in risk assessment because they are the location of the people and economic activities
Population	Density of population, distribution in space, distribution in time, age distribution, gender distribution, handicapped, income distribution	Population distribution is essential for social vulnerability and risk and for most planning activities
Agriculture and livestock	Type of crops, crop calendar, area of crops, crop yield, types of livestock, density of livestock	Agriculture is a vital component and should be considered in any risk assessment
Essential facilities	Emergency shelters, Schools, Hospitals, Fire Brigades, Police	They play a key role in disaster response and should be evaluated separately and individually.
Transportation facilities	Roads, railways, public transportation systems, harbour facilities, and airports.	These are essential for emergency response and recovery after a disaster event
Lifelines	Water supply, electricity supply, gas supply, telecommunications, mobile telephone network, sewage system	These are providing essential services for society and could be disrupted
Socio-economic elements	Organization of population, governance, community organization, government support, and socio-economic levels. Cultural heritage and traditions	These are the cultural values and traditions that disasters might seriously impact.
Economic activities	Spatial distribution of economic activities, input-output table, dependency, redundancy, unemployment, economic production in various sectors	Economic activities in different sectors, such as industry, commerce, tourism, and banking (remittance), are relevant
Environment	Ecosystems, protected areas, natural parks, environmentally sensitive areas, forests, wetlands, aquifers, flora, fauna, biodiversity	One of the most critical assets are forests and national parks, which may be impacted by multi-hazards

The assets are also linked to different sectors. The Post Disaster Needs Assessment reports (e.g., the report for the 2017 Hurricane Maria in Dominica (Dominica, 2017) classify sectors and provide a good basis for the classification of assets into different sectors.

It is also relevant to indicate how the various assets could be spatially represented at the three levels of interest in the Caribbean (Regional, National, and local), as grids, land parcels, building footprints, points, lines, or as statistical information per administrative unit. It is also relevant to evaluate what the required attribute information for these assets should be in order to be able to use them in single and multi-hazard risk assessment (See Table 3.3).

Building data can be obtained from a number of global datasets, such as through crowdsourcing (See Annex 9): (OpenStreetMap), Artificial Intelligence (Microsoft Building Footprints, Google Open Buildings, OpenBuildingMap), and Built-up area from Satellite data (World Settlement Map, Global Human Settlement Layer).

Population data can be obtained from a number of international data sources - LandScan , WorldPop , GHS , Gridded Population of World Version 4 (GPWv4), and META High-resolution population Density Maps. Population characteristics can be obtained from the PopGrid initiative. Land use/land cover data can be obtained from a number of global data sources, such as Global Forest Cover, Copernicus Land cover , CORINE Land Cover (CLC), GlobCover (from ENVISAT, MERIS), ESA WorldCover. See also Annex 9.

The type of asset itself plays a very important role in the **dynamic nature of exposure** and vulnerability. It is also relevant to consider that the spatial extent and characteristics of elements-at-risk will change over time as a result of long-term trends (socio-economic developments, population pressure, land use patterns, disaster risk management, climate adaptation), which may also be a reaction to ongoing trends in hazard events related to climate change. The occurrence of major disaster events will certainly modify the elements-at-risk in such a way that it will be difficult to make long-term multi-hazard risk assessments without taking into account such feedback loops. Elements-at-risk have their own dynamics, which differ in time, depending on the type. Population is one of the most dynamic elements, varying over short and long time periods. Population information has become more easily available, especially for more general applications, with the availability of many satellite and census-based products .

Table 3.3: Proposed representation and attributes of assets at the regional, national, and local levels (R= Spatial Representation, A = Proposed Attributes).

Type	Regional level	National level	Local/ municipal level
Buildings	R = Grid A = Number of buildings, Area of buildings, value of buildings	R = Building footprints A = Area, Height, Value, Occupancy type, Value, Number of People	R = Building footprints A = Area, Occupancy Type, Construction type, number of floors, Number of people at different times
Population	R = Grid A = Population density, Births per grid,	R = Grid, Wards A = Number, Age, Gender, Schooling, etc. Other indicators can be obtained from Census data.	R = Population per building (cluster) A = Number for different time periods, Age, Gender, Schooling, Health, and Livelihood.
Agriculture and livestock	R = Gridded land use/land cover map. A = Land use and livestock statistics per municipality or ward.	R = Gridded land use/land cover maps. R = Livestock information per ward or linked to build-up areas.	R = Land use parcels A = Crop type, Crop Yield, Livestock types, and numbers.
Essential facilities	R =Points A = Type, Capacity	R = Points A = Type, Area, Capacity, Construction type, number of floors, Number of people in different times	R= building footprints A =Type, Area, Capacity, Construction type, number of floors, Number of people in different times
Transportation facilities	R = Lines A = Type, Capacity	R = Lines A = Type, Capacity	R = Lines and Points A = Type, Capacity, Value, Importance
Lifelines	R = Lines A = Type, Capacity	R = Lines A = Type, Capacity	R = Lines and Points A = Type, Capacity, Value, Importance
Socio-economic elements	R = Municipality / Ward A = Statistical information	R = Ward A = Statistical information per ward	R = Ward A = Statistical information per ward
Economic activities	R = Municipality / Ward A = Statistical information	R = Ward A = Statistical information per ward	R = Ward A = Statistical information per ward
Environment	R = Gridded land use/land cover map. A = Ecosystem characteristics.	R = Gridded land use/land cover maps. R = Detailed ecosystem characteristics, biodiversity	R = Land use parcels A = Detailed characteristics of plants and animals.

Whereas it is customary to use different scenarios for different times (daytime/nighttime/seasonal) as a basis for the exposure and loss estimation, the dynamics of population in relation to simultaneous or consecutive hazard impacts should also be considered, for example, in the case of the earthquake-flood sequence mentioned above. Other elements-at-risk may also have important dynamics to consider, such as crop cycles in relation to consecutive events.For the SPHERA catastrophe model asset information about building stock, infrastructure and crops were used. With the exception of airports and ports, whose exact location is known, all other assets were distributed in space within each administrative division (CCRIF, 2019).

3.3 Multi-hazard vulnerability

Vulnerability is defined as "the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards (UNDRR, 2017)" This concept has proved to be one of the most confusing due to the multi-dimensionality of vulnerability and the widely varying approaches for evaluating it. Most of the methods for representing physical vulnerability are either based on indices or on vulnerability curves (Hollenstein, 2005; De Ruiter et al., 2017). Vulnerability curves display the average degree of damage (e.g., on a scale of 0=no damage to 1=completely damaged) to elements-at-risk of a certain type, against the intensity of the hazard (e.g., flood depth in meters, wind speed in m/s etc.). Curves can also display the Mean Damage Ratio (e.g., on a scale from 0 to 100%) of all elements-at-risk exposed to a given intensity. Fragility curves display the probability of elements-at-risk reaching a predefined damage state against the intensity.

The type of hazards and their interactions have a large influence on both exposure and vulnerability, where the area impacted, the severity of the intensity, the duration of the hazard impact, and the time between successive events are important factors. The interaction type also plays an important role. In the case of trigger-coupled events, the same elements-at-risk may be impacted by several processes simultaneously, requiring combined vulnerability curves or indicators (Kappes et al., 2012).

Vulnerability assessment can be carried out basically using two major approaches:

Technical vulnerability approach

The technical approach focuses on **quantifying the physical vulnerability** and aims at expressing the degree of loss through vulnerability curves, fragility curves, or vulnerability matrices. Methods for generating vulnerability curves are indicated in Annex 11 . Repositories for vulnerability curves are still very rare, and it is generally quite difficult to find appropriate vulnerability curves for the specific combination of asset type and hazard type for Caribbean countries. One of the main sources for vulnerability is the database linked to HAZUS (FEMA, 2013; 2020; 2021a; 2021b). Nirandjan et al. (2024) provide a review of vulnerability curves for multi-hazards (flooding, earthquake, windstorm and landslides) based on an extensive literature survey. The resulting database is available online as a set of Excel sheets[1]. Specific curves for the Caribbean are poorly represented in this database. There are global repositories for flooding (Huizinga et al., 2017), and earthquakes (OpenQuake, 2016), but these also show large differences for similar typologies of asset types. Windstorm vulnerability curves have been integrated within the CLIMADA tool (Eberenz et al., 2021). Landslide vulnerability curves are more difficult to generate because the term landslides is a general term for many different types of processes (fall, slide, flow, complex movement) that cannot be captured by a single or multiple intensity type (Luo et al., 2023). A common approach is to assume that exposed elements-at-risk are considered as destroyed (also called v=1 approach). Forest fire vulnerability curves are very rare, as most of the assets that are impacted by forest fires are considered to be fully destroyed. Further, forest fires cannot be modeled easily with an intensity scale. A collection of global vulnerability curve has been gathered within an open database linked to an open-source loss estimation tool (RiskChanges, 2024).

The most common approach is the use of indicator values grouped into different groups based on surrounding vegetation, openings, gutters, ground covering, etc. (Papathome-Kohle et al., 2022). Vulnerability assessment approaches for transportation infrastructure have been developed (Argyroudis et al., 2019). Vulnerability assessment of assets for multi-hazard events

[1] https://doi.org/10.5281/zenodo.13889558

is still in development and has not resulted in formalized vulnerability approaches. Here, the hazard interaction type plays a major role. If events occur consecutively, it is important to consider the sequential impact of different hazardous events on the same assets. This means that vulnerability curves should be dynamic and should change after the impact of one event . For example Korswagen et al. (2018) developed a probabilistic framework that considers the subsequent damage of two successive hazardous events (e.g. earthquake and flooding) on a structure. Another approach that is more suitable for concurrent events (e.g., events happening at the same time and affecting the same area) is the use of combinations of two intensities for assessing the vulnerability (See Figure 3.3) .

The holistic vulnerability approach

The holistic approach to vulnerability assessment, focusing on combining physical, social, economic , environmental and institutional vulnerability, is based on the use of a set of indicators, incorporating all types of vulnerability, capacity, and resilience. The indicators can either be linked to administrative units (e.g., Wards) or have their own spatial representation. In the first case, they are collected from census data, which is aggregated to Ward levels and combined using multi-criteria evaluation, for example, the Analytical Hierarchy Process (AHP). In the latter method, a series of indicators, each with its own spatial representation (and with different boundaries), are integrated using Spatial Multi-Criteria Evaluation. A multitude of different approaches exist for the use of indicators in representing vulnerability. Table 3.4 gives a summary of the main types of indicators suggested.

Dynamic assessment

The impacted area of a hazardous event might vary considerably among different combinations of hazard type and element-at-risk type. Further, the directly impacted area, as obtained from the exposure analysis, might be much smaller than the area that is indirectly impacted, and this area might also **change dynamically over time** as the impacts of an event cascade over different sectors. The time that direct and indirect impacts take place may also be quite different, as indirect impacts may last a much longer time than direct impacts.

The expected changes in multi-hazard, exposure, vulnerability, and risk also determine the appropriate method for multi-hazard risk assessment. These changes can be related to:

- **Climate change**: climate change affects the frequency, intensity, and interrelation of hazards. Extreme events might become more frequent, thereby increasing the number of consecutive events. They might also lead to higher intensities, which in turn lead to larger losses. Climate scenarios should be developed for specific future years, and their consequence in the hazard modeling should be analyzed. Climate change might also change the interrelationships between hazard types (introducing new hazard combinations or intensifying existing ones).
- **Changing assets**: future developments such as population changes, further urbanization, globalization, and infrastructure development may drastically change the exposure and vulnerability of assets, which should be considered in future multi-hazard risk assessments.
- **Disaster occurrence**: Disasters cause drastic changes in assets and hazards as well. The recovery time, the time needed for the environment to recover from a previous event (e.g a forest fire), is important to the occurrence of pre-conditioning events, and the longer the time between these events, the less likely that the second one will turn into a hazardous event. Further, the time needed for society to recover from the impact of a previous event is

essential in determining the impact of consecutive events. The recovery, however, is very difficult to take into account in the multi-hazard risk assessment of consecutive events, as it depends on many factors that are difficult to predict beforehand, such as the specific impact of previous events, the funding available for reconstruction, the economic situation, and the risk governance situation. Although this concept is considered conceptual, hardly any studies have developed concrete examples.

Table 6.4: Some examples of vulnerability and capacity indicators

Examples of vulnerability indicators	**Examples of adaptive capacity indicators**
Demographic characteristics: gender (male and female); urban and rural population, age group (children, elderly, youth, adult), population density, economic status (poor, rich).	Socio-economic capability: Human Development Index (HDI), Gross National Income (GNI), Gross Domestic Income (GDI), Gross Domestic Product (GDP), economically active population, land ownership by female.
Socio-economic characteristics: population growth, population density, sex ratio, Dalit, and Indigenous Peoples (Janajati), differently abled, people with health issues, poverty incidences, female household population, smallholder farmers, landless population, refugees, slum dwellers, orphans, the dependency ratio.	Access to goods and services: access to roads, infrastructures, communication, technology, education, health facilities, seeds, planting materials and fertilizers, households with radio and television, rescue and rehabilitation centers, water purification and refinement, standardized roads, alternative means of transportation
Characteristics of infrastructures - types, age, location (proximity to hazards) etc.	Access to technology: climate-smart and climate-resilient technologies, risk reduction and management technologies, water-efficient technologies, soil and land management technologies, crop management technologies, early warning systems, bioengineering technologies, sustainable forest management, Agro advisories.
Biophysical factors: soil types, topography, the trend of change in land use, and land cover.	Access to finance: investments and allocations, budget, insurance, credit, and grants facilities
Intrinsic characters: forest types, slope, landslide, and flood intensity.	Policy and institutions: law, policy, plans, number of active agencies working, networks and groups, reinforcement of building codes.
Disturbance regimes: forest fire, invasive alien plants, degradation and fragility status, pest, and disease susceptibility.	Awareness and knowledge: local and Indigenous knowledge, knowledge on climate change, and response measures.
Others: drainage density, sedimentation yield, demand, and supply.	Human resources: skilled human resources in disaster risk reduction and management, skilled human resources in other areas.

To include the dynamic aspects of exposure and vulnerability within a multi-hazard risk assessment, it is very relevant to distinguish between an assessment that considers the current situation and the coming years (loss prediction), where any combination of hazardous events might take place, and situations where a particular disaster hazard event has already occurred. Many of the studies that illustrate the importance of multi-hazard risk assessment are based on historical events for which specific hazard interactions and timing between events were already known (forensic analysis).

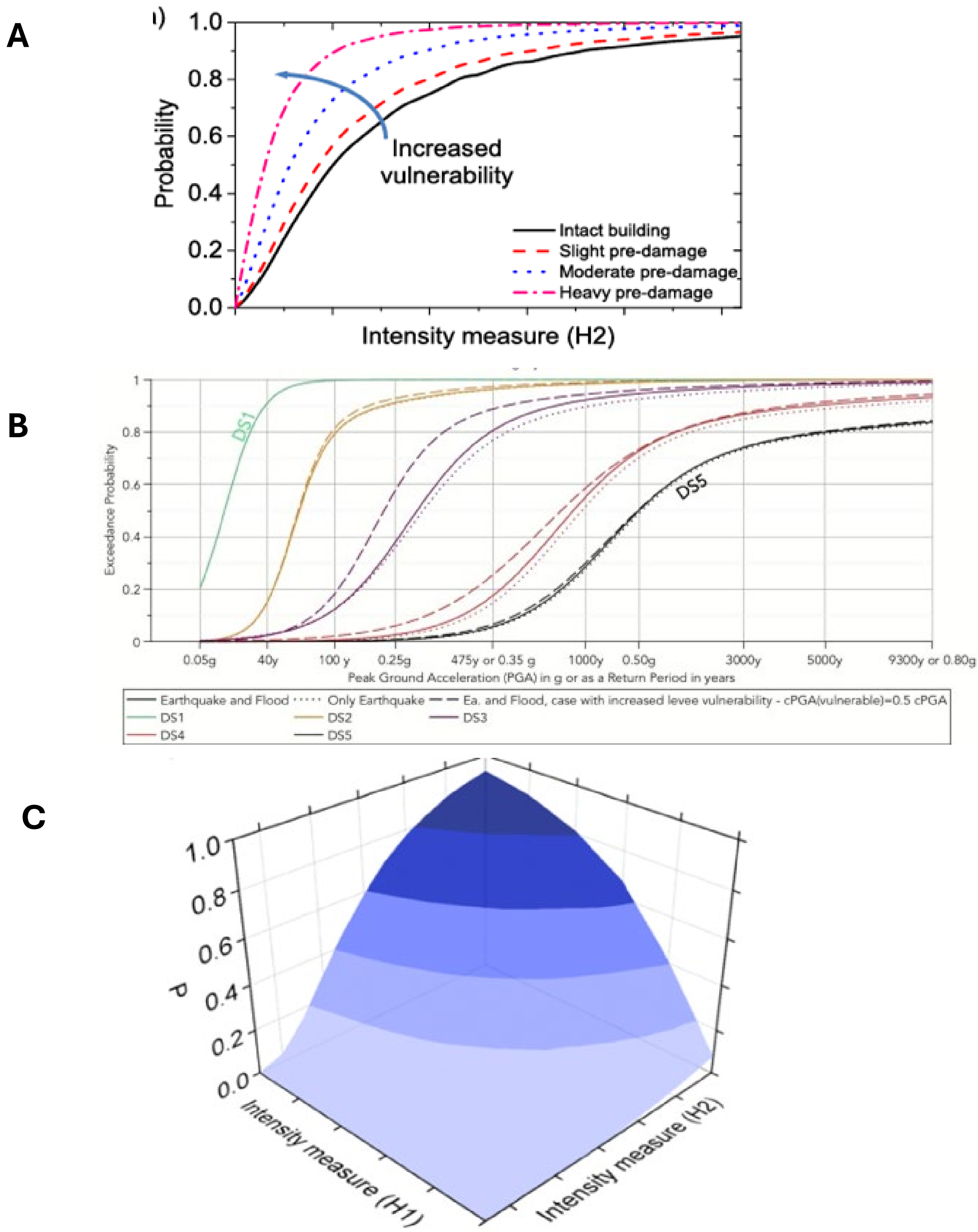


Figure 3.3: A Schematic example of a fragility curve that is modified as a result of one hazardous event in relation to the occurrence of another hazardous event (Luo et al., 2023); B: Example of a fragility curves with Damage States for an earthquake followed by flooding (Korswagen et al., 2018) C: Example of a combination of two intensities in a two dimensional matrix (Luo et al., 2023)

Chapter 4. Multi-hazard Risk Assessment

Disaster risk assessment is defined as "a qualitative or quantitative approach to determine the nature and extent of disaster risk by analyzing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend (UNDRR, 2017). It integrates the hazard, exposure, and vulnerability components by first analyzing the loss related to specific scenarios of hazard events, with their own frequency of occurrence, and integrating this into the risk assessment. When considering the multi-hazard risk, the most conventional approach is to consider the **multilayer single hazard** approach (Gill and Malamud, 2014), in which the exposure and losses for each combination of individual hazard type, frequency, and element-at-risk are calculated separately and aggregated per administrative unit. The total risk is then analyzed by integrating the losses into Average Annual Losses (AAL) and adding these for the individual hazard/element-at-risk combinations. Many methods for multi-hazard risk assessment have been outlined in literature (Delmonaco et al., 2006; Marzocchi et al, 2012., Kappes et al., 2012; Liu et al., 2015; Gallina et al., 2016). A comprehensive multi-hazard risk assessment (MHRA) is essential for enhancing resilience and reducing the socio-economic impacts of these disasters (Owolabi and Sajjad, 2023). Multi-hazard risk assessment identifies, analyses, and quantifies the risks posed by multiple hazards to a given area, infrastructure, or population (8). Unlike single-hazard assessments, MHRA considers the potential for simultaneous or cascading events, recognising that the impact of one hazard can exacerbate another (Gill and Malamud, 2014). For example, hurricanes can trigger flooding, landslides, and coastal erosion, while volcanic eruptions can lead to tsunamis. MHRA is particularly important in the Caribbean, where overlapping hazards can cause compounding damage. According to CDEMA (2014) , understanding the interactions between hazards and the vulnerability of various sectors, such as housing, infrastructure, and agriculture, is vital to developing effective disaster risk reduction (DRR) and climate change adaptation (CCA) strategies. CDEMA's guidelines also stress the importance of regional collaboration, A robust MHRA framework typically includes the following core components (See Figure 1.3 and 4.1):

- **Multi- Hazard Assessment**: Determining the types of hazards that can impact a region, including their frequency, intensity, and duration. Hazard identification is based on historical data, environmental monitoring, and climate projections (See Chapter 5).
- **Exposure Assessment**: Identifying the elements at risk, including people, buildings, infrastructure, and ecosystems, and determining their proximity to hazard-prone areas (See chapter 6).
- **Vulnerability Analysis**: Analysing the susceptibility of exposed elements to damage. This involves understanding the socio-economic factors (e.g., poverty, age, disability) and physical factors (e.g., building quality) that contribute to vulnerability (See chapter 6).
- **Risk Calculation**: Quantifying hazards' probability and potential impact on exposed elements. Risk is often expressed as a combination of hazard likelihood, exposure, and vulnerability). This includes **an uncertainty and sensitivity analysis**: Addressing uncertainties in data, models, and future projections. This is particularly important in regions like the Caribbean, where climate change alters the frequency and intensity of hazards.
- **Risk Evaluation**: analysing if the level of risk is acceptable or not. In the absence of risk acceptability standards for the Caribbean, by comparing with other types of risk;

- **Scenario Analysis**: Developing potential future disaster scenarios based on expected change in climate, hazards, assets, vulnerability and exposure.
- **Risk Reduction Alternatives**: that helps planners and policymakers prioritise areas of concern and prepare appropriate mitigation measures .

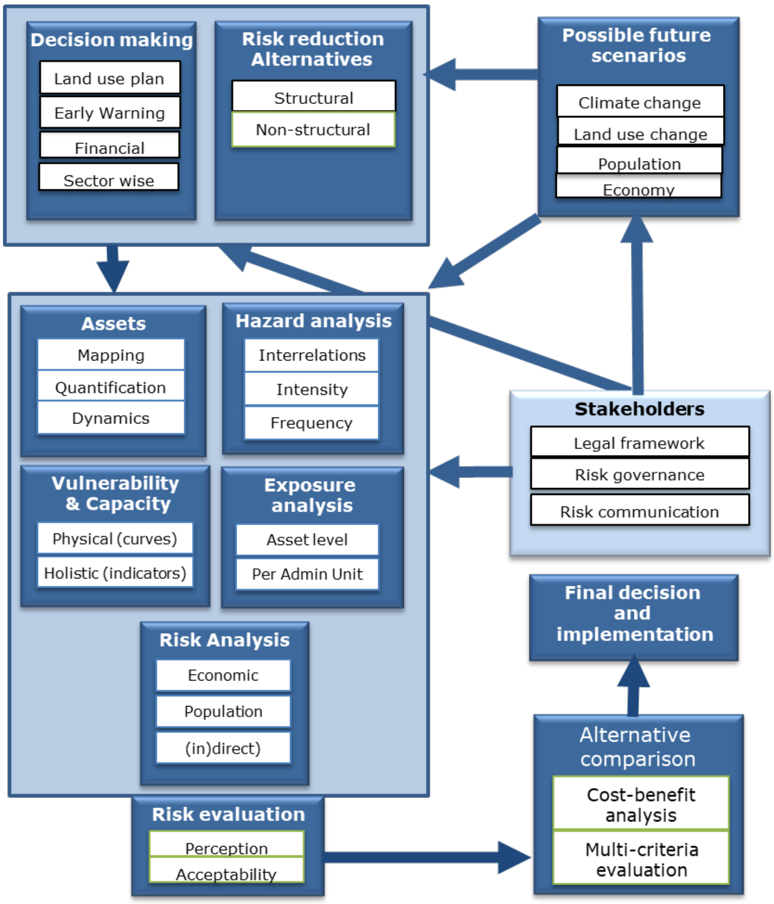


Figure 4.1: Framework for Multi-Hazard Disaster Risk Reduction

4.1 Scales of Risk Assessment

Concerning scales of analysis, approaches have been developed ranging from a global scale to a local level. Ward et al. (2020) provide an overview of risk assessment methods at the global scale and conclude that the interactions between hazards and the dynamic nature of exposure and vulnerability are difficult to incorporate at this scale. This is also the case when dealing with regional scale analysis, such as transboundary analysis of multi-hazard risk for the Caribbean region (UNDRR, 2022). This report investigated the current status within the Caribbean countries on the implementation possibility of Multi-Hazard Early Warning system under the EW4ALL initiative. The report identifies country-by-country what the current capacity is in terms of risk governance, availability of data, resources and expertise in hazard and risk assessment, monitoring, early warning and disaster response. The study concluded that in total 8 Caribbean countries had an operational Multi-Hazard Early Warning system in place (Anguilla, the British Virgin Islands, the Cayman Islands, Martinique, Guadeloupe, Puerto Rico, Trinidad & Tobago, and the Turks & Caicos Islands (UNDRR, 2022). With respect to the presence of national disaster databases, there are many more Caribbean countries (Antigua and Barbuda, Barbados, Dominica, Dominican Republic, Grenada, Guyana, Jamaica, Saint Kitts and Nevis, Saint Vincent and the Grenadines, Trinidad and Tobago), although many of them without recent updates (most up to 2014) (DesInventar, 2024). According to a study by Rahat (2020) there at least 7 projects addressing multi-hazards in the period 2015-2020 that were funded by international organizations. Rahat (2020) indicates that impact-based forecasting has become one of the main focus areas for multi-hazard risk assessment among projects such as the Climate Risk & Early Warning Systems (CREWS) Caribbean project, the Enhancing Weather & Climate Early Warning Systems and Impact-based Forecasting Platforms in the Caribbean Region project, and the Expanded Weather & Climate Forecasting and Innovative Product & Service Development & Delivery in the Caribbean project. WorldBank GFDRR has carried out Country Disaster Risk Profiles (CDRPs), that estimate the potential economic losses to property caused by natural hazards, in Dominican Republic, Grenada, Haiti, Jamaica and Saint Lucia (GFDRR, 2018). These have been used extensively for informing these countries' disaster risk financing strategies. Furthermore, it should be noted that projects have evolved from simply modelling, monitoring, and predicting hazards, to include the consequent impacts & effects of the hazards. Impact-based forecasting has become a common theme (Rahat 2020).

There are several good examples of multi-hazard risk assessment at local administrative level e.g., Bell & Glade (2004), Marzocchi et al (2012). Chen et al. (2016), Van Westen et al. (2014) and Di Angeli et al. (2022).

In the subsequent sections an overview is given of the approaches for multi-hazard risk assessment, which can be subdivided in qualitative and quantitative ones.

4.2 Qualitative risk assessment approaches

The main methods for multi-hazard risk assessment that follow a qualitative approach are listed in Table 4.1. They have in common that the actual losses are not quantified numerically, but are described in (semi) quantitative terms. Even when using numbers, these do not represent the losses but a score that is used to compare different administrative units.

Community-Based Risk Assessment (CBRA)

Community-based risk assessment empowers local communities and civil society organizations (CSOs) to take an active role in reducing the impact of natural disasters. It involves a bottom-up, participatory approach involving local populations in risk assessment, prioritizing local knowledge, resources, and needs (CADRI, 2020; Matharage et al., 2024). This method incorporates local knowledge, perceptions, and priorities into formal risk assessments, ensuring that strategies are contextually relevant and socially accepted (Ryan et al, 2020). One of the tools, developed by the IFRC is the Vulnerability and Capacity Assessment (VCA) (IFRC, 2024).

The Caribbean Natural Resources Institute (CANARI) is developing a programme to empower civil society and local communities to build resilience to hurricanes and climate extremes in the Eastern Caribbean (CANARI, 2023), focusing on Eco-DRR. The Eastern Caribbean Community Resilience Programme (ECCRP) aims to build the resilience of countries in the Eastern Caribbean region to natural disasters and the impacts of climate change. The program is funded by the United Kingdom government's Department for International Development (DFID) and implemented by the Caribbean Development Bank (CDB) (OECS, 2024). In Dominica, CBRA has involved local communities in hazard mapping, vulnerability assessments, and disaster preparedness planning . This bottom-up approach has fostered greater community ownership of DRR initiatives, enhancing resilience at the grassroots level (Maurya, 2024).

Table 4.1: Methods for quantitative multi-hazard risk assessment

Method	Description	Advantages	Disadvantages
Community-Based Disaster Risk Assessment	A process to empower local communities to assess the hazards, vulnerability, capacity and risk, and design risk reduction options.	It is essential to involve local communities in all aspects of disaster risk management as they are the key stakeholders.	Local communities may not have experience with high impact, low probability events, and emerging multi-hazard scenarios.
Indicator-based, Multi-Criteria Evaluation	A method in which the risk components (hazard, exposure, vulnerability, capacity) are represented by a series of indicators, which are combined by giving them a weight.	The method can be standardized (as in the case of the INFORM Risk method) and can be carried out by planning experts without extensive hazard modeling.	The method doesn't provide actual values of the frequency of losses but merely scores per administrative unit that can be used to prioritize them for risk reduction actions.
Impact-chain analysis	Co-development of visual representation of hazard interactions and direct and indirect impacts for different sectors.	This method is a good approach to understanding the multi-hazard interactions and cascading impacts and can be used as a basis for the quantification using other methods.	The method doesn't quantify the losses. Even though indirect losses are also included, the quantification of these is extremely complicated and often very case-specific. Impact chains can be very complicated.
Risk Matrix Approach	A simplified method where risk classes are defined based on frequency classes and loss classes into a matrix, which can be used for zoning.	This method is a good basis for land use planning and doesn't require very detailed quantified data. The method is used in many countries as the basis for planning.	The method is not often applied in a multi-hazard context. The same area might be falling under various combinations of frequency and losses. Only the highest is considered.

Indicator-based approaches , using Multi-Criteria Evaluation

One of the most common approaches for multi-hazard risk assessment linked to spatial planning is the application of weighting methods, such as Spatial Multi-Criteria Evaluation (SMCE) or the Delphi method, which are used to compare the impact of different hazards in a region by applying weights given by experts (Olfert et al, 2006). The INFORM method (2024) has been developed by the Joint Research Center of the EU in collaboration with UN organizations. It has become one of the most popular qualitative methods, where a range of indicators are weighted for exposure, vulnerability, and capacity. The method has been applied at national and sub-national scales in many countries. The global INFORM GRI model was adapted to Latin America and the Caribbean (LAC-INFORM RI). These results (Table 4.2) support planning or resource allocation processes at the regional level, and can be used to support regional prevention and preparedness actions, for example of the Regional Group on Risks, Emergencies, Disasters for Latin America and the Caribbean (REDLAC, 2024). It can also contribute to the implementation of the Sendai Framework for Disaster Risk Reduction, the Sustainable Development Goals, etc.

The INFORM method has been applied to a number of countries on a sub-national scale, but not yet for The Caribbean. The method was also used to evaluate changes in multi-hazard risk (for river and coastal floods, and drought under several global climate scenarios (Marzi et al., 2021). In Cuba, the Risk Assessment Group of the Environment Agency (AMA), under the Ministry of Science, Technology and Environment (CITMA), developed a methodology for local multi-hazard risk assessment (AMA, 2016). The methodology for river floods, coastal floods, windstorms, and drought follows a spatial multi-criteria methodology, where weights are assigned to contributing factors to make a hazard and a vulnerability index, which are combined into a risk index.

Table 4.2: INFORM Risk scores for Caribbean countries. The columns indicate the scores (Source: INFORM, 2020)

so3	CountryName	Hazard & exposure	Vulnerability score	Lack of coping capacity score	INFORM Risk Score
ATG	Antigua and Barbuda	3.2	2.6	4.3	3.3
BHS	Bahamas	4.8	2.4	4.6	3.8
BRB	Barbados	2.4	2.8	2.9	2.7
CUB	Cuba	5.7	3.6	4.2	4.4
DMA	Dominica	3.6	4.4	3.3	3.7
DOM	Dominican Republic	6.1	5.6	6.9	6.2
GRD	Grenada	1	3.2	4.1	2.4
GUY	Guyana	4	5.9	6.3	5.3
HTI	Haiti	7.7	8.3	8.3	8.1
JAM	Jamaica	5.9	4.2	6.6	5.5
KNA	Saint Kitts and Nevis	3.8	3.4	5.6	4.2
LCA	Saint Lucia	3.2	3.2	4.4	3.6
VCT	Saint Vincent and the Grenadines	3.3	3.9	3.5	3.6
SUR	Suriname	2.8	2.7	5.4	3.4
TTO	Trinidad and Tobago	3.8	2.9	6.4	4.1

Impact chains

Coinciding, cascading, and consecutive hazard events often cause cascading impacts, where direct impacts lead to secondary ones in a chain of events, so it is important to represent them in a qualitative multi-hazard risk assessment. The concept of Impact chains (ICs) has been developed initially in the climate impact analysis (Zebisch et al., 2022) and has been adapted for use in a comprehensive assessment of related risks following the comprehensive risk management framework (UNDRR 2022c). Impact chains are conceptual representations of the chain of triggers, hazards, exposure, vulnerabilities, and impacts that are caused by complex events. Impact chains are developed through stakeholder workshops, and forensic analysis (Atun et al., 2024). They can be used to analyze how future scenarios might lead to different impact chains, and where in an impact chain it is best to intervene through risk reduction activities. A conceptual example of an impact chain is presented in Figure 4.1. Figure 4.2

presents an impact chain that focuses on the impact of a hurricane on food security. Several examples of impact chains for the Caribbean can be found in Cocuccioni et al. (2023).

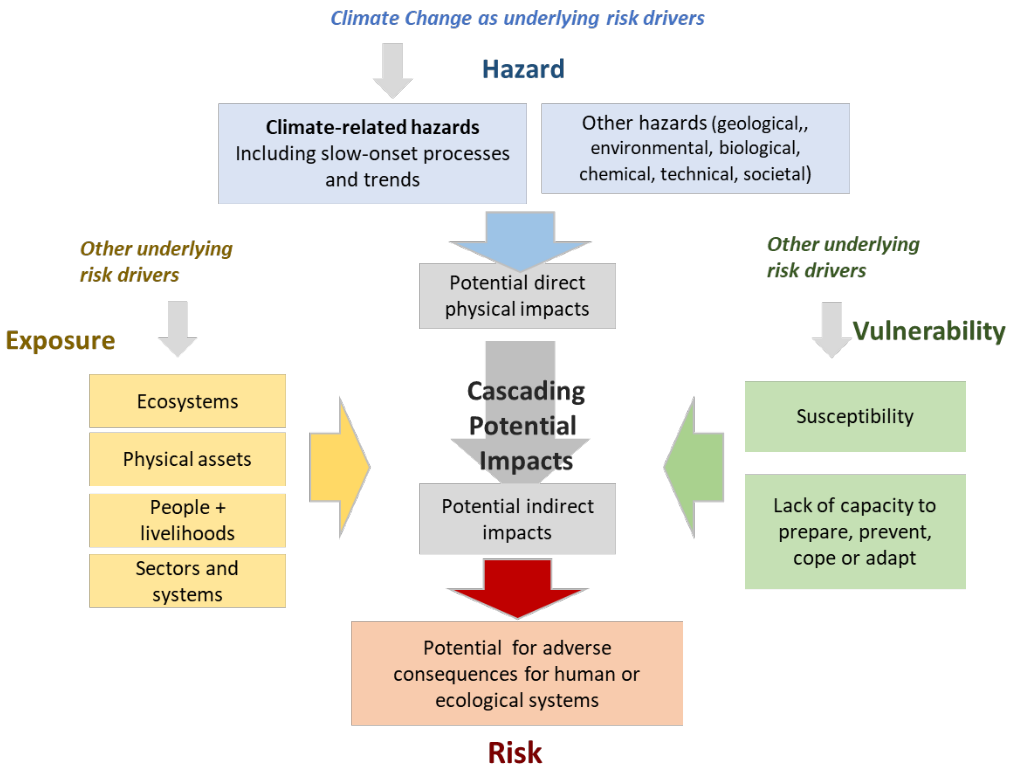


Figure 4.1: General structure of an impact chain (Cocuccioni et al., 2023)

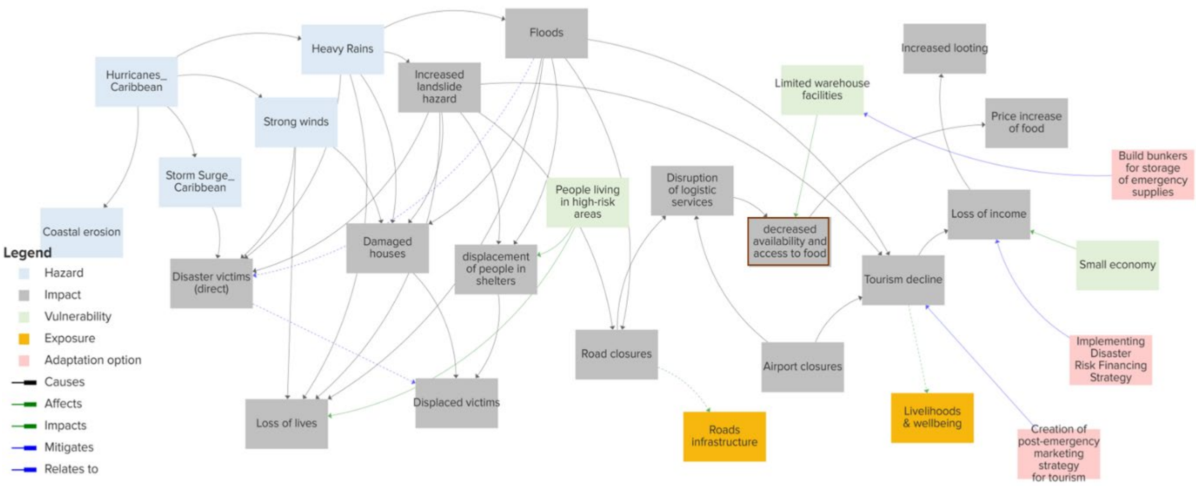


Figure 4.2: Example of an impact chains for decreased food availability after a hurricane. See this link for the detailed version (Cocuccioni et al., 2023)

Impact chains can be used also in combination with other approaches, such as indicators or quantified scenarios. They are widely used in climate risk assessment at national and regional scale and recently also included into an ISO standard (ISO/IEC 2020).

Risk Matrix Approach

The risk matrix approach is a standard approach for the characterization of the risk to natural hazards, by combining the two components of risk: frequency and expected impact. This approach can be done for different scales, ranging from national scales to local levels. For example, the method has been used by Green (2020) as an illustration for Dominica. An adapted version of the risk matrix approach was used by Sammonds et al (2023) for multi-hazard risk assessment in Dominica, however, considering the risk of the single hazards individually before combining them in a multi-hazard risk assessment. Risk matrix approaches are standard for many applications (e.g. DFID, 2023). They can also be used as the basis for spatial planning, by mapping zones (e.g. local administrative units) and determining their highest risk level for each of the hazards to which it might be exposed.

Risk classes		Impact				
		1	2	3	4	5
Frequency	1	L	M	H	VH	VH
	2	L	M	H	VH	VH
	3	VL	L	M	H	VH
	4	VL	VL	L	M	H
	5	VL	VL	M	L	H

Level	Descriptor	Description of Impact
1	Insignificant	Destination, tourism operators and tourists are unaffected by the event.
2	Minor	Minimal disruption to tourism activity; few media reports.
3	Moderate	Some disruption to tourism activity; some level of inconvenience to tourists and financial losses to tourism operators; some media coverage.
4	Significant	Major disruption to tourism activity; infrastructure is affected; financial losses are incurred. Tourists are affected and reports of dissatisfaction exists in the media; negative spotlight on destination and/or tourism business.
5	Catastrophic	Tourism sector is severely impacted; financial losses are very high, tourism assets; basic services and tourism businesses affected; widespread media coverage; national and international responses are needed to assist tourists and locals in the destination; bookings cancelled; events postponed/cancelled; destination's image temporarily tarnished.

Hazard	Likelihood	Impact	Overall Risk
Hurricane	Highly Likely	Catastrophic	High
Urban Flood	Highly Likely	Catastrophic	High
River Flood	Unlikely	Minor	Very Low
Coastal Flood	Possible	Moderate	Medium
Earthquake	Possible	Moderate	Medium
Tsunami	Possible	Moderate	Medium

Level	Descriptor	Description of Impact
1	Rare	Hazard event may occur in unique circumstances *0 - 10% Probability*
2	Unlikely	Hazard event could occur *10 - 25% Probability*
3	Possible	Hazard event might occur *25 - 60% Probability*
4	Likely	Hazard event will probably occur *60 - 80% Probability*
5	Highly Likely	Hazard event is expected to occur *80 - 100% Probability*

Figure 4.3: Risk matrix approach, where risk is defined as a combination of probability and severity of the impact. The example is shown for Dominica (Green, 2020)

The risk matrix approach is widely used, also outside of disaster risk applications, and can be used for several applications:

- Assessing the level of risk of individual hazard types for specific areas
- Comparing the levels of risk between different hazard types, in a multi-hazard approach
- Use them as the basis for prioritizing areas where qualitative risk assessment would be needed
- Use the risk matrix as a basis for risk evaluation, by adjusting the risk levels according to acceptability levels, and comparing the changes that occur when implementing risk mitigation measures.

4.3 Quantitative approaches

The quantitative multi-hazard risk assessment approaches result in quantitative expressions of the risk, which may vary from simple exposure information to complex metrics such as Average Annual Losses. Table 4.3 gives an overview of the types of risk, and the way they can be quantified. Some of the quantitative metrics can be used as the basis for **risk evaluation**, where risk levels are compared with thresholds defining acceptable and tolerable risk levels. These are based on individual or societal population risk metrics. Unfortunately, none of the Caribbean countries has an official risk acceptability threshold adopted (UNDRR ROAMC, 2021), although some attempts have been made to develop qualitative scores (Maharaj, 2010). Risk thresholds are also very important for the establishment of Early Action protocols in Impact-Based Forecasting (AdaptAction, 2022).

Table 4.3: Different metrics to qualitative describe or quantify risk

<table>
<tr><th colspan="2">Type</th><th colspan="2">Principle</th></tr>
<tr><td rowspan="2">Qualitative</td><td>Classes</td><td colspan="2">Based on relative risk classes categorized by expert judgment. Risk classes: High, Moderate and Low</td></tr>
<tr><td>Scores</td><td colspan="2">Based on relative ranking and weights assignments by a given criteria. Risk index: ranked values (0-1, 0-10 or 0-100) (dimensionless). Used for prioritizing certain administrative units</td></tr>
<tr><td rowspan="8">Quantitative</td><td>Numbers</td><td>Exposed assets</td><td>Quantification of the exposed assets to a (multi-)hazard scenario</td></tr>
<tr><td rowspan="4">Monetary Economic risk</td><td>Single event loss</td><td>Quantification of the losses associated with a single (multi-)hazard event</td></tr>
<tr><td>Probable Maximum Loss (PML)</td><td>The largest loss believed to be possible by (multi-) hazard events with low probability & high impact. Relevant for financial risk mitigation strategies.</td></tr>
<tr><td>Average Annual Loss (AAL)</td><td>Expected loss per year when averaged over a very long period (e.g., 1,000 years). Computationally, AAL is the summation of products of event losses and event occurrence probabilities for all stochastic events in a loss model. Relevant for financial risk mitigation tools.</td></tr>
<tr><td>Loss Exceedance curve (LEC)</td><td>Risk curve plotting the consequences (losses) against the probability for many different events with different return periods.</td></tr>
<tr><td rowspan="3">Population risk</td><td>Exposed population</td><td>Number of people exposed to a particular multi-hazard scenario</td></tr>
<tr><td>Individual risk</td><td>The risk of fatality or injury to any identifiable (named) individual who live within the zone impacted by a hazard; or follows a particular pattern of life that might subject him or her to the consequences of a hazard.</td></tr>
<tr><td>Societal risk</td><td>The risk of multiple fatalities or injuries in society as a whole: one where society would have to carry the burden of a hazard causing a number of deaths, injury, financial, environmental, and other losses.</td></tr>
</table>

Table 4.4 gives a summary of the quantitative methods that can be implemented for multi-hazard risk assessment. For each method, a short description is given, and the main advantages and disadvantages are outlined.

Individual scenario Analysis

In this approach the impacts of an individual multi-hazard scenario are quantified. First a multi-hazard scenario is defined, based on the hazard relations outlined in chapter 3 (causal, spatial and temporal relations). The generation of an impact chain can be useful in this stage. Next the hazards are modelled for this scenario, which could be a combined hazard modelling if the events occur simultaneously. Exposure and vulnerability assessments are carried out, and the losses are quantified, depending on the assets that were used (e.g. population, buildings, transportation etc.).

Table 4.4: Methods for quantitative multi-hazard risk assessment

Method	Description	Advantages	Disadvantages
Individual scenario analysis	Losses are calculated for specific hazard interaction scenarios without considering their frequency. It can be simplified by calculating only exposure or using the V=1 approach	This method is ideal as the basis for disaster preparedness actions, for instance, for the modeling of population exposure as the basis for Early Warning. It is also helpful for validating historical events	The scenarios are generally limited, and in reality, other events might occur as foreseen. The frequency is not considered in this approach. The method is often applied in data-scarce regions where data on elements-at-risk are lacking.
Simplified Quantitative Risk Assessment	Losses are calculated for specific combinations of hazard scenarios with their return period and exposure. Risk is calculated from four or more loss scenarios by calculating the area under the curve.	This approach requires a limited number of hazard interaction scenarios. It is important to have these for a range of frequencies (both frequent and infrequent). The analysis can be done without	It can be difficult to determine the specific frequency of certain hazard interactions. It can work well with trigger-coupled and independent events by taking the frequency of the trigger. Not all possible scenarios are evaluated. This can also be done using
Probabilistic risk assessment	Calculate losses of all possible hazard interaction scenarios and include uncertainties of risk components	Provides complete analysis of average annual losses as a basis for financial decision-making. The analysis requires	Requires specialized software and is not applicable for all types of hazards (e.g., landslides, volcanoes, flooding). Very data-demanding. The analysis requires specific software tools
Event-tree Analysis/ Bayesian networks/Graph Theory	Hazard interactions and impacts are structured into a tree structure, and the probability of each branch is calculated	Allows the modelling of a sequence of events and works well for domino effects	The probabilities for the different nodes are difficult to assess, and spatial implementation is very difficult due to a lack of data. The method requires specific expertise and tools.
Artificial intelligence	Predict the losses of hazard interactions based on a large training dataset using AI, with relevant covariates	No need to develop datasets on risk components. No hazard, exposure, or vulnerability assessment is needed.	There are only a few examples where loss datasets were large enough to do this. The analysis requires a high level of expertise and programming skills

In the most simple version also the exposure can be used as a proxy, or a single vulnerability values (V=1) if the relation between intensity and damage degree cannot be determined. Indirect impacts could be quantified as well, for example by analyzing the areas that are not accessible due to the occurrence of the event. Deterministic scenario analysis involves selecting a worst-case scenario for each hazard based on past events or expert judgment. This approach is beneficial for emergency response planning, as it helps identify the most severe potential impacts of hazards. In the Caribbean, deterministic analysis is often used for hurricanes and tsunamis, where worst-case scenarios are modelled based on the intensity of past storms or seismic events (Mycoo & Donovan, 2017).

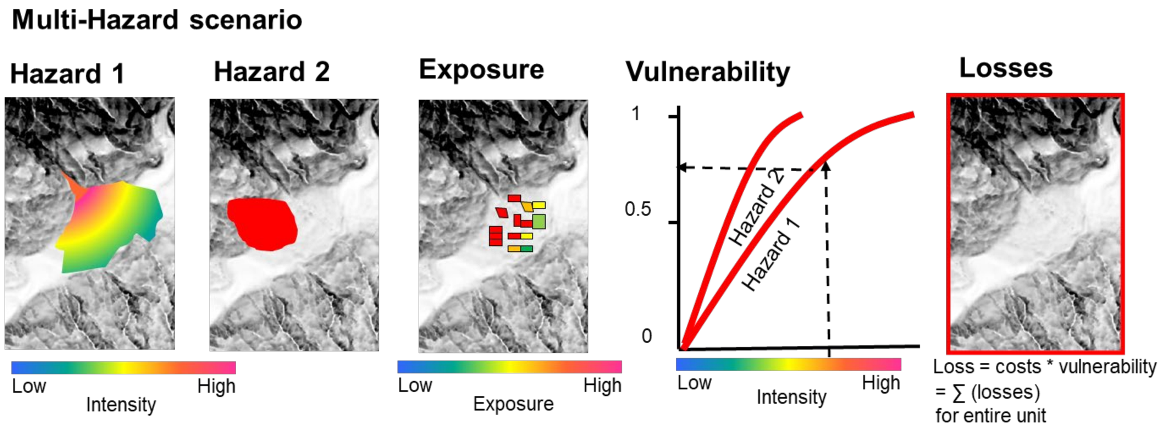


Figure 4.4: Schematic representation of the quantitative assessment of the impact of a multi-hazard scenario. Here two hazard types threaten the same settlement. Each one has different intensity and different vulnerability curves are used.

Simplified Quantitative risk assessment

In this approach (Figure 4.5) a limited number of multi-hazard scenarios are considered, each one with a particular return period. For example, the processes that are related to a tropical storm (wind, floods, debris flows, landslides, storm surge).

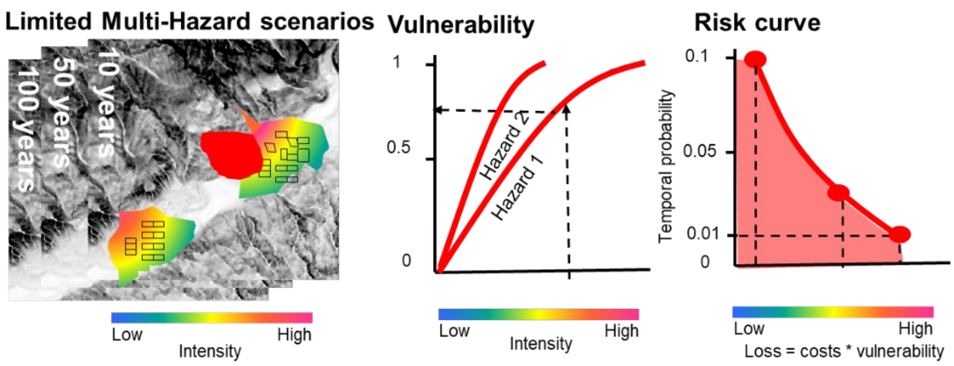


Figure 4.5: Schematic representation of a simplified quantitative risk assessment, in which a limited number of multi-hazard scenarios is used

The processes are modelled for different magnitudes of the associated storm, and the frequency of the storm is used as the frequency of the associated processes. Losses are plotted against the annual probability of occurrence and a risk curve is drawn by connecting the points, after which the area under the curves gives an approximation of the Average Annual Loss (Chen et al., 2016) This approach is also used at national scale, especially when the modelling of individual multi-hazard events is complicated. Figure 7.6 gives an example for Saint Vincent (CHARIM, 2014)

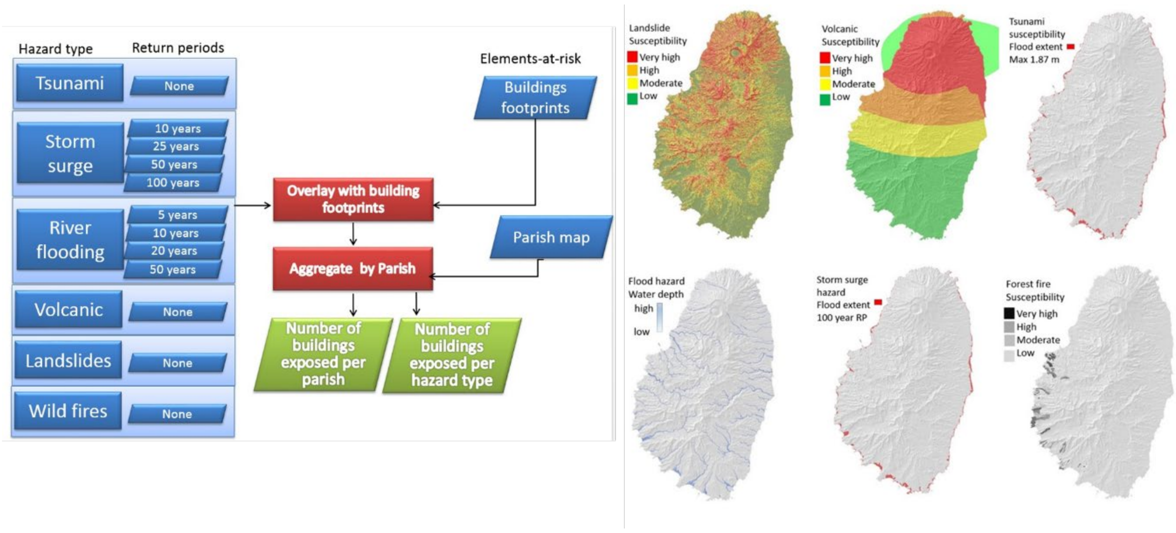


Figure 4.6: Example of simplified multi-hazard risk assessment for Saint Vincent (CHARIM, 2014)

For example, in the aftermath of Hurricane Maria in 2017, a deterministic scenario analysis was used to evaluate the potential damage of a Category 5 hurricane striking Dominica. The analysis revealed significant vulnerabilities in housing and infrastructure, leading to policy changes that required more robust building codes and better hurricane preparedness measures (Sammonds et al., 2023).

Probabilistic Risk Assessment (PRA)

Probabilistic country risk assessments consider all possible risk scenarios in a certain geographical area, which include the low frequency, high loss impact events, as well as high frequency, lower loss impact events. Included is their probability of occurrence, and all elements of the risk equation ,their variability and uncertainty ranges. PRA is based on catastrophe models, which are essential tools in assessing the risk associated with catastrophic events.

Probabilistic risk assessment is widely used in the Caribbean to estimate the likelihood of different hazards occurring over a specific time frame (Joyette et al., 2014). PRA combines historical hazard data with statistical models to estimate the probability of hurricanes, floods, or earthquakes. This method also includes Monte Carlo simulations, which generate thousands of scenarios to quantify uncertainties in hazard occurrence and potential damage (13, 18, 19).

The Caribbean Catastrophe Risk Insurance Facility (CCRIF) uses probabilistic risk models to calculate insurance premiums and pay-outs for member countries affected by hurricanes, earthquakes, and excess rainfall (CCRIF, 2019). By assessing the probability of catastrophic events and their potential economic impact, CCRIF provides financial resilience against natural disasters.

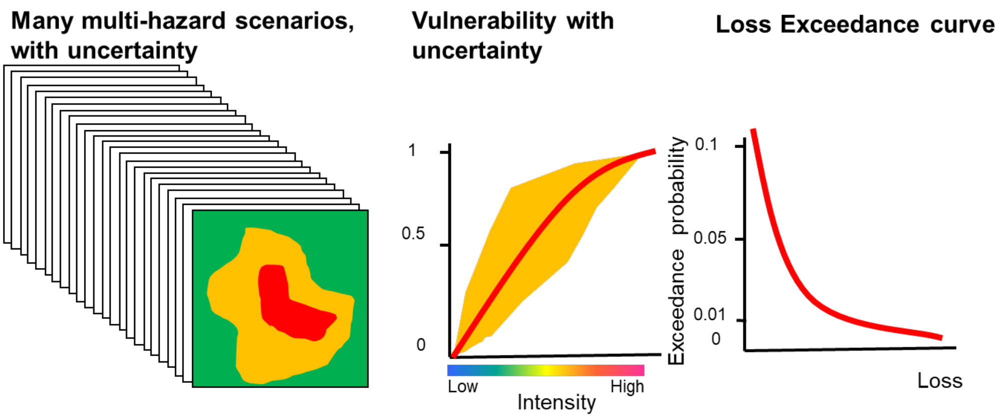
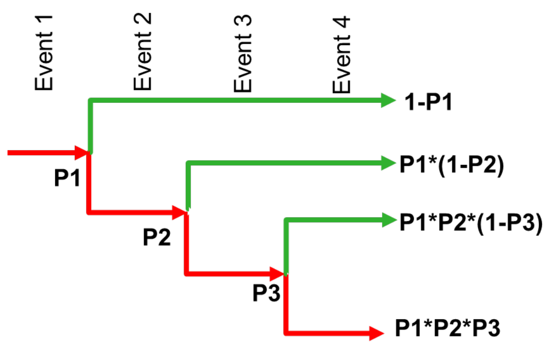
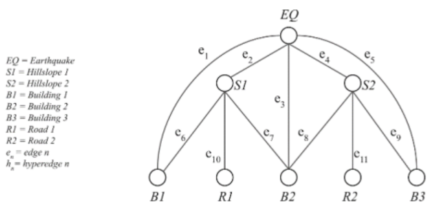


Figure 4.7: Simplified indication of probabilistic multi-hazard risk assessment

Event Trees, Bayesian Belief Networks and Graph theory

A number of hazard may occur in chains: one hazard causes the next. These are also called domino effects, or concatenated hazards. These are the most problematic types to analyze in a multi-hazard risk assessment. The best approach for analyzing such hazard chains is to use so-called event-trees. An event tree is a system which is applied to analyze all the combinations (and the associated probability of occurrence) of the parameters that affect the system under analysis. All the analyzed events are linked to each other by means of nodes (See Figure 4.8) all possible states of the system are considered at each node and each state (branch of the event tree) is characterized by a defined value of probability of occurrence.





	e1	e2	e3	e4	e5	e6	e7	e8	e9	e10	e11
EQ	1	1	1	1	1						
S1		1				1	1			1	
S2				1				1	1		1
B1	1					1					
B2			1				1	1			
B3					1				1		
R1										1	
R2											1

Figure 7.8: Left: Principle of an Event-Tree to calculate the probability of cascading events. Right: principle of Graph Theory (Dunant et al., 2021)

In the Graph Theory a graph consists of a set of nodes connected by edges. The nodes represent a geographical location (a slope unit, a building) or a nominal property (e.g. the occurrence of a hurricane) and the edges represent the relations between the nodes (e.g. the rainfall affecting the slope units and the buildings). In the Graph Theory all the connections between the nodes can be modelled for multiple hazards (Dunant et al., 2021).

Artificial Intelligence for Multi-Hazard Risk Assessment

With the increasing availability of damage data it has become feasible to apply artificial intelligence techniques to quantify the expected losses, based on a database of past losses (Wang et al., 2023). Machine Learning Approaches have been used extensively for assessing multi-hazard susceptibility, by combining inventories of different hazard types with a series of causal factors (e.g. Yousefi et al., 2020). Pasino et al (2021) identified the following method as most suitable for multi-hazard risk assessment (Artificial Neural Network (ANN), Support Vector Machine (SVM), Boosted Regression Tree (BRT), Generalized Additive Model (GAM), Genetic Algorithm Rule-Set Production (GARP), and Quick Unbiased Efficient Statistical Tree (QUEST)). For multi-hazard impact assessment detailed damage records should be available for administrative units (e.g. countries or related to past disaster events, such as hurricanes. The associated information on the hurricane characteristics (location, magnitude) should also be known. Through methods such as Light Gradient Boosting (LGB) the long term impact can be assessed by using a synthetic dataset of hurricanes. The method can also be used as a basis for Impact-Based Forecasting where a real-time impact calculation is done based on the location and magnitude of an approaching hurricane and its expected trajectory (Kooshi et al., 2024)

4.4 Tools for multi-hazard risk assessment

There are also a number of tools developed for multi-hazard risk assessment that could be of use in the Caribbean context. Annex 12 gives an overview.
In the Caribbean region the SPHERA model is used to:

- Produce ex-ante estimates of future EQ- and TC-induced losses in the countries to be used for parametric insurance policy pricing
- Estimate in near real time the modelled losses to buildings and infrastructure due to earthquake ground motion and to TC-induced wind and storm surge caused by events in the region
- Compute the payout to the insured countries due to the occurrence of an earthquake or a tropical cyclone according to the event parameters defi ned by United States Geological Survey (USGS) and the United States National Oceanic and Atmospheric Administration (NOAA)

Chapter 5. Recommended Multi-hazard Risk Assessment Approaches

Based on the review of international frameworks, scientific literature, the inventory of previous work done on multi-hazard risk assessment in The Caribbean, and the stakeholder consultations, the framework was developed. The central question in the framework is:

What is the most appropriate and feasible Multi-Hazard Risk Assessment approach in different situations, considering many factors?

The proposed methods should be appropriate for the intended goals (risk reduction applications), multi-hazard interrelations, dynamics of assets and vulnerability, and climate change scenarios. The proposed methods should also be feasible given the data availability, the spatial scale at different administrative levels, and the level of expertise available. Further, accuracy and precision play a role in the selection of risk assessment approaches. This refers both to the available input data but also to the chosen method of risk assessment, which may vary from qualitative to quantitative.

5.1 Consequences of hazard interaction for multi-hazard risk assessment

The first aspect to consider is the applicability of the methods for the various hazard interactions. Liu et al (2016) and Pasino et al. (2021) provide an overview of the quantitative methods for myulti-hazard risk assessment. Table 8.1 gives an overview of the consequences of the events relations listed in Chapter 5. Examples of the assessment of exposure, vulnerability, and risk for various multi-hazard risk cases are presented in Table 5.1 for independent, compounding, and cascading events. For compounding events, the time between successive events is very important in terms of recovery. As indicated in Table 5.1, compounding events that are occurring simultaneously (for example, because they are coupled by the same triggering event) can be properly considered in a risk assessment study that looks at possible future events. Consecutive events that occur during the recovery of a previous event are much more difficult to take into account in a risk assessment due to the unknown time period between future successive events and the unknown rate of recovery from the previous event, although for the latter recovery from historical extreme events could be considered. In such cases, scenario-based risk assessment is the best option. For cascading events, the problem is often more related to the uncertainty in modeling the cascading events spatially and temporally due to uncertainty in input data and the inadequacy of the hazard intensity modelling.

5.2 Suitability of MHRA for Early Warning and IBF

One of the most important applications of MHRA is for Multi-Hazard Early Warning Systems (MHEWS) and Impact-Based Forecasting (IBF).

The Climate Risk Early Warning Systems (CREWS) initiative, supported by the World Meteorological Organization (WMO), aims to improve early warning systems for multiple hazards in the Caribbean (48). CREWS provides technical assistance and capacity building to enhance hydrometeorological services, ensuring that risk assessments incorporate real-time data and impact-based warnings (Ibid).

Table 5.1: Consequences of hazard assessment approaches for the different types of multi-hazard interrelations.

Hazard interrelation	Vulnerability Assessment	Exposure Assessment	Loss assessment
Independent events	Standard set of vulnerability curves used for the assets. Separate assessment.	Independently calculated for each event with a certain frequency	Independently calculated for each event. Average Annual Losses are added.
Simultaneous events	Ideally: use two-dimensional vulnerability surface	Exposure by one or both events should be analyzed	Combined losses (alt. only the maximum losses)
Trigger coupled events	Ideally: use two-dimensional vulnerability surface	Exposure by one or both events should be analyzed	Combined losses (alt. only the maximum losses)
Cascading events	Use vulnerability curves that are lowered due to previous damage	Exposure depends on loss of previous (exclude destroyed)	Losses of each step are combined
Consecutive events	Use vulnerability curves that are lowered due to previous damage	Exposure depends on loss of previous (exclude destroyed)	Losses of each step are combined

CREWS promotes the use of multi-hazard early warning systems (MHEWS) that address a range of risks, including hurricanes, floods, and droughts (48). By improving the accuracy and timeliness of early warnings, CREWS enhances disaster preparedness and response capabilities across the Caribbean (ibid).

Impact-Based Forecasting is a near real-time estimation of expected losses, considering the forecasted hazard trigger (e.g tropical storms, rainfall, flooding, drought). The approach can be based on actual continuous modelling of hazards, exposure, vulnerability, and losses or based on machine learning approaches. The models should be fast enough to run in real time for process-based modelling. The method requires a direct coupling with real-time hazard forecasting. Depending on the data availability, three different approaches for the MHRA component could be selected:

- Indicator-based approach, linked with a single scenario impact model
- Quantitative single impact model, linked with physically based modelling of hazard events.
- AI approach linked with a database of previously modelled events.
- AI approach based on a dataset of damage data.

5.3 Suitability of MHRA for Risk Financing

Parametric insurance products are insurance contracts that make payments based on the intensity of an event (for example, hurricane wind speed, earthquake intensity, volume of rainfall) and the amount of loss calculated in a pre-agreed model caused by these events (CCRIF, 2019).

The selection of a parametric instrument as a basis for the CCRIF policies was largely driven by the fact that parametric insurance is generally less expensive than an equivalent traditional indemnity insurance product as it does not require a loss assessment procedure in case of a disaster. Parametric insurance also allows for claims to be settled quickly. However, despite the many benefits to parametric insurance, parametric products are exposed to basis risk, i.e., the possibility that calculated or modelled losses may be higher or lower than actual losses on the ground. Although this is a significant challenge in terms of the development of a parametric instrument, careful design of input parameters (identified in specially prepared country risk profiles) and the loss model as undertaken by CCRIF helps reduce the basis risk (CCRIF, 2023). As indicated before the Caribbean Catastrophe Risk Insurance Facility (CCRIF) has developed its own tool for probabilistic risk assessment for tropical cyclones(wind and storm surge) and earthquakes in the SPHERA model, and for extreme rainfall through the XSR model. These run at coarse resolution (900 m pixels) and give information for an entire country. They are not designed to provide information at higher levels of details, as for that the exposure data is not sufficient and the hazard outputs are not spatially varying sufficiently (e.g. in order to capture the spatial variation in wind or flood occurrence).

5.4 Summary of suitable of MHRA approaches

While Caribbean nations have made significant progress in implementing multi-hazard risk assessments, several challenges remain. Nevertheless, despite these challenges, MHRA presents significant opportunities for improving resilience in the Caribbean. By integrating scientific data, community participation, and regional collaboration, Caribbean nations can better understand and mitigate the risks posed by multiple hazards.

Multi-hazard risk assessment is a vital tool for reducing disaster risks and building resilience in the Caribbean. The region’s vulnerability to hurricanes, earthquakes, floods, and other hazards necessitates a comprehensive approach that considers the interactions between hazards, exposure, and vulnerability. Methodologies such as probabilistic risk assessment, deterministic scenario analysis, geospatial risk mapping, and community-based assessments provide valuable insights into the risks facing Caribbean nations.

Guidelines from organisations like CDEMA, CHARIM, and CREWS ensure that MHRA is conducted using standardised, scientifically sound procedures. By leveraging these tools and guidelines, Caribbean nations can enhance their disaster preparedness, improve early warning systems, and build more resilient communities in the face of an increasingly uncertain climate future. Table 5.2 gives the recommended methods for multi-hazard risk assessment in The Caribbean based on the aspects discussed in the earlier sections. In this table, only those combinations of administrative level and DRR application that are common in The Caribbean are indicated, based on the information from earlier tables. Chapter 2 gave an overview of the policy, planning, and management activities that require risk information and the main requirements at national, provincial, and local levels. Chapters 3 showed the data availability and recommended hazard assessment approaches for different hazards. Chapter 3 also presented the recommended elements-at-risk and vulnerability approaches for each scale. These, in combination with the method for multi-hazard risk assessment presented in Chapter 4, provide the basis for the recommended approaches in Table 5.2.

It matters a lot here whether the main event has already taken place (e.g., a sequence of events that can be learned using forensic analysis and impact chains) or whether the sequence and location of possible events are not know.

Table 5.2:: Recommended multi-hazard risk assessment approaches for DRM applications at different levels. Boxes shaded with horizontal lines are combinations of applications that are mostly done at another level.

Multi-Hazard Risk Assessment Methods and Applications				
	Applications	**Regional Level (< 1:100,000; Grid > 20 m)**	**National level (1:25,000-1:100,000; Grid 5-20 m)**	**Local / Ward level (>1:25.000, Grid< 5 m)**
Prevention & Mitigation	Prioritization DRR	Indicator Multi-Criteria Evaluation	Indicator Multi-Criteria Evaluation	Multi-Criteria &, Community-Based DRA
	Environment Assessment	Indicator Multi-Criteria Evaluation	Indicator Multi-Criteria Evaluation	Multi-Criteria &, Community-Based DRA
	Risk informed planning	Not a suitable scale for this	Simplified QRA, Risk Matrix, Indicator Multi Criteria Evaluation	Scenario-based risk assessment, Risk Matrix Approach
	Regulatory zoning and building regulations	Probabilistic risk analysis	Simplified QRA	Simplified QRA
	Design of risk mitigation measures	Not a suitable scale for this	Impact chains, Event-tree analysis, Simplified & Probabilistic risk analysis	Impact-chains, Community-Based, Simplified & Probabilistic risk assessment
	Planning critical infrastructure and essential facilities	Impact chains, Event-tree analysis, Simplified & Probabilistic risk analysis	Impact chains, Event-tree analysis, Simplified & Probabilistic risk analysis	Impact-chains, Community-Based, Simplified & Probabilistic risk assessment
	Risk financing instruments	Probabilistic risk analysis	Probabilistic risk assessment	Not a suitable scale for this
Response & Recovery	Multi-Hazard Early warning	Impact chain analysis Scenario-based analysis	Impact chain analysis Scenario-based analysis	Impact chains analysis, Community-Based DRA, Scenario-based analysis
	Impact based forecasting	Indicator-based & AI	Physical modelling & AI	
Preparedness	Disaster Response Planning	Impact chains Scenario-based analysis	Impact chains, Scenario-based analysis	Impact chains Community-based DRA scenario-based analysis
	Reconstruction planning for recovery	Impact chains, Scenario-based analysis, Multi-criteria evaluation	Impact chains, Scenario-based risk assessment, Multi-criteria evaluation, Risk Matrix approach	Impact chain analysis, Community-based DRA, Scenario-based risk assessment

To conclude this chapter, it is relevant to express the responsibilities of the stakeholders involved in carrying out the MHRA for different applications, as well as the costs and time required to do this. The various administrative levels have different responsibilities outlined in the framework. In municipalities with limited (human) resources, the MHRA should be carried out mostly by consultants, often with the support from development partners and NGOs, with oversight by municipal engineers. In municipalities with more resources, the technical staff of the municipality itself might lead in collaborating with consultants, academic institutions, and national expert organizations. At the provincial and basin levels, the various district authorities will be responsible for issuing the MHRA, which will be carried out mostly by consultants, academia, and national expert organizations. At the national level, the national expert organizations (CIMH, UWI Seismic etc.) have a leading role. At all levels, the Task Force for MHRA will have a leading role, with CDEMA as the coordinating agency for issuing the guidelines on the approaches to be adopted and on the dissemination of the resulting hazard, vulnerability, capacity, and risk information. ODMs and CDEMA also play a crucial role in initiating the regular updating of MHRA data based on new developments in future climate, hazard, and exposure scenarios. ODMs and CDEMA should actively support risk-informed decision -making at the Risk management cycle for informed decision-making.

In terms of the final selection of the risk assessment method for specific policy, management, or planning activities, stakeholders that are responsible for the development of Terms of Reference for risk assessment projects should clearly state the following:

- The purpose of the multi-hazard risk assessment.
- The requirements in terms of the risk results (qualitative, semi-quantitative, quantitative) and metrics (number of assets losses, population exposed, casualties, monetary losses).
- The spatial units for the risk assessment (administrative units or smaller subdivisions, based on boundaries provided by the stakeholders themselves). Risk assessment should not be carried out at a pixel level (as these are not linked to administrative units and provide a false sense of detail) or at an individual building level (due to privacy reasons).
- A detailed explanation of the method used and the assumptions.
- A detailed explanation of the legend of the resulting risk map should always be provided.

Chapter 6. Recommendations for Enhancing Multi-Hazard Risk Assessment in the Caribbean

The Caribbean is one of the most hazard-prone regions globally, facing various risks, including hurricanes, earthquakes, floods, volcanic eruptions, and the growing impacts of climate change. Multi-hazard risk assessment (MHRA) is essential for improving regional disaster preparedness, mitigation, and resilience. However, significant gaps and challenges remain, such as limited institutional capacity, fragmented data, and inadequate coordination. Five key recommendations are proposed to strengthen the MHRA in the Caribbean based on the analysis of these challenges.

Enhance Regional Coordination and Centralise Data Management

A more coordinated regional approach is critical to overcoming fragmented institutional responsibilities in the Caribbean. The Caribbean Disaster Emergency Management Agency (CDEMA) should enhance its role as the central coordinating body for multi-hazard risk assessment. Establishing a regional hub for hazard data housed under CDEMA or another regional organisation would improve information sharing across countries and institutions.

This hub could act as a data repository where all relevant national agencies upload their hazard-related data, including meteorological, seismic, and socio-economic data. Additionally, this would facilitate regional-level analysis and offer small countries without the capacity to conduct comprehensive assessments access to the necessary data. Collaborative regional partnerships and common data standards would be needed to ensure data compatibility and utility for all stakeholders (Simpson et al., 2020).

Invest in Capacity Building for National and Local Agencies

Many Caribbean nations face challenges related to limited technical capacity, which hinders the effectiveness of their multi-hazard risk assessments. A concerted effort should be made to invest in human resource development across national disaster management agencies. Specialised training in areas like Geographic Information Systems (GIS), remote sensing, climate modelling, and hazard mapping is essential to building technical expertise.

Capacity-building initiatives can be supported through partnerships with regional universities, international organisations, and specialised training programs. For example, the Caribbean Institute for Meteorology and Hydrology (CIMH) could play a more prominent role in providing technical training for national agencies (Mycoo et al., 2017). Target training for women-led community organisations and SIDS (Small Island Developing States) with limited resources. These capacity-building efforts would ensure that countries are better equipped to conduct comprehensive risk assessments and integrate emerging hazards like climate change into their planning processes.

Develop Standardised Protocols for Data Collection and Sharing

One of the main challenges limiting the effectiveness of multi-hazard risk assessment in the Caribbean is the lack of standardised data formats and protocols for data sharing across institutions and countries. Developing a standardised protocol for hazard data collection, analysis, and dissemination would enhance the comparability and utility of hazard data. These protocols should address data resolution, time intervals, metadata standards, and quality control mechanisms.

By adopting UNDRR's Sendai Framework indicators for hazard data (e.g., mortality, economic loss), and standardised data collection and sharing protocols, national and regional organisations can more effectively collaborate on multi-hazard assessments. This would also allow for integrating data from different hazard types, such as combining meteorological data with seismic or hydrological data to assess compound risks. Initiatives such as the Caribbean Climate Online Risk and Adaptation Tool (CCORAL) have already laid the groundwork for such standardised approaches, but more widespread implementation is needed.

Promote Public-Private Partnerships (PPPs) for Hazard Monitoring and Data Acquisition

The private sector can play a crucial role in enhancing multi-hazard risk assessment capabilities in the Caribbean. Public-Private Partnerships (PPPs) can facilitate investments in advanced hazard monitoring technologies, such as high-resolution satellite imagery, early warning systems, and real-time monitoring networks. For example, telecommunications companies could be enlisted to support disaster early warning systems, while insurance companies could contribute to risk assessments through data on vulnerability and exposure (Pandey and Bradley, 2013).

Additionally, PPPs can foster innovation by leveraging private sector expertise in data analytics, artificial intelligence, and geospatial technologies. Governments and regional organisations should engage with the private sector to develop shared risk assessment platforms, incentivise data sharing, and co-invest in monitoring infrastructure.

Strengthen Community-Based Hazard Assessments

While regional and national multi-hazard assessments are critical, integrating community-based hazard assessments is essential to provide local-level insights into vulnerability and risk. Many communities in the Caribbean are highly exposed to hazards, but they cannot often participate in top-down risk assessment processes. Therefore, governments and NGOs should work to include community stakeholders in hazard mapping and vulnerability assessments.

Community-based approaches ensure that local knowledge about hazards, particularly those related to slow-onset events like droughts or sea-level rise, is incorporated into broader risk assessments. Engaging local communities in hazard assessments can also improve the accuracy of exposure data, especially in informal settlements or remote areas where data collection by national agencies may be limited (Liu et al. 2018). Additionally, this approach empowers communities to take ownership of disaster preparedness and risk reduction efforts.

Conclusion

Addressing the challenges of multi-hazard risk assessment in the Caribbean requires a multi-faceted approach that enhances regional coordination, invests in technical capacity, and improves data sharing. By strengthening regional and local partnerships, adopting standardised data protocols, and engaging with the private sector and relevant international partners, the region can improve its capacity to assess and mitigate multiple hazards. Additionally, integrating community-based assessments ensures that risk management strategies are grounded in local realities, making them more effective in building resilience. Implementing these recommendations will enhance the Caribbean's ability to cope with its unique vulnerability to natural hazards and the growing impacts of climate change.

References

Abdulkadri A, Evans A, Ash T. 2016. An assessment of big data for official statistics in the Caribbean: Challenges and opportunities. 2016.

AdaptAction 2022. Regional forecast-based financing for hurricanes in the Eastern Caribbean: A feasibility study. https://www.climatecentre.org/downloads/files/Forecast%20based%20early%20action_Final_11%20June.pdf

ACPS 2023. EDF 11 Intra-ACP Basic Projects Inventory Matrix. Brussels: Organisation of African, Caribbean and Pacific States

Aguilar, A. G., and F. M. L. Guerrero. 2022. "Urban Poverty and Social Inequality in Latin America and the Caribbean: Social Vulnerability in the Era of Sustainable Development." In *The Routledge Handbook of Urban Studies in Latin America and the Caribbean*, 257-285. Routledge.

Alexander D, Pescaroli G. (2019) What are cascading disasters? UCL Open: Environment;(1):03. Available from: https://dx.doi.org/10.14324/111.444/ucloe.000003

Alexander, K., and G. Thongs. 2023. "Designing a Drought Monitoring System for Caribbean Sids." Journal of Geoscience and Environment Protection 11 (2): 69-89.

Al Hudaib, H. T., and R. P. Ray. 2023. "The Methodologies and Main Challenges of Assessment the Multi-Hazard Interaction and Risk Management Associated with Roads Infrastructures and Dam Safety: A Review." International Journal of Integrated Engineering 15 (7): 174-188.

AMA 2016. Cuba Methodologies For Determining Disaster Risks At Local Level. Risk Assessment Group of the Environment Agency (AMA), under the Ministry of Science, Technology and Environment (CITMA), with support from UNDP. https://www.cdema.org/virtuallibrary/index.php/cdm-sector-resources-2?task=download.send&id=380&catid=71&m=0

Amat NB, Bonilla LR, Parkinson J. 2022 Using Climate Risk and Vulnerability Assessments to Prioritise Caribbean Road Investments. Proceedings of the Institution of Civil Engineers - Engineering Sustainability. 2022;175(5):224-35

Amelia, P., D. Meigawati, and R. H. Sampurna. 2023. "Strategy of the Regional Disaster Management Agency in Tackling Disasters in Sukabumi City." Jurnal Ilmiah Ilmu Administrasi Publik 13 (1): 11. https://doi.org/10.26858/jiap.v13i1.43277. https://dx.doi.org/10.26858/jiap.v13i1.43277.

Arango, E., M. Nogal, M. Yang, H. S. Sousa, M. G. Stewart, and J. C. Matos. 2023. "Dynamic Thresholds for the Resilience Assessment of Road Traffic Networks to Wildfires." Reliability Engineering & System Safety 238: 109407. https://doi.org/https://doi.org/10.1016/j.ress.2023.109407. https://www.sciencedirect.com/science/article/pii/S0951832023003216.

Argyroudis, S.A. Mitoulis, M.G. Winter, A.M. Kaynia.Fragility of transport assets exposed to multiple hazards: State of the art review toward infrastructural resilience.Reliab. Eng. Syst. Saf., 191 (2019), Article 106567

Atun, F., Sliuzas, R., Romagnoli, F., Armas, I., Mocanu, R., Kundak, S. (2024). Forensic Analysis of Historical Disasters to Develop Quantifiable Multi-hazard Impact Chains Models. In: Erberik, M.A., Askan, A., Kockar, M.K. (eds) Proceedings of the 7th International Conference on Earthquake Engineering and Seismology. ICEES 2023. Lecture Notes in Civil Engineering, vol 401. Springer, Cham. https://doi.org/10.1007/978-3-031-57357-6_40

Ayala, J. J. H., and M. Heslar. 2019. "Examining the Spatiotemporal Characteristics of Droughts in the Caribbean Using the Standardised Precipitation Index (Spi)." Climate Research 78 (2): 103-116.

Baboolal H, Stoute V, Chadee S, Balladin D.2019 Statistical air pollution index (API) for Trinidad and Tobago based on observed data on Trinidad's West Coast. Journal of Geoscience and Environment Protection. 2019;7(10):120.

Bacarreza, G. J. C., A. Conconi, S. Olivieri, and M. Serio. 2024. "Understanding Vulnerability to Poverty and Natural Disasters in Latin America and the Caribbean."

Baird. 2016. CRMP Sediment Transport Study – Final Report – 2.6 – Coastal Risk Assessment and Management Program – Provision of Consulting Services of Contract 1 of Components 1&2. Submitted April 22, 2015, revised June 28, 2016.

Baird. 2017. National Coastal Risk Information and Planning Platform – Final Hazard Report. Prepared for the Coastal Zone Management Unit of the Government of Barbados. St. Michael, Barbados.

Baksh, M. A. 2022. "Future Work Plans for the Caribbean Region: The Caribbean Disaster Emergency Management (Cdema)." Strengthening environment, climate change and disaster information in the Caribbean, Santiago, Chile.

Barker, D. 2012. "Caribbean Agriculture in a Period of Global Change: Vulnerabilities and Opportunities." Caribbean Studies 40 (2): 41-61.

Barclay J, Wilkinson E, White C, Shelton C, Forster J, Few R, et al.2018 Historical Trajectories of Disaster Risk in Dominica. 2018

Becker A, Hallisey N, Bove G. 2021 Toward regional hazard risk assessment: a method to geospatially inventory critical coastal infrastructure applied to the Caribbean. Journal of Infrastructure Preservation and Resilience. 2021;2(1):13.

Beharry, S. L., D. Gabriels, D. Lobo, and R. M. Clarke. 2019. “A 35-Year Meteorological Drought Analysis in the Caribbean Region: Case Study of the Small Island State of Trinidad and Tobago.” SN Applied Sciences 1: 1-16.

Bell, R. and Glade, T.: Quantitative risk analysis for landslides – Examples from Bíldudalur, NW-Iceland, Nat. Hazards Earth Syst. Sci., 4, 117–131, https://doi.org/10.5194/nhess-4-117-2004, 2004.

Bertolotto M, McArdle G, Schoen-Phelan B. 2020. Volunteered and crowdsourced geographic information: the OpenStreetMap project. Journal of Spatial Information Science. 2020;20

Bloemendaal, N Carine Homan, Iris Keizer, Eva van der Kooij, Frédérik Ruijs, Peter Siegmund, Bart Verheggen. De staat van ons klimaat in 2023 = The state of Our Climate in 2023: Weather in Caribbean Netherlands in a Changing Climate = Estado di nos Klima 2023: Wer na Hulanda Karibense den tempunan di kambio di Klima KNMI number: KNMI-publicatie-24-02, Year: 2024, Pages: 20

Boger, R., and S. Perdikaris. 2022. “Water Use and Availability on Barbuda from the Colonial Times to the Present: An Intersection of Natural and Social Systems.” In Barbuda, 40-58. Routledge India.

Bozzoni, F., M. Corigliano, C. Lai, W. Salazar; L. Scandella, E. Zuccolo, J. Latchman; L. Lynch; R. Robertson (2011) Probabilistic Seismic Hazard Assessment at the Eastern Caribbean Islands, Bulletin of the Seismological Society of America. 101(5):2499-2521

Brink Ut, Flores C. 2018 Caribbean Tsunami and Earthquake Hazards Studies Woods Hole, MA: Woods Hole Coastal and Marine Science Center , USGS; 2018 [updated August 21, 2018. Available from: https://www.usgs.gov/centers/whcmsc/science/caribbean-tsunami-and-earthquake-hazards-studies.

Burón, L. L. 2022. "The Caribbean Consolidates Its Partnership for Advancing Multi-Hazard Early Warning Systems in the Region." UNDRR. Accessed October 8. https://www.undrr.org/news/caribbean-consolidates-its-partnership-advancing-multi-hazard-early-warning-systems-region.

CADRI 2020. Compendium of Good Practices on Community Based Disaster Risk Management. Capacity for Disaster Risk Reduction Initiative. https://www.cadri.net/system/files/2021-09/CADRI%20-%20Good%20Practices%20-%20CBDRM_2020.pdf

CANARI (2023) CSOs for Disaster Resilience: Empowering civil society and local communities to build resilience to hurricanes and climate extremes in the Eastern Caribbean. Caribbean Natural Resources Institute. https://canari.org/csos-for-disaster-resilience/

Carbognin, L., P. Teatini, A. Tomasin, and L. Tosi. 2010. "Global Change and Relative Sea Level Rise at Venice: What Impact in Term of Flooding." *Climate Dynamics* 35: 1039-1047.

Carby, B. 2019. "A Knowledge Management Initiative in Support of the Caribbean Comprehensive Disaster Management Framework and DRM Capacity Building." Strengthening Disaster Resilience in Small States: Commonwealth Perspectives 125: 125-142.

Carter, B., and P. Pozarny. 2016. National Disaster Management Authorities. GSDRC Helpdesk Research Report 1359.

Cashin, P. 2006. "8 Government Responses to Natural Disasters in the Caribbean." In The Caribbean: From Vulnerability to Sustained Growth, edited by David Robinson, Paul Cashin and Ratna Sahay. Washington, DC.: International Monetary Fund.

Cashman, A. 2014. Water Security and Services in the Caribbean. *Water*, *6*(5), 1187-1203. https://doi.org/10.3390/w6051187

Cashman, A. C., L. A. Nurse, and J. Charlery. 2010. “Climate Change in the Caribbean: The Water Management Implications.” The Journal of Environment & Development 19 (1): 42-67. https://doi.org/10.1177/1070496509347088.

Castillo GB. 2018. Multi-Hazard Model for Developing Countries. Natural Hazards. 2018;92(2):1081-95

Cavallo, E. A., S. Gómez, I. Noy, and E. Strobl. 2024. "Climate Change, Hurricanes, and Sovereign debt in the Caribbean Basin."

CCCCC 2020. Caribbean Climate Resilience and Adaptation Initiatives Belmopan, Belize: CCCCC Publications.

CCCCC 2024. Caribbean Climate Online Risk and Adaptation tool (CCORAL). https://caribbeanclimate.org/tools/ccoral/

CCRIF 2019. Technical Workshop on CCRIF Models. https://www.ccrif.org/sites/default/files/publications/technical-materials/CCRIFSPC_TechnicalWorkshopManual_Barbados_March2019.pdf

CCRIF 2023. The evolution of of CCRIF’s Parametric Insurance Models. The Journey from EQECAT to SPHERA and Beyond. https://www.ccrif.org/publications/technical-paper/evolution-ccrifs-parametric-insurance-models?language_content_entity=en

CDB. 2016. Disaster Management Strategy. Barbados: Caribbean Development Bank.

CDB. 2020. Disaster Risk Reduction in the Caribbean: Integrating Disaster Risk Management into Development Planning. Barbados: Caribbean Development Bank.

CDEMA. 2009a. "About Cdm (Strategy) - the Caribbean Disaster Emergency Management Agency." CDEMA. https://www.cdema.org/cdm.

CDEMA 2009b. "Who We Are: About Us." The Caribbean Disaster Emergency Management Agency. https://www.cdema.org/index.php/about.

CDEMA 2014. Regional Comprehensive Disaster Management (Cdm) Strategy and Results Framework, 2014-2024. Barbados: Caribbean Disaster Emergency Management Agency.

CDEMA 2018. Building a Caribbean Pathway for Disaster Resilience in the Caribbean Community (Caricom). Bridgetown, Barbados: Caribbean Disaster Emergency Management Agency.

CDEMA 2014. Caribbean Disaster Emergency Management Agency (CDEMA). Regional Comprehensive Disaster Management (CDM) Strategy and Programming Framework 2014-2024. https://www.cdema.org/CDM_Strategy_2014-2024.pdf

Centella-Artola, A., A. Bezanilla-Morlot, M. A. Taylor, D. A. Herrera, D. Martinez-Castro, I. Gouirand, M. Sierra-Lorenzo, A. Vichot-Llano, T. Stephenson, and C. Fonseca. 2020. "Evaluation of Sixteen Gridded Precipitation Datasets over the Caribbean Region Using Gauge Observations." Atmosphere 11 (12): 1334

CIMH/RCC. 2007. "About the Regional Climate Centre ". CIMH. https://rcc.cimh.edu.bb/about/about-the-rcc/.

CIMH 2019. Caribbean Institute for Meteorology and Hydrology (CIMH). Drought and Flood Risk Monitoring in the Caribbean. . St. James, Barbados: CIMH Publications

CIMH 2022 CIfMaH. Annual Hurricane Activity Reports. Barbados: Caribbean Institute for Meteorology and Hydrology

Ciurean, R., Gill, J.C., Reeves, H., O'Grady, S.K., Donald, K., & Aldridge, T. (2018). Review of multi-hazards research and risk assessments, British Geological Survey Engineering Geology & Infrastructure Programme. Open Report OR/18/057, 109 pp. Available at: http://nora.nerc.ac.uk/id/eprint/524399/

CHARIM 2014. Use case 6.1 National multi-hazard exposure analysis. Caribbean Handbook on Disaster Risk Information. https://www.cdema.org/virtuallibrary/index.php/charim-hbook/use-case-book/6-risk-assessment/6-1-national-multi-hazard-exposure-analysis

CHARIM, 2017. Caribbean Handbook on Risk Information Management. https://charim.net/Zero-a

Chaulagain, D., O. F. M. Aroca, N. N. Same, A. O. Yakub, B. E. K. Nsafon, D. Suh, J. M. Triolo, and J.-S. Huh. 2023. "Extreme Dry and Wet Events in the Pacific Region of Colombia Estimated in the 21st Century Based on the Standardised Precipitation Index and Cordex Climate Projections." Atmosphere 14 (2): 260

Chen, L., Van Westen, C. J., Hussin, H., Ciurean, R. L., Turkington, T., Chavarro-Rincon, D., & Shrestha, D. P. (2016). Integrating expert opinion with modelling for quantitative multi-hazard risk assessment in the Eastern Italian Alps. *Geomorphology*, *273*, 150-167. https://doi.org/10.1016/j.geomorph.2016.07.041

Choi, E., J.-G. Ha, D. Hahm, and M. K. Kim. 2021. "A Review of Multihazard Risk Assessment: Progress, Potential, and Challenges in the Application to Nuclear Power Plants." *International Journal of Disaster Risk Reduction* 53: 101933. https://doi.org/https://doi.org/10.1016/j.ijdrr.2020.101933.

Clement, C. 2014. "International Disaster Response Laws, Rules, and Principles: A Pragmatic Approach to Strengthening International Disaster Response Mechanisms." In The International Law of Disaster Relief, edited by David D. Caron, Michael J. Kelly and Anastasia Telesetsky, 67-88. Cambridge: Cambridge University Press

Climate Studies Group Mona (Eds.). 2020. "The State of the Caribbean Climate". Produced for the Caribbean Development Bank.

Cocuccioni, S., Romagnoli, F., Pittore, M., Ergün Konukçu, B., Kundak, S., Göksu, Ç., Aşıcı, A., Arslanlı, K., Kalkanlı, D., Pak, E. Ö., Savelberg, L., Kalubowila, P., Armas, I., Danila, D. T., Osaci, G., Albulescu, C., Wenzel, T., Marr, P., Atun, F., ... Witvliet, B. (2023). Report on participatory workshops in the four application case study sites, including impact chains diagrams for each analysed event (Version 3). Zenodo. https://doi.org/10.5281/zenodo.8200493

Collymore J. 2011 Disaster management in the Caribbean: Perspectives on institutional capacity reform and development. Environmental Hazards. 2011;10:6-22.

Collymore, J. 2016. ''Early Warning Systems in The Caribbean: A Desk Review''.

Collymore, J. 2020. ''Final Model National Multi-Hazard Early Warning Systems''. European Civil Protection and Humanitarian Aid Operations (ECHO).

CORDIS 2024. CORDIS – EU Research results on Multi-Hazard risk. https://cordis.europa.eu/search?q=%27Multi%27%20AND%20%27Hazard%27%20AND%20%27risk%27&p=1&num=10&srt=Relevance:decreasing&archived=true

CRCC 2024. Dry Spell Outlook Experimental Barbados: Caribbean Institute for Meteorology and Hydrology; https://rcc.cimh.edu.bb/dry-spells-outlook-experimental/.

CRIS 2024. Caribbean Risk Information System. https://www.cdema.org/virtuallibrary/index.php

CROSQ 2020. "Crosq: About Us- Organisation." CROSQ. Accessed October 9. https://website.crosq.org/organisation/.

CTO. 2020. "CTO Produces Multi-Hazard Risk Management Guide for Caribbean Tourism." Caribbean Tourism Organisation. Last Modified Noverber 13, 2020. Accessed October 8. https://www.onecaribbean.org/cto-produces-multi-hazard-risk-management-guide-for-caribbean-tourism/.

Daley, O., W.-A. P. Isaac, A. John, R. Roopnarine, and K. Forde. 2022. "An Assessment of the Impact of Covid-19 on the Agri-Food System in Caribbean Small Island Developing States." Frontiers in Sustainable Food Systems 6: 861570.

De Angeli, S., Malamud, B. D., Rossi, L., Taylor, F. E., Trasforini, E., & Rudari, R. (2022). A multi-hazard framework for spatial-temporal impact analysis. *International Journal of Disaster Risk Reduction*, *73*, 102829. https://doi.org/10.1016/j.ijdrr.2022.102829

de Beurs K, McThompson N, Owsley B, Henebry G. 2019. Hurricane damage detection on four major Caribbean islands. Remote Sensing of Environment. 2019;229:1-13. DOI: 10.1016/j.rse.2019.04.028

de Hamer, J. 2019. "Disaster Governance on St. Maarten." A study on how disaster governance in combination with St. Maarten's development affected the disaster response in the wake of Hurricane Irma, Development and Rural Innovation: 101.

Delmonaco et al., 2006 Delmonaco, Giuseppe et al. "ARMONIA methodology for multi-risk assessment and the harmonisation of different natural risk map.". https://www.scribd.com/document/616732009/ARMONIA-PROJECT-Deliverable3-1

Depsky, N., and D. Pons. 2020. "Meteorological Droughts Are Projected to Worsen in Central America's Dry Corridor Throughout the 21st Century." Environmental Research Letters 16 (1): 014001

De Ruiter, M.C. , Ward, P. J., Daniell, J. E., and Aerts, J.C. (2017). A comparison of flood and earthquake vulnerability assessment indicators. Nat. Hazards EarthSyst.Sci.17,1231–1251

de Ruiter, M. C., and A. F. van Loon. 2022. "The Challenges of Dynamic Vulnerability and How to Assess It." *iScience* 25 (8): 104720. https://doi.org/https://doi.org/10.1016/j.isci.2022.104720.

DesInventar (2024) DesInventar Sendai. Disaster los data for Sustainable Development Goals and Sendai Framework Monitoring System. https://www.desinventar.net/

DeVito R, Landeen E, Dyjack D, Labbo R, Gill G, Gerding J, et al. 2022 Rebuilding Caribbean Environmental Health Post-Crisis Programs: Case Study for Virtual Mentorship. 2022

DFID 2023. Multi-Hazard Disaster Risk Assessment (v2) Guidance Notes to assist DFID country offices. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/204933/Multi-hazard_risk_assessment_guidance.pdf

Docherty JM, Mao F, Buytaert W, Clark J, Hannah DM. 2020. A Framework for Understanding Water-Related Multi-Hazards in a Sustainable Development Context. Progress in Physical Geography Earth and Environment. 2020;44(2):267-84

Dominica, 2017. Government of the Commonwealth of Dominica, 2017. Post-disaster Needs Assesment. Hurricane Maria, September 18, 2017. https://www.gfdrr.org/en/dominica-hurricane-maria-post-disaster-assessment-and-support-recovery-planning

Dookie, D. S., and J. Spence-Hemmings. 2022. "The Timing of Storm Awareness in the Caribbean: The Utility of Climate Information for Improved Disaster Preparedness." Disasters 46: S101-S127.

Dubrie A, Emanuel E, Grant V, Opadeyi J. 2023. Advancing geospatial information management for disaster risk management in the Caribbean. 2023

Dunant, A., Bebbington, M., & Davies, T. (2021). Probabilistic cascading multi-hazard risk assessment methodology using graph theory, a New Zealand trial. *International Journal of Disaster Risk Reduction*, *54*, 102018. https://doi.org/10.1016/j.ijdrr.2020.102018

Eberenz, S., Lüthi, S. & Bresch, D. N. 2021 Regional tropical cyclone impact functions for globally consistent risk assessments. *Nat. Hazards Earth Syst. Sci.* **21**, 393–415. https://doi.org/10.5194/nhess-21-393-2021 (2021)

ECLAC 2004. Mainstream Disaster Planning and Management in the Preparation and Implementation of Land Use Plans Santiago: ECLAC; 2004

ECLAC 2024. Demographic Observatory Latin America and the Caribbean 2023. Population dynamics in Latin America and their effects on the labour force. Santiago: ECLAC; 2024.

Eckstein, D. , Künzel,V. and Schäfer, L., 2021. Global Climate Risk Index 2021: Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2019 and 2000–2019. Berlin: Germanwatch.

ELeader. 2024. "The 2024 Atlantic Hurricane Season: A Critical Turning Point." E=E Leader. Last Modified October 15. Accessed October 15.

Elusma, M., C.-p. Tung, and C.-C. Lee. 2022. "Agricultural Drought Risk Assessment in the Caribbean Region: The Case of Haiti." International Journal of Disaster Risk Reduction 83: 103414.

EM-DAT, CRED / UCLouvain, 2024, Brussels, Belgium – www.emdat.be

Euphrasie-Clotilde L, Molinié J, Feuillard T, Brute F. 2017 The relationship between coastal West African dust level and Caribbean island dust. WIT Transactions on Ecology and the Environment. 2017;211:121-7.

EurOtop (2016). Manual on wave overtopping of sea defences and related structures. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schuttrumpf, H., Troch, P. and Zanuttigh, B. Second Edition. URL: www.overtopping-manual.com.

Eppinga, M. B., and C. A. Pucko. 2018. "The Impact of Hurricanes Irma and Maria on the Forest Ecosystems of Saba and St. Eustatius, Northern Caribbean." *Biotropica* 50 (5): 723-728

Evanson, Danielle. 2021. ''Multi-Hazard Early Warning Systems (MHEWS) Checklist and Analysis in the Caribbean: Regional Summary Report''. https://wrd.unwomen.org/sites/default/files/2022-03/Multi-Hazard%20Early%20Warning%20Systems%20Checklist_v6.pdf

Farrell, D. A., A. R. Trotman, and C. Cox. 2010. Drought Early Warning and Risk Reduction: A Case Study of the Caribbean Drought of 2009-2010. ISDR. United Nations.

FEMA (2005). Final draft guidelines for coastal flood hazard analysis and mapping for the Pacific coast of the United States. Report prepared by Northwest Hydraulic Consultants. Federal Emergency Management Agency

FEMA: Multi-hazard loss estimation methodology: flood model, Department of Homeland Security and Federal Emergency Management Agency, Washington, D.C., 569 pp., https://www.fema.gov/sites/default/files/2020-09/fema_hazus_flood-model_technical-manual_2.1.pdf (last access: 28 November 2024), 2013.

FEMA: Hazus Earthquake Model Technical Manual: Hazus 4.2 SP3, Federal Emergency Management Agency, 436 pp., https://www.fema.gov/sites/default/files/2020-10/fema_hazus_earthquake_technical_manual_4-2.pdf (last access: 28 November 2024), 2020.

FEMA: Hazus Hurricane Model Technical Manual: Hazus 4.2 Service Pack 3, Federal Emergency Management Agency, 624 pp., https://www.fema.gov/sites/default/files/documents/fema_hazus-hurricane-technical-manual-4.2.3_0.pdf (last access: 28 November 2024), 2021a.

FEMA: Hazus Inventory Technical Manual: Hazus 4.2 Service Pack 3, Federal Emergency Management Agency, 185 pp., https://www.fema.gov/sites/default/files/documents/fema_hazus-inventory-technical-manual-4.2.3.pdf (last access: 28 November 2024), 2021b.

FEMA. (2020). Hazus Technical Manual. [FEMA Hazus](https://www.fema.gov/hazus).

Fernández TD, Crompvoets J, editors. 2008 Evaluating Spatial Data Infrastructures in the Caribbean for sustainable development. Proceedings of the 10th GSDI conference; 2008.

Filimonau, V., and D. De Coteau. 2020. "Tourism Resilience in the Context of Integrated Destination and Disaster Management (Dm²)." *International Journal of Tourism Research* 22 (2): 202-222. https://doi.org/10.1002/jtr.2329. https://dx.doi.org/10.1002/jtr.2329.

Fobert M-A, Singhroy V, Spray JG. 2021. InSAR Monitoring of Landslide Activity in Dominica. Remote Sensing. 2021;13(4):815. https://doi.org/10.3390/rs13040815

Forde, M.S., Cashman, A. & Mitchell, K. Sustainability of water resources in Caribbean small island developing states: an overview. *Discov Sustain* **5**, 265 (2024). https://doi.org/10.1007/s43621-024-00478-x

Forde M, Morrison K, Dewailly E, Badrie N, Robertson L. 2011 Strengthening integrated research and capacity development within the Caribbean region. BMC International Health and Human Rights. 2011;11:1-11.

Fuchs, S., Heiss, K., and Hübl, J.: Towards an empirical vulnerability function for use in debris flow risk assessment, Nat. Hazards Earth Syst. Sci., 7, 495–506, https://doi.org/10.5194/nhess-7-495-2007, 2007.

Fuller, C., H. E. Kurnoth, and B. Mosello. 2020. "Climate-Fragility Risk Brief: The Caribbean."

Galasso, C., Pregnolato, M., & Parisi, F. (2021). A model taxonomy for flood fragility and vulnerability assessment of buildings. *International Journal of Disaster Risk Reduction*, *53*, 101985. https://doi.org/10.1016/j.ijdrr.2020.101985

allina, V., S. Torresan, A. Critto, A. Sperotto, T. Glade, and A. Marcomini. 2016. "A Review of Multi-Risk Methodologies for Natural Hazards: Consequences and Challenges for a Climate Change Impact Assessment." *Journal of Environmental Management* 168: 123-132. https://doi.org/https://doi.org/10.1016/j.jenvman.2015.11.011.

Gencer, E. A. 2013. An Overview of Urban Vulnerability to Natural Disasters and Climate Change in Central America & the Caribbean Region. Geneva Switzerland: UNDRR.

Gentile, R., Cremen, G., Galasso, C., Jenkins, L. T., Manandhar, V., Menteşe, E. Y., Guragain, R., & McCloskey, J. (2022). Scoring, selecting, and developing physical impact models for multi-hazard risk assessment. *International Journal of Disaster Risk Reduction*, *82*, 103365. https://doi.org/10.1016/j.ijdrr.2022.103365

GFDRR 2018. DISASTER RISK MANAGEMENT IN THE CARIBBEAN: The World Bank's Approaches and Instruments for Recovery and Resilience. https://www.gfdrr.org/sites/default/files/publication/WBG%20Caribbean%20DRM%20Engagement_web.pdf

Gill, J. C., & Malamud, B. D. (2014). Reviewing and visualizing the interactions of natural hazards. Reviews of Geophysics, 52(4), 680-722. https://doi.org/10.1002/2013RG000445

Gill, J. C., and B. D. Malamud. 2016. "Hazard Interactions and Interaction Networks (Cascades) within Multi-Hazard Methodologies." *Earth System Dynamics* 7 (3): 659-679.

Gill, J.C., Duncan, M., Ciurean, R., Smale, L., Stuparu, D., Schlumberger, J, de Ruiter M., Tiggeloven, T., Torresan, S., Gottardo, S., Mysiak, J., Harris, R., Petrescu, E. C., Girard, T., Khazai, B., Claassen, J., Dai, R., Champion, A., Daloz, A. S., … Ward, P. 2022. MYRIAD-EU D1.2 Handbook of Multihazard, Multi-Risk Definitions and Concepts. H2020 MYRIAD-EU Project, grant agreement number 101003276, pp 75.

Gionnazzi S. 2013. Shared Data Helps Caribbean Islands to be Better Prepared for Disasters Washington, D.C.: World Bank Group; 2013 [updated Feb. 28, 2013

George G, Rhodes B, Laptiste C. 2019 What is the financial incentive to immigrate? An analysis of salary disparities between health workers working in the Caribbean and popular destination countries. BMC Health Services Research. 2019;19:1-11

Glas, H., M. Jonckheere, A. Mandal, S. James-Williamson, P. De Maeyer, and G. Deruyter. 2017. "A Gis-Based Tool for Flood Damage Assessment and Delineation of a Methodology for Future Risk Assessment: Case Study for Annotto Bay, Jamaica." *Natural Hazards* 88 (3): 1867-1891. https://doi.org/10.1007/s11069-017-2920-5. https://doi.org/10.1007/s11069-017-2920-5.

Godfrey, A., Ciurean, R., Van Westen, C., Kingma, N., & Glade, T. (2015). Assessing vulnerability of buildings to hydro-meteorological hazards using an expert based approach – An application in Nehoiu Valley, Romania. *International Journal of Disaster Risk Reduction*, *13*, 229-241. https://doi.org/10.1016/j.ijdrr.2015.06.001

Goldblatt, R., N. Jones, and J. Mannix. 2020. "Assessing Openstreetmap Completeness for Management of Natural Disaster by Means of Remote Sensing: A Case Study of Three Small Island States (Haiti, Dominica and St. Lucia)." *Remote Sensing* 12 (1): 118.

Green, E 2020. Multi-Hazard Risk Management Guide for the Caribbean Tourism Sector. Caribbean Tourism Organization (CTO), https://ourtourism.onecaribbean.org/resources/mhrmg-english/

Hamer, M. J. M., P. L. Reed, J. D. Greulich, and C. W. Beadling. 2019. "Enhancing Global Health Security: Us Africa Command's Disaster Preparedness Program." *Disaster medicine and public health preparedness* 13 (2): 319-329.

Hajat A, Hsia C, O'Neill MS. 2015 Socioeconomic disparities and air pollution exposure: a global review. Current environmental health reports. 2015;2:440-50

Harbitz CB, Glimsdal S, Bazin S, Zamora N, Løvholt F, Bungum H, et al. 2012 Tsunami hazard in the Caribbean: Regional exposure derived from credible worst case scenarios. Continental Shelf Research. 2012;38:1-23.

Harvey, B., P. Cook, L. Shaffrey, and R. Schiemann. 2020. "The Response of the Northern Hemisphere Storm Tracks and Jet Streams to Climate Change in the Cmip3, Cmip5, and Cmip6 Climate Models." *Journal of Geophysical Research: Atmospheres* 125 (23): e2020JD032701.

Helbing, D. (2013). Globally networked risks and how to respond. Nature, 497(7447), 51–9.

Hernández-Delgado, E. A., P. Alejandro-Camis, G. Cabrera-Beauchamp, J. S. Fonseca-Miranda, N. X. Gómez-Andújar, P. Gómez, R. Guzmán-Rodríguez, I. Olivo-Maldonado, and S. E. Suleimán-Ramos. 2024. "Stronger Hurricanes and Climate Change in the Caribbean Sea: Threats to the Sustainability of Endangered Coral Species." *Sustainability* 16 (4): 1506.

Herron, H. , Bohn, B., Roy, S. and Evans, W. 2016 Climate Change Data and Risk Assessment Methodologies for the Caribbean. Interamerican Development Bank, Environmental Safeguards Unit. Technical Note IDB-TN-633. https://webimages.iadb.org/publications/english/document/Climate-Change-Data-and-Risk-Assessment-Methodologies-for-the-Caribbean.pdf

Herfort B, Lautenbach S, Porto de Albuquerque J, Anderson J, Zipf A. 2021 The evolution of humanitarian mapping within the OpenStreetMap community. Scientific Reports. 2021;11(1):3037.

Herrera, D. A., T. R. Ault, J. T. Fasullo, S. J. Coats, C. M. Carrillo, B. I. Cook, and A. P. Williams. 2018. "Exacerbation of the 2013–2016 Pan-Caribbean Drought by Anthropogenic Warming." Geophysical Research Letters 45 (19): 10,619-10,626. https://doi.org/https://doi.org/10.1029/2018GL079408.

Hoagland-Grey H. 2015 Climate Change Risk Management Options for the Transportation Sector. 2015.

Hochrainer-Stigler, S. , SakicTrogrlic, R., Reiter, K., Ward, P.K., de Ruiter, M.C. , Duncan, M.J. Torresan, S., Ciurean, R. , Mysiak, J., Stuparu, D. and Gottardo, S. (2023). Towards a framework for systemic multi-hazard and multi-risk assessment and management. iScience, Volume 26, Issue 5, 106736. https://doi.org/10.1016/j.isci.2023.106736

Hofman, C. L., C. E. Stancioff, A. Richards, I. Nanichi Auguiste, A. Sutherland, and M. L. Hoogland. 2021. "Resilient Caribbean Communities: A Long-Term Perspective on Sustainability and Social Adaptability to Natural Hazards in the Lesser Antilles." *Sustainability* 13 (17): 9807.

Holland, G.J., 1980. An Analytic Model of the Wind and Pressure Profiles in Hurricanes. Mon. Weather Rev. 108, 1212–1218. doi:10.1175/1520-0493(1980)108<1212:AAMOTW>2.0.CO;2

Hollenstein, K. (2005) Reconsidering the risk assessment concept: Standardizing the impact description as a building block for vulnerability assessment, Nat. Hazards Earth Syst. Sci., 5, 301–307, https://doi.org/10.5194/nhess-5-301-2005,2005

Hollis, S. 2014. "Disaster Risk Reduction in the Caribbean: Opportunities and Challenges for Achieving Greater Resilience." *Caribbean Journal of International Relations and Diplomacy* 2 (4).

Huizinga, J., De Moel, H. and Szewczyk, W., 2017. Global flood depth-damage functions: Methodology and the database with guidelines, EUR 28552 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-67781-6, doi:10.2760/16510, JRC105688.

HUMDAT, 2024. Humanitarian Data Exchange . https://data.humdata.org/

Husaini DC, Reneau K, Balam D. 2022 Air pollution and public health in Latin America and the Caribbean (LAC): a systematic review with meta-analysis. Beni-Suef University Journal of Basic and Applied Sciences. 2022;11(1):122

IDB. 2024. "IDB Joins UNDP to Support Data Systems to Tackle Climate Change in Latin America & the Caribbean." IDB. Accessed October 9.

IFRC, 2024. Vulnerability and Capacity Assessment (VCA) and other Assessment Tools https://www.rcrc-resilience-southeastasia.org/disaster-risk-reduction/community-based-disaster-risk-reduction/vulnerability-and-capacity-assessment-vca-and-other-assessment-tools/

INFORM 2024 . INFORM Risk Assessment method. https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk

INFORM 2020 . INFORM regional model of Latin America and Caribbean. https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Subnational-Risk/Latin-America-and-Caribbean/moduleId/1800/id/368/controller/Admin/action/Results

IPCC (2018). Managing the risks of extreme events and disasters to advance climate change adaptation. Intergovernmental Panel on Climate Change,Geneva. Available from: https://www.ipcc.ch

IOM. 2021 Evacuations And Disaster Risk Reduction In The Caribbean. San José, Costa Rica: International Organization for Migration; 2021

ISO/IEC. (2020), ISO/DIS 14091: Adaptation to Climate Change — Guidelines on Vulnerability, Impacts, and Risk Assessment. https://www.iso.org/obp/ui/#iso:std:iso:14091:dis:ed-1:v1:en

Jagessar, R. C. 2023 "A Review of the Effects of Global Warming on Caribbean States." The CAS23-2023 Conference on The Sustainability and Development Initiatives of the Caribbean.

Jamaica Ministry of Local Government and Community Development. (2015). Disaster Risk Management framework. [Jamaica DRMF](https://www.local.gov.jm)

Jerez Columbié, Y. 2022. "Adapting to Climate Change through Disaster Risk Reduction in the Caribbean: Lessons from the Global South in Tackling the Sustainable Development Goals." In *Creating Resilient Futures: Integrating Disaster Risk Reduction, Sustainable Development Goals and Climate Change Adaptation Agendas*, edited by Stephen Flood, Yairen Jerez Columbié, Martin Le Tissier and Barry O'Dwyer, 183-203. Cham: Springer International Publishing.

Jonckheere, M., P. De Maeyer, and G. Deruyter. 2015. "A Gis-Based Flood Risk Tool for Jamaica: The First Step Towards a Multi-Hazard Risk Assessment in the Caribbean." 15th International Multidisciplinary Scientific GeoConference & EXPO SGEM2015, Bulgaria.

Jones, E., K. Doughorty, and P. Brown. 2022. "'Building Back Better'in the Context of Multi-Hazards in the Caribbean." *Disasters* 46: S151-S165.

Jones F. 2024. Population and development in the Caribbean (2018–2023): accelerating implementation of the Montevideo Consensus. Studies and Perspectives series-ECLAC Subregional Headquarters for the Caribbean. Santiago: Economic Commission for Latin America and the Caribbean; 2024

Johnson C. 2015 Green networks : A solution to the urban heat island effect. Transactions on Ecology and The Environment. 2015;194:205-14

Joseph EP, Camejo-Harry M, Christopher T, Contreras-Arratia R, Edwards S, Graham O, Johnson M, Juman A, Latchman JL, Lynch L , et al. 2022. Responding to eruptive transitions during the 2020–2021 eruption of La Soufrière volcano, St. Vincent. Nature Communications 13:4129

Joyette ART, Nurse LA, Pulwarty RS. Disaster risk insurance and catastrophe models in risk-prone small Caribbean islands. Disasters. 2015;39(3):467-92

Joyette, A. R. T. 2015. "The Management of Drought in St. Vincent and the Grenadines: Are We There Yet." UWI Open Campus St. Vincent and the Grenadines Country Conference, Kingstown, St. Vincent, March 11-12, 2015.

Joyette, A. R. T. 2018. "Persistent Drought in the Eastern Caribbean: Observed and Projected Impacts under a Changing Climate." Doctoral Product, University of The West Indies, Cave Hill.

Kappes, M.S., Papathoma-Kohle, M., Keiler,M., (2012). Assessing physical vulnerability for multi-hazards using an indicator-based methodology. Appl.Geogr.32, 577-590. http://dx.doi.org/10.1016/j.apgeog.2011.07.002

Kappes, M.S., Keiler, M., von Elverfeldt, K. *et al.* 2012 Challenges of analyzing multi-hazard risk: a review. *Nat Hazards* **64**, 1925–1958 (2012). https://doi.org/10.1007/s11069-012-0294-2

Karatzetzou, A., S. Stefanidis, S. Stefanidou, G. Tsinidis, and D. Pitilakis. 2022. "Unified Hazard Models for Risk Assessment of Transportation Networks in a Multi-Hazard Environment." *International Journal of Disaster Risk Reduction* 75: 102960. https://doi.org/10.1016/j.ijdrr.2022.102960.

Karatzetzou, A., S. Stefanidou, G. Tsinidis, and O. Markogiannaki. 2022. *Hazard, Vulnerability and Risk Assessment of Road Networks against Multiple Natural Hazards*.

Karmalkar, A. V., M. A. Taylor, J. Campbell, T. S. Stephenson, M. New, A. Centella, A. Benzanilla, and J. Charlery. 2013. "A Review of Observed and Projected Changes in Climate for the Islands in the Caribbean." *Atmósfera* 26 (2): 283-309. https://doi.org/http://dx.doi.org/10.1016/S0187-6236(13)71076-2.

Kelman I. 2017 How Can Island Communities Deal With Environmental Hazards and Hazard Drivers, Including Climate Change? Environmental Conservation. 2017;44(3):244-53.

Knutson, T. R., M. V. Chung, G. Vecchi, J. Sun, T.-L. Hsieh, and A. J. Smith. 2021. *Climate Change Is Probably Increasing the Intensity of Tropical Cyclones*. Tyndall Centre for Climate Change Research.

Knutson, T. R., J. J. Sirutis, M. Zhao, R. E. Tuleya, M. Bender, G. A. Vecchi, G. Villarini, and D. Chavas. 2015. "Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of Cmip5/Rcp4.5 Scenarios." *Journal of Climate* 28 (18): 7203-7224. https://doi.org/https://doi.org/10.1175/JCLI-D-15-0129.1.

Kooshki Forooshani, M., van den Homberg, M., Kalimeri, K., Kaltenbrunner, A., Mejova, Y., Milano, L., Ndirangu, P., Paolotti, D., Teklesadik, A., and Turner, M. L. 2024: Towards a global impact-based forecasting model for tropical cyclones, Nat. Hazards Earth Syst. Sci., 24, 309–329, https://doi.org/10.5194/nhess-24-309-2024, 2024.

Korswagen, P., Jonkman, S., & Terwel, K. (2018). Probabilistic assessment of structural damage from coupled multi-hazards. *Structural Safety*, *76*, 135-148. https://doi.org/10.1016/j.strusafe.2018.08.001

Lachaud, M. A., B. E. Bravo-Ureta, and C. E. Ludena. 2022. "Economic Effects of Climate Change on Agricultural Production and Productivity in Latin America and the Caribbean (Lac)." *Agricultural Economics* 53 (2): 321-332.

Lai C, Bozzoni F, Zuccolo E, Salazar W, Corigliano M, Scandella L, et al. 2012. Probabilistic Seismic Hazard Assessment in the Eastern Caribbean Islands

Lanlan, J., M. N. I. Sarker, I. Ali, R. R. Firdaus, and M. A. Hossin. 2024. "Vulnerability and Resilience in the Context of Natural Hazards: A Critical Conceptual Analysis." *Environment, Development and Sustainability* 26 (8): 19069-19092.

Lau, Y.-Y., T.-L. Yip, M. A. Dulebenets, Y.-M. Tang, and T. Kawasaki. 2022. "A Review of Historical Changes of Tropical and Extra-Tropical Cyclones: A Comparative Analysis of the United States, Europe, and Asia." *International journal of environmental research and public health* 19 (8): 4499.

Lavell, A., and T. López-Marrero. 2013. "Disaster Risk Management in Latin America and the Caribbean: Four Decades of Evolution and Change, 1970–2010." In Disaster Management, 229-247. Routledge.

Lempert RJ, Miro ME, Prosdocimi D. 2021 A DMDU Guidebook for Transportation Planning Under a Changing Climate. 2021

Lindsay JM, Robertson REA, Shepherd JB, Ali S , Editors. 2005. Volcanic Hazard Atlas of the Lesser Antilles. St Augustine, Trinidad and Tobago: Seismic Research Center

Liu Z, Nadim F, Garcia-Aristizabal A, Mignan A, Fleming K, Luna BQ. A three-level framework for multi-risk assessment. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards. 2015;9(2):59-74

Liu, B., Siu, Y. L., and Mitchell, G. 2016: Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment, Nat. Hazards Earth Syst. Sci., 16, 629–642, https://doi.org/10.5194/nhess-16-629-2016, 2016.

Liu X, Peerally JA, Fuentes CD, Ince D, Vredenburg H. 2022 Who Makes or Breaks Energy Policymaking in the Caribbean Small Island Jurisdictions? A Study of Stakeholders' Perceptions. Sustainability. 2022;14(3):1902

Longuevergne, L., B. R. Scanlon, and C. R. Wilson. 2010. "Grace Hydrological Estimates for Small Basins: Evaluating Processing Approaches on the High Plains Aquifer, USA." Water Resources Research 46 (11).

López-Saavedra, M., and J. Martí. 2023. "Reviewing the Multi-Hazard Concept. Application to Volcanic Islands." *Earth-Science Reviews* 236: 104286.

Luo, H., Zhang, L., Zhang, L., He, J., & Yin, K. (2023). Vulnerability of buildings to landslides: The state of the art and future needs. Earth-Science Reviews, 238, 104329. https://doi.org/10.1016/j.earscirev.2023.104329

Lv, Y., M. N. I. Sarker, and R. B. R. Firdaus. 2024. "Disaster Resilience in Climate-Vulnerable Community Context: Conceptual Analysis." *Ecological Indicators* 158: 111527. https://doi.org/https://doi.org/10.1016/j.ecolind.2023.111527. https://www.sciencedirect.com/science/article/pii/S1470160X23016692.

Machin AB, Nascimento L, Mantovani K, Machin E. 2019 Effects of exposure to fine particulate matter in elderly hospitalizations due to respiratory diseases in the South of the Brazilian Amazon. Brazilian Journal of Medical and Biological Research. 2019;52:e8130

Maini, R., L. Clarke, K. Blanchard, and V. Murray. 2017. "The Sendai Framework for Disaster Risk Reduction and Its Indicators—Where Does Health Fit In?" *International Journal of Disaster Risk Science* 8: 150-155.

Maharaj, R.R. 2010. Acceptable Risk In Caribbean Terrace And Port Royal, Jamaica. Centre for Environmental Management, University of the West Indies, Mona, Jamaica. https://islandvulnerability.org/m/maharajm.pdf

Mandal, A., T. Stephenson, J. Campbell, M. Taylor, S. Watson, L. Clarke, D. Smith, J. Darsan, and M. Wilson. 2022. "An Assessment of the Impact of 1.5 Versus 2 and 2.5 C Global Temperature Increase on Flooding in Jamaica: A Case Study from the Hope Watershed." *Philosophical Transactions of the Royal Society A* 380 (2221): 20210141.

Markogiannaki, O., A. Karatzetzou, S. Stefanidou, and G. Tsinidis. 2023. *Resilience Assessment of Road Bridges in Multi-Hazard Environment*.

Mathieu P-P, Borgeaud M, Desnos Y-L, Rast M, Brockmann C, See L, et al. 2017 The ESA's earth observation open science program [space agencies]. IEEE Geoscience and Remote Sensing Magazine. 2017;5(2):86-96

Martyr-Koller, R., A. Thomas, C.-F. Schleussner, A. Nauels, and T. Lissner. 2021. "Loss and Damage Implications of Sea-Level Rise on Small Island Developing States." *Current Opinion in Environmental Sustainability* 50: 245-259. https://doi.org/https://doi.org/10.1016/j.cosust.2021.05.001.

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P. *et al*. Basic principles of multi-risk assessment: a case study in Italy. *Nat Hazards* **62**, 551–573 (2012). https://doi.org/10.1007/s11069-012-0092-x

Maurya S. Dominica Building Resilience Through Community Early Warning Systems Fairfax, VA: The Global Disaster Preparedness Center 2024 [Available from: https://preparecenter.org/story/dominica-building-resilience-through-community-early-warning-systems.

Marzi, S., Mysiak, J., Essenfelder, A. H., Pal, J. S., Vernaccini, L., Mistry, M. N., Alfieri, L., Poljansek, K., Marin-Ferrer, M., & Vousdoukas, M. (2021). Assessing future vulnerability and risk of humanitarian crises using climate change and population projections within the INFORM framework. *Global Environmental Change*, *71*, 102393. https://doi.org/10.1016/j.gloenvcha.2021.102393

Marzocchi, W., Mastellone, M., Di Ruocco, A., Novelli, P., Romeo, E. and Gasparini, P. (2009). Principles of multi-risk assessment. Interaction Amongst Natural and Man-induced Risks. European Commission. http://publications.europa.eu/resource/cellar/22eb788f-5d0a-496a-92d4-4759b0b57fde.0001.03/DOC_2

Marzocchi, W., Garcia-Aristizabal,A. , Gasparini, P., Mastellone, M.L. and Di Ruocco,A. (2012) Basic principles of multi-risk assessment: a case study in Italy, Nat. Hazards 62 (2) (2012) 551–573, https://doi.org/10.1007/s11069-012-0092-x

Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, . . . B. Zhou, eds. 2021. *IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA

Matharage, Shalini Shawari and Ishiwatari, Mikio and Aldrich, Daniel P., Empowering Communities: A Bottom-Up Approach to Disaster Risk Reduction. Available at SSRN: https://ssrn.com/abstract=4816738 or http://dx.doi.org/10.2139/ssrn.4816738

McDaniel GW. 2023 Data Poverty, SDGs and Coloniality in the Anglophone Caribbean. Culture: Policy, Management, and Entrepreneurship,. 2023;2(2):59-80

McClanahan, T. R., and J. Cinner. 2012. *Adapting to a Changing Environment: Confronting the Consequences of Climate Change*. OUP USA.

McMichael A. 1997 Global environmental change and human health:. impact assessment, population vulnerability, and research priorities. Ecosystem Health. 1997;3(4):200-10.

Mercer, J., I. Kelman, L. Taranis, and S. Suchet-Pearson. 2010. "Framework for Integrating Indigenous and Scientific Knowledge for Disaster Risk Reduction." *Disasters* 34 (1): 214-239.

Mike, M., R. Telg, A. Harder, J. Loizzo, A. Lindsey, and S. Rampold. 2021. "Disaster Management During Tropical Storm Karen: The Story of Trinidad Extension." *Journal of International Agricultural and Extension Education* 28 (2): 68-90.

Mimura, N. 2013. "Sea-Level Rise Caused by Climate Change and Its Implications for Society." *Proceedings of the Japan Academy, Series B* 89 (7): 281-301.

Ming, X., Q. Liang, R. Dawson, X. Xia, and J. Hou. 2022. "A Quantitative Multi-Hazard Risk Assessment Framework for Compound Flooding Considering Hazard Inter-Dependencies and Interactions." *Journal of Hydrology* 607: 127477. https://doi.org/10.1016/j.jhydrol.2022.127477.

Ming X, Xü W, Li Y, Du J, Liu B, Shi P. 2014. Quantitative Multi-Hazard Risk Assessment With Vulnerability Surface and Hazard Joint Return Period. Stochastic Environmental Research and Risk Assessment. 2014;29(1):35-44

Mohan P., 2015. Impact of Hurricanes on Agriculture: Evidence from the Caribbean. Natural Hazards Review. 2016;18:04016012.

Mohan P, Strobl E. 2016. A hurricane wind risk and loss assessment of Caribbean agriculture. Environment and Development Economics. 2016;-1:1-23

Mohan, S., R. M. Clarke, and X. T. Chadee. 2020. "Variations in Extreme Temperature and Precipitation for a Caribbean Island: Barbados (1969–2017)." *Theoretical and Applied Climatology* 140 (3): 1277-1290.

Monteith A. 2024. Breaking the silence on data deprivation in Caribbean poverty assessments Kingston, Jamaica: Jamaica Observer; 2024 [updated January 3, 2024. Available from: https://www.jamaicaobserver.com/2024/01/03/breaking-the-silence-on-data-deprivation-in-caribbean-poverty-assessments/

Moore, W., W. Elliott, and T. Lorde. 2017. “Climate Change, Atlantic Storm Activity and the Regional Socio-Economic Impacts on the Caribbean.” Environment, Development and Sustainability 19: 707-726.

Moraes, F. D., T. L. Mote, and L. Seymour. 2022. “Ocean–Atmosphere Variability and Drought in the Insular Caribbean.” International Journal of Climatology 42 (10): 5016-5037

Murray, M., and P. K. Watson. 2022. "Policy Implementation for Extreme Hazard Events in Caribbean Small Island Developing States: A case Study – Trinidad and Tobago and Grenada." *Disaster Prevention and Management: An International Journal* 31 (5): 508-520. https://doi.org/10.1108/DPM-03-2022-0079. https://doi.org/10.1108/DPM-03-2022-0079.

Murray, V., et al.. (2021). Hazard Information Profiles: Supplement to UNDRR-ISC Hazard Definition & Classification Review: Technical Report: Geneva, Switzerland, United Nations Office for Disaster Risk Reduction; Paris, France, International Science Council. DOI: 10.24948/2021.05

Mutetwa B, Taioli E, Attong-Rogers A, Layne P, Roach V, Ragin C. 2010 Prostate cancer characteristics and survival in males of African Ancestry according to place of birth: data from Brooklyn—New York, Guyana, Tobago and Trinidad. The Prostate. 2010;70(10):1102-9.

Mycoo M, Donovan M. 2017 A Blue Urban Agenda: Adapting to Climate Change in the Coastal Cities of Caribbean and Pacific Small Island Developing States

Mycoo, M. A. 2018. "Beyond 1.5 C: Vulnerabilities and Adaptation Strategies for Caribbean Small Island Developing States." *Regional environmental change* 18 (8): 2341-2353.

Mycoo M, et al. 2022. Small Islands. Climate Change 2022: Impacts, Adaptation and Vulnerability Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK and New York, NY, USA. p. 2043–1201. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FullReport.pdf

NASA 2024. NASA Caribbean Geoportal. https://www.caribbeangeoportal.com/pages/nasa-disaster-maps

Nash JH. 2021 Open Government Data (OGD): Don’t Overlook This Open Source of Information. Caribbean Library Journal. 2021.

Nature Conservancy, 2023. The Nature Conservancy in the Caribbean. https://caribbeanscienceatlas.tnc.org/

NDCFI, 2024. OECS Caribbean NDC Finance Initiative. https://ndcfi.oecs.org/

ODPM Trinidad and Tobago. (2020). National Disaster Management Plan. http://www.odpm.gov.tt

Nicholson, G. 2017. No Red Tape or Black Holes! International Disaster Response Law Leaves No Grey Areas in Disaster Response. Washington, DC.: OAS.

Nirandjan, S., Koks, E. E., Ye, M., Pant, R., Van Ginkel, K. C. H., Aerts, J. C. J. H., and Ward, P. J.: Review article: Physical vulnerability database for critical infrastructure hazard risk assessments – a systematic review and data collection, Nat. Hazards Earth Syst. Sci., 24, 4341–4368, https://doi.org/10.5194/nhess-24-4341-2024, 2024.

NOAA, 2015. NOAA Caribbean Strategy: Accomplishments Report. Washington DC: National Oceanic and Atmospheric Administration

NOAA, N. O. a. A. A. 2020. Atlantic Hurricane Season Outlook. Lakeland, FL: NOAA Publications.

NOAA, 2024. National Hurricane Center. https://www.nhc.noaa.gov/

OpenQuake (2016). OpenQuake 2016 Global Vulnerability Database. https://platform.openquake.org/vulnerability/list/

ODPM, 2011 Climate Risk Atlas of Coastal Hazards and Risk in Negril, 2011 : ODPEM

ODPM, 2013. Multihazard Risk assessment for Annoto Bay St. Mary, 2013: ODPEM

ODPM, 2014 Multi Hazard Risk Assessment for Falmoutyh Trelawny, 2014: ODPEM

OECS 2024. Eastern Caribbean Community Resilience Programme (ECCRP) Organisation of Eastern Caribbean States . https://oecs.int/en/eastern-caribbean-community-resilience-programme

Ogra, A., and P. Weekly. 2022. "The National Disaster Management Plan, 2019." *Economic & Political weekly* 57 (3): 17.

Olfert, Alfred & Greiving, Stefan & Batista, Maria & Greiving, A & Batista, S. (2006). Regional multi-risk review, hazard weighting and spatial planning response to risk-Results from European case studies. Geological Survey of Finland, Special Paper. 42. 125-151.

Oliveira ML, Valença GO, Pinto D, Moro LD, Bodah BW, Mores GdV, et al. 2023 Hazardous Elements in Sediments Detected in Former Decommissioned Coal Mining Areas in Colombia: A Need for Environmental Recovery. Sustainability. 2023;15(10):8361

O'Shea, D., R. Nathan, C. Wasko, M. Ho, and A. Sharma. 2024. "Evaluation of Key Flood Risk Drivers under Climate Change Using a Bottom-up Approach." Journal of Hydrology 640: 131694. https://doi.org/https://doi.org/10.1016/j.jhydrol.2024.131694

OpenStreetMap. (n.d.). OpenStreetMap Website. [OSM](https://www.openstreetmap.org)

Owolabi, T. A., and M. Sajjad. 2023. "A Global Outlook on Multi-Hazard Risk Analysis: A Systematic and Scientometric Review." *International Journal of Disaster Risk Reduction* 92: 103727. https://doi.org/https://doi.org/10.1016/j.ijdrr.2023.103727.

Pandey B, Bradley Lyon. 2013 Open Data for Resilience in the Caribbean. Washington, DC: World Bank group; 2013

Papathome-Kohle, M. Schlögl, M., & Fuchs, S. (2019). Vulnerability indicators for natural hazards: An innovative selection and weighting approach. *Scientific Reports*, *9*(1), 1-14. https://doi.org/10.1038/s41598-019-50257-2

Papathome-Kohle, M. Schlögl, M., Garlichs, C., Diakakis, M., Mavroulis, S., & Fuchs, S. (2022). A wildfire vulnerability index for buildings. Scientific Reports, 12(1), 1-15. https://doi.org/10.1038/s41598-022-10479-3

Pasino, A. Silvia De Angeli, Umberto Battista, Davide Ottonello, Andrea Clematis 2021. A Review of Single and Multi-Hazard Risk Assessment Approaches for Critical Infrastructures Protection. International Journal of Safety and Security Engineering, 2021, 11 (4), pp.305-318. ff10.18280/ijsse.110403ff. ffhal-04307559f

Pearson, L., and M. Pelling. 2015. "The Un Sendai Framework for Disaster Risk Reduction 2015–2030: Negotiation Process and Prospects for Science and Practice." *Journal of Extreme Events* 2 (01): 1571001.

Pelling, M., and J. I. Uitto. 2001. "Small Island Developing States: Natural Disaster Vulnerability and Global Change." *Global Environmental Change Part B: Environmental Hazards* 3 (2): 49-62. https://doi.org/10.1016/s1464-2867(01)00018-3.

Pelydryn Ltd. 2015. "Coastal Zone LiDAR Study, Survey Report. LiDAR Bathymetric and Topographic Survey [LB-BRD-009]."

Pescaroli, G., & Alexander, D. (2018). Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework. Risk Analysis, 38 (5) DOI: 10.1111/risa.13128

Pereira EE, Steenge AE. 2022. Vulnerability and resilience in the Caribbean island states; The role of connectivity. Networks and Spatial Economics. 2022;22(3):515-40.

Piasecki, M., and E. Harmsen. 2022. Hydrology in the Caribbean Basin. MDPI

Picard, M. 2017. "Disaster Management, Risk Reduction and International Disaster Response Laws in the Commonwealth." *Commonwealth Law Bulletin* 43 (3-4): 403-437.

Pinos, J., and A. Quesada-Román. 2021. "Flood Risk-Related Research Trends in Latin America and the Caribbean." *Water* 14 (1): 10.

locoste T, Dorville J-F, Monjoly S, Jacoby-Koaly S, André M. 2018 Assessment of nitrogen oxides and ground-level ozone behavior in a dense air quality station network: Case study in the Lesser Antilles Arc. Journal of the Air & Waste Management Association. 2018;68(12):1278-300.

Pourghasemi, H. R., N. Kariminejad, M. Amiri, M. Edalat, M. Zarafshar, T. Blaschke, and A. Cerda. 2020. "Assessing and Mapping Multi-Hazard Risk Susceptibility Using a Machine Learning Technique." *Scientific Reports* 10 (1): 3203. https://doi.org/10.1038/s41598-020-60191-3. https://doi.org/10.1038/s41598-020-60191-3.

Pulwarty, R. S., L. A. Nurse, and U. O. Trotz. 2010. "Caribbean Islands in a Changing Climate." Environment: Science and Policy for Sustainable Development 52 (6): 16-27. https://doi.org/10.1080/00139157.2010.522460.

QGIS. (n.d.). QGIS Official Website. [QGIS](https://www.qgis.org)

Rahat, Saudia. 2020. ''Desk Review of Early Warning Systems (EWS) in the Caribbean: An Examination of the Level of Investment Established to Strengthen the 4 Pillars of EWS at the Regional, National and Community Levels''. https://dipecholac.net/docs/xfiles/1054-DESK%20REVIEW-OF-EARLY-WARNING-SYSTEMS-EWS-IN-THE-CARIBBEAN.pdf

Ram J, Cotton J, Frederick R, Elliott W. 2019. A Multidimensional Vulnerability Index for the Caribbean: Measuring Vulnerability: A Multidimentional Vulnerability Index for the Caribbean. Bridgetown: Caribbean Development Bank; 2019.

Rasool, S., I. A. Rana, and H. B. Waseem. 2024. "Assessing Multidimensional Vulnerability of Rural Areas to Flooding: An Index-Based Approach." *International Journal of Disaster Risk Science* 15 (1): 88-106. https://doi.org/10.1007/s13753-024-00547-9.

REDLAC 2024. Regional Group on Risks, Emergencies, Disasters for Latin America and the Caribbean (REDLAC) https://response.reliefweb.int/latin-america-and-caribbean/regional-group-risks-emergencies-disasters-latin-america-and-caribbean

Rhiney K.2015. Geographies of Caribbean vulnerability in a changing climate: Issues and trends. Geography Compass. 2015;9(3):97-114

RiskChanges (2024). RiskChanges, a web-based open-source tool for multi-hazard risk assessment. http://www.riskchanges.org

Rölfer L, Winter G, Máñez Costa M, Celliers L. 2020. Earth observation and coastal climate services for small islands. Climate Services. 2020;18:100168. DOI:10.1016/j.cliser.2020.100168

Roopnarine, R., G. Eudoxie, M. N. Wuddivira, S. Saunders, S. Lewis, R. Spencer, C. Jeffers, T. Haynes-Bobb, and C. Roberts. 2021. "Capacity Building in Participatory Approaches for Hydro-Climatic Disaster Risk Management in the Caribbean." *International Journal of Disaster Risk Reduction* 66: 102592. https://doi.org/https://doi.org/10.1016/j.ijdrr.2021.102592.

Rosario Michel, G., S. Muñoz Tapia, V. Guzman Javier, and J. Crompvoets. 2020. "Identifying Users' Requirements of Geographic Information for Disaster Risk Management in the Dominican Republic." *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 6: 99-106.

Rozenberg J, Browne N, De Vries Robbé S, Kappes M, Lee W, Prasad A. 2021 360° Resilience: A Guide to Prepare the Caribbean for a New Generation of Shocks. Washington, D.C.: World Bank Group; 2021.

Rusk, J., A. Maharjan, P. Tiwari, T.-H. K. Chen, S. Shneiderman, M. Turin, and K. C. Seto. 2022. "Multi-Hazard Susceptibility and Exposure Assessment of the Hindu Kush Himalaya." *Science of The Total Environment* 804: 150039. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.150039.

Ryan, B., Johnston, K. A., Taylor, M., & McAndrew, R. (2020). Community engagement for disaster preparedness: A systematic literature review. *International Journal of Disaster Risk Reduction*, *49*, 101655. https://doi.org/10.1016/j.ijdrr.2020.101655

Šakić Trogrlić, R., H. E. Thompson, E. Y. Menteşe, E. Hussain, J. C. Gill, F. E. Taylor, E. Mwangi, E. Öner, V. G. Bukachi, and B. D. Malamud. 2024. "Multi-Hazard Interrelationships and Risk Scenarios in Urban Areas: A Case of Nairobi and Istanbul." *Earth's Future* 12 (9): e2023EF004413.

Šakić Trogrlić, R., K. Reiter, R. L. Ciurean, S. Gottardo, S. Torresan, A. S. Daloz, L. Ma, N. Padrón Fumero, S. Tatman, S. Hochrainer-Stigler, . . . P. J. Ward. 2024a. "Challenges in Assessing and Managing Multi-Hazard Risks: A European Stakeholders Perspective." *Environmental Science & Policy* 157: 103774. https://doi.org/https://doi.org/10.1016/j.envsci.2024.103774. https://www.sciencedirect.com/science/article/pii/S1462901124001084.

Šakić Trogrlić, R., H. E. Thompson, E. Y. Menteşe, E. Hussain, J. C. Gill, F. E. Taylor, E. Mwangi, E. Öner, V. G. Bukachi, and B. D. Malamud. 2024b. "Multi-Hazard Interrelationships and Risk Scenarios in Urban Areas: A Case of Nairobi and Istanbul." *Earth's Future* 12 (9): e2023EF004413. https://doi.org/https://doi.org/10.1029/2023EF004413. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2023EF004413.

Sakic, R. T. 2024. "Challenges in Assessing and Managing Multi-Hazard Risks: A European Stakeholders' Perspective." https://doi.org/10.5194/egusphere-egu24-3843.

Sammonds, P., A. Alam, S. Day, K. Stavrianaki, and I. Kelman. 2023. "Hurricane Risk Assessment in a Multi-Hazard Context for Dominica in the Caribbean." *Scientific reports* 13 (1): 20565. https://doi.org/10.1038/s41598-023-47527-5

Shultz JM, Cohen MA, Hermosilla S, Espinel Z, McLean A. 2016 Disaster risk reduction and sustainable development for small island developing states. Disaster Health. 2016;3(1):32-44

Schweikert, A., G. L'her, L. Nield, S. Kerber, R. Flanagan, and M. Deinert. 2020. "Resilience in the Caribbean: Natural Hazards Exposure Assessment and Areas for Future Work."

Scolobig, A., N. Komendantova, and A. Mignan. 2017. "Mainstreaming Multi-Risk Approaches into Policy." *Geosciences* 7 (4): 129.

Scott, D., M. C. Simpson, and R. Sim. 2012. “The Vulnerability of Caribbean Coastal Tourism to Scenarios of Climate Change Related Sea Level Rise.” Journal of Sustainable Tourism 20 (6): 883-898. https://doi.org/10.1080/09669582.2012.699063.

Sillmann, J., Christensen, I., Hochrainer-Stigler, S., Huang-Lachmann, J., Juhola, S., Kornhuber, K., Mahecha, M., Mechler, R., Reichstein, M., Ruane, A.C., Schweizer, P.J. and Williams, S. (2022). ISC-UNDRR-RISK KAN Briefing note on systemic risk, Paris, France, International Science Council, DOI: 10.24948/2022.01, UNDRR (2015) Sendai Framework for Disaster Risk Reduction 2015-2030

Silva, R., Govaere, G., Salles, P., Bautista, G., Díaz, G., 2002. Oceanographic vulnerability to hurricanes on the Mexican coast, in: Coastal Engineering 2002: Solving Coastal Conundrums. pp. 39–51.

Simpson, M., D. Scott, and U. Trotz. March 2011 2011. Climate Change’s Impact on the Caribbean’s Ability to Sustain Tourism, Natural Assets, and Livelihoods. (Inter-American Development Bank).

Simpson, M. C., C. S. Mercer Clarke, J. D. Clarke, D. Scott, and A. J. Clarke. 2012. Coastal Setbacks in Latin America and the Caribbean: A Study of Emerging Issues and Trends That Inform Guidelines for Coastal Planning and Development. Inter-American Development Bank (IDB).

Simpson MC, Clarke JF, Scott D, Silver N. 2020 Climate Risk Management in the Caribbean. . Berlin, Germany: Climate Analytics.;

Singh, B. 1997. “Climate-Related Global Changes in the Southern Caribbean: Trinidad and Tobago.” Global and Planetary Change 15 (3-4): 93-111

Smith, G., and T. Ariyachandra. 2022. "Bi and Analytics for Effective Disaster Recovery Management Lessons from the Bayou." In *Achieving Organizational Agility, Intelligence, and Resilience through Information Systems*, 197-217. IGI Global.

Soanes, L. M., S. Pike, D. Barker, C. Butt, L. John, K. Medcalf, E. Naumann, C. Rouse, C. A. Samuel, and F. Mukhida. 2023. "Opportunity Mapping for Nature-Based Solutions: Mitigating Storm Surge and Land Erosion in the Caribbean." *Nature-Based Solutions* 4: 100095. https://doi.org/https://doi.org/10.1016/j.nbsj.2023.100095.

Stalhandske, Z., Steinmann, C.B., Meiler, S., Sauer, I.J., Vogt, T., Bresch, D.N., *et al*. (2024) Global Multi-Hazard Risk Assessment in a Changing Climate. *Scientific Reports*, 14, Article No. 5875. https://doi.org/10.1038/s41598-024-55775-2

StormCarib. 2024 Caribbean Hurricane Network https://www.stormcarib.com/.

SRC, 2024. Caribbean Volcanoes. Trinidad: University of the West Indies, Seismic Research Centre. https://uwiseismic.com/volcanoes/caribbean-volcanoes/

Taylor, M. A., T. S. Stephenson, A. A. Chen, and K. A. Stephenson. 2012. "Climate Change and the Caribbean: Review and Response." *Caribbean Studies* 40 (2012): 169-200.

Thomas, A., O. Shooya, M. Rokitzki, M. Bertrand, and T. Lissner. 2019. "Climate Change Adaptation Planning in Practice: Insights from the Caribbean." *Regional Environmental Change* 19 (7): 2013-2025. https://doi.org/10.1007/s10113-019-01540-5.

Thompson, D. D. P. 2015. "Disaster Logistics in Small Island Developing States: Caribbean Perspective." *Disaster Prevention and Management* 24 (2): 166-184. https://doi.org/10.1108/DPM-09-2014-0187. https://doi.org/10.1108/DPM-09-2014-0187

Tilloy, A., Malamud, B. D., Winter, H., & Joly-Laugel, A. (2019). A review of quantification methodologies for multi-hazard interrelationships. *Earth-Science Reviews*, *196*, 102881. https://doi.org/10.1016/j.earscirev.2019.102881

Trotman, A., B. Mehdi, A. Gollamudi, and C. Senecal. 2008. “Drought and Precipitation Monitoring for Enhanced Integrated Water Resources Management in the Caribbean.” Fourth Caribbean Environmental Forum, Grenada.

Trotman, A. R., A. R. Joyette, C. Van Meerbeeck, R. Mahon, N. Cave, S. Cox, and D. Farrell. 2017. "Drought Risk Management in the Caribbean - Early Warning Information and Other Risk Reduction Considerations." In *Drought and Water Crises: Science, Technology, and Management Issues*, edited by D. A. Wilhite and R. S. Pulwarty, 432-447. Boca Raton, FL: CRC Press.

Trotman, A., R. Mahon, C. V. Meerbeeck, J. E. Riley, G. Brown, T. Browne, S. Young, V. Pascual, D. Ballantyne, V. Richards, . . . S. Stoute. 2021. Advancing Drought Risk Management in the Caribbean: A Multi-Sectoral Perspective. St. James, Barbados: Caribbean Institute for Meteorolgy and Hydrology.

Turner C, Powell M, Finalle R, Westmoreland K, Osterhoudt KC, Paulino RC, et al. 2021 Talking Trash: Perspectives on Community Environmental Health in the Dominican Republic. Plos One. 2021;16(3):e0248843.

UNISDR, 2015. Sendai Framework for Disaster Risk Reduction (2015-2030). https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

Uitto J, Kohlitz J, Todd D. 2017. Evaluating sustainable development in SIDS-lessons from the Pacific and the Caribbean. Evaluation for Agenda 2030: Providing Evidence on Progress and Sustainability. Exeter, England: International Development Evaluation Association (IDEAS)

UN. 2018. "In the Eye of the Caribbean Storm: One Year on from Irma and Maria." United Nations Secretariat https://reliefweb.int/report/antigua-and-barbuda/eye-caribbean-storm-one-year-irma-and-maria.

UN. 2022. "Small Islands Are Increasingly Affected by Climate Change: IPCC Report." United Nations. Accessed February 22. https://caribbean.un.org/en/173533-small-islands-are-increasingly-affected-climate-change-ipcc-report

UNDP , 2024. After the Rain: The Lasting Effects of Storms in the Caribbean. https://www.undp.org/latin-america/after-rain-lasting-effects-storms-caribbean

UNDRR. 2017. Report of the Open-Ended Intergovernmental Expert Working Group on Indicators and Terminology Relating to Disaster Risk Reduction. New York, https://www.undrr.org/drr-glossary/terminology

UNDRR, 2021. Hazard Information Profiles. Supplement to: UNDRR-ISC Hazard Definition & Classification Review Technical Report. https://www.undrr.org/publication/hazard-information-profiles-hips

UNDRR, 2021. Regional Action Plan For The Implementation Of The Sendai Framework For Disaster Risk Reduction 2015-2030 In The Americas And The Caribbean (Updated November 2021). https://rp-americas.undrr.org/2021/sites/default/files/inline-files/Regional%20Action%20Plan_EN.pdf

UNDRR, 2022. Multi-Hazard Early Warning Systems'capacities in the Caribbean Region. Geneva, Switzerland: UNDRR.

UNDRR. 2022a. Caribbean Multi-Hazard Early Warning Systems (MHEWS) Thematic Case View. Geneva, Switzerland: UNDRR.

UNDRR, 2022. The Midterm Review of the Implementation of the Sendai Framework for Disaster Risk Reduction 2015-2030 Geneva, Switzerland: UNDRR; 2022

UNDRR 2022b. Multi-Hazard Early Warning Systems'capacities in the Caribbean Region. United Nations Office for Disaster Risk Reduction (UNDRR). Geneva, Switzerland: UNDRR. https://caribbean.un.org/en/249460-multi-hazard-early-warning-systems%E2%80%99-capacities-caribbean-region

UNDRR 2022c. Technical Guidance on Comprehensive Risk Assessment and Planning in the Context of Climate Change. United Nations Office for Disaster Risk Reduction. https://www.undrr.org/publication/technical-guidance-comprehensive-risk-assessment-and-planning-context-climate-change

UNDRR 2022d. Disaster risk Reduction in the Caribbean: situational analysis 2022. https://www.undrr.org/publication/disaster-risk-reduction-caribbean-situational-analysis-2022

UNDRR . 2023. Warning, Regional Integrated Multi-Hazard Early: Compendium of Multi-Hazard Early Warning Cooperation. Geneva, Switzerland: UNDRR.

UNDRR, 2023 Global status of multi-hazard early warning systems 2023 Geneva, Switzerland: UNDRR; https://www.undrr.org/reports/global-status-MHEWS-2023

UNDRR & ISC (2020). Hazard Definition and Classification Review: Technical Report. Geneva, Switzerland, United Nations Office for Disaster Risk Reduction; Paris, France, International Science Council. https://www.undrr.org/publication/hazard-definition-and-classification-review-technical-report

UNDRR ROAMC 2021 Regional assessment report on disaster risk in Latin America and the Caribbean (RAR 2021) https://www.undrr.org/publication/undrr-roamc-regional-assessment-report-disaster-risk-latin-america-and-caribbean-rar

UNDRR & WMO. 2023. Global Status of Multi-Hazard Early Warning Systems Geneva, Switzerland: UNDRR

UNEP 2011 DoE, Assessment. UNEP year book 2011: emerging issues in our global environment: UNEP/Earthprint; 2011

UNISDR, 2017 Words into Action Guidelines National Disaster Risk Assessment . https://www.undrr.org/publication/words-action-guidelines-national-disaster-risk-assessment

USGCRP. 2018. "Us Caribbean." In *Fourth National Climate Assessment*. Washington, DC: US Global Change Research Program.

UWISeismic 2024. The University of the West Indies Seismic Research Centre. https://uwiseismic.com/

Valero, S., J. J. Miranda, and M. Murisic. 2021. "Nature-Based Solutions for Improving Resilience in the Caribbean." *World Bank: Washington, DC, USA*.

Van Verseveld, H.C.W., Van Dongeren, A.R., Plant, N.G., Jäger, W.S., Den Heijer, C. (2015). Modelling multi-hazard hurricane damages on an urbanized coast with a Bayesian Network approach. Coastal Engineering, 103: 1-14. https://doi.org/10.1016/j.coastaleng.2015.05.006

Van Westen, C.J., et al, 2011, Multi-Hazard Risk Assessment: Distance education course – Guidebook", United Nations University – ITC School on Disaster Geo-information Management, 2011. Available at http://ftp.itc.nl/pub/westen/Multi_hazard_risk_course/Guidebook/Guidebook%20MHRA.pdf .

van Westen, C., Kappes, M.S., Luna, B.Q., Frigerio, S., Glade, T., Malet, JP. (2014). Medium-Scale Multi-hazard Risk Assessment of Gravitational Processes. In: Van Asch, T., Corominas, J., Greiving, S., Malet, JP., Sterlacchini, S. (eds) Mountain Risks: From Prediction to Management and Governance. Advances in Natural and Technological Hazards Research, vol 34. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-6769-0_7

Van Westen, C.J. 2016 National Scale Landslide Susceptibility Assessment for Dominica. *World Bank Caribb. Handb. Risk Inf. Manag. Tech. Rep.* **2016**.

Van Westen CJ. 2016b The World Bank CHARIM Caribbean Handbook on Risk Information Management National Scale Landslide Susceptibility Assessment for Saint Lucia. New York, NY: World Bank Group

van Westen, C. J. et al. 2020. Multi-Hazard Risk Assessment in Tajikistan: web-based platform. Web publication/site http://tajirisk.ait.ac.th/index.php?page=default

Verrest H. 2007. Home-based economic activities and Caribbean urban livelihoods: Vulnerability, ambition and impact in Paramaribo and Port of Spain: Amsterdam University Press; 2007.

Vinck EE, Ebels T, Hittinger R, Peterson TF.2021 Cardiothoracic surgery in the Caribbean. Brazilian Journal of Cardiovascular Surgery. 2021;36(5):599-606

Vosper, E. L., D. M. Mitchell, and K. Emanuel. 2020. "Extreme Hurricane Rainfall Affecting the Caribbean Mitigated by the Paris Agreement Goals." *Environmental Research Letters* 15 (10): 104053.

Wang, N., Cheng, W., Zhang, H., Van Westen, C., Xiong, J., Liu, C., & Lombardo, L. (2023). Impact-based probabilistic modeling of hydro-morphological processes in China (1985–2015). *Journal of Environmental Management*, *344*, 118463. https://doi.org/10.1016/j.jenvman.2023.118463

Ward, P. J., V. Blauhut, N. Bloemendaal, J. E. Daniell, M. C. de Ruiter, M. J. Duncan, R. Emberson, S. F. Jenkins, D. Kirschbaum, and M. Kunz. 2020. "Natural Hazard Risk Assessments at the Global Scale." *Natural Hazards and Earth System Sciences* 20 (4): 1069-1096.

Wilkinson, E., B. Arvis, J. Mendler de Suarez, L. Weingärtner, C. Jaime, N. Grainger, C. Simonet, J. Bazo, and A. Kruczkiewicz. 2021. *Preparing for Extreme Weather in the Eastern Caribbean*. Working Paper 603.

Weiskopf SR, Rubenstein MA, Crozier LG, Gaichas S, Griffis R, Halofsky JE, et al. 2020 Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. Science of The Total Environment. 2020;733:137782.

Windy, 2024. http://windy.com

WMO, 2023. "Regional Project Strengthens Early Warnings in the Caribbean." WMO. Accessed October 9.

WMO, 2024. "New Funding to Strengthen Multi-Hazard Early Warning Systems in the Caribbean." World Metorological Organisation. Accessed October 9. https://wmo.int/media/magazine-article/new-funding-strengthen-multi-hazard-early-warning-systems-caribbean.

World Bank. 2018. Disaster Risk Management in the Caribbean: The World Bank's Approaches and Instruments for Recovery and Resilience Washington, DC: World Bank Group. https://www.gfdrr.org/sites/default/files/publication/WBG%20Caribbean%20DRM%20Engagement_web.pdf

WorldBank 2023. Caribbean Islands - Digital Elevation Model. https://datacatalog.worldbank.org/search/dataset/0039936/Caribbean-Islands---Digital-Elevation-Model

Wright N. 2013. Small Island Developing States, disaster risk management, disaster risk reduction, climate change adaptation and tourism. Background paper for the Global Assessment report on DRR 2013. https://www.preventionweb.net/english/hyogo/gar/2013/en/bgdocs/Wright,%20N.,%202013.pdf

Yang, J., P. Gong, R. Fu, M. Zhang, J. Chen, S. Liang, B. Xu, J. Shi, and R. Dickinson. 2013. "The Role of Satellite Remote Sensing in Climate Change Studies." *Nature Climate Change* 3: 875-883. https://doi.org/10.1038/nclimate2033

Yousefi, S., Pourghasemi, H. R., Emami, S. N., Pouyan, S., Eskandari, S., & Tiefenbacher, J. P. (2020). A machine learning framework for multi-hazards modeling and mapping in a mountainous area. *Scientific Reports*, *10*(1), 1-14. https://doi.org/10.1038/s41598-020-69233-2

Yu H, Tan Q, Zhou L, Zhou Y, Bian H, Chin M, et al. 2021 Observation and modeling of a historic African dust intrusion into the Caribbean Basin and the southern US in June 2020. Goldschmidt2021• Virtual• 4-9 July. 2021.

Zebisch, M., Terzi, S., Pittore, M., Renner, K., Schneiderbauer, S. (2022). Climate Impact Chains—A Conceptual Modelling Approach for Climate Risk Assessment in the Context of Adaptation Planning. In: Kondrup, C., *et al*. Climate Adaptation Modelling. Springer Climate. Springer, Cham. https://doi.org/10.1007/978-3-030-86211-4_25

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., van den Hurk, B., AghaKochak, A., Jézéquel, A., Mahecha, M.D., Maraun, D., Ramos, A.M., Ridder, N.N., Thiery, W. & Vignotto, E. (2020). A typology of compound weather and climate events. Nature reviews earth & environment, 1(7), 333-347, https://doi.org/10.1038/s43017-020-0060-z.

Zschau. (2017). Where are we with multihazards, multirisks assessment capacities?, in: Science for disaster risk management 2017: knowing better and losing less, edited by: Poljansek, K., Marin Ferrer, M., De Groeve, T., and Clark, I., European Union, Brussels, Belgium. Available at: https://drmkc.jrc.ec.europa.eu/knowledge/science-for-drm/science-for-disaster-risk-management-2017

Annex 1: Overview of relevant definitions related to multi-hazard risk assessment

Susceptibility is the relative likelihood of occurrence of a dangerous phenomena
Hazard is a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation.
Hazard Assessment: analyzing the probability of occurrence of a potentially damaging phenomena with a given intensity within a given area and given time period
Multi-hazard means (1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and considering the potential interrelated effects.
Exposure refers to the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas.
Vulnerability refers to the conditions determined by physical, social, economic, and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.
Capacity refers to the combination of all the strengths, attributes, and resources available within an organization, community, or society to manage and reduce disaster risks and strengthen resilience.
Disaster is a serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability, and capacity, leading to one or more of the following: human, material, economic and environmental losses, and impacts.
Disaster risk is the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society, or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity.
Disaster risk assessment is defined as a qualitative or quantitative approach to determine the nature and extent of disaster risk by analyzing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods, and the environment on which they depend.
Disaster risk reduction is aimed at preventing new and reducing existing disaster risk and managing residual risk, all of which contribute to strengthening resilience and therefore to the achievement of sustainable development.
Disaster risk management is the application of disaster risk reduction policies and strategies to prevent new disaster risks, reduce existing disaster risks and manage residual risks, contributing to the strengthening of resilience and the reduction of disaster losses.
A **multi-hazard risk assessment** should identify all possible and relevant hazards and the valid comparison of their contributions to hazard potential, including the contribution to hazard potential from hazard interactions and spatial/temporal coincidence of hazards, while also taking into account the dynamic nature of vulnerability to multiple stresses
Compounding Risk the concurrence of several hazardous events from different origins, and it has become a general term to indicate that several hazardous events worsen the impact on society
Interacting risk is used to highlight the importance of hazard interactions in terms of their causal mechanisms and the effect they have on other hazardous processes
Interconnected risk is used to highlight the importance of interconnected causality networks that generate and amplify disasters and the interlinkages between human, environmental, and technological components
Cascading Risk is used to focus specifically on the progressive impact of disaster events, which propagate from one component or sector to another.
NaTech disasters, where extreme events with a natural origin (e.g., earthquake) cause a secondary technological disaster chain
Systemic Risk : those impacts that may impede the functioning of a system. The cascading effects of one or more interacting extreme events may pass over to other sectors of society and other regions, causing cross-boundary effects that may lead to the collapse of the functioning of a part of society or event extending to several geographical areas
Emerging Risk: possible threats and their impacts that have not manifested themselves in the past or for which the available knowledge is weak. One of the important emerging risks is related to climate change and the impact of possible tipping points

.

Annex 2: Some Recent European Research project on Multi-Hazard Risk Assessment

For more Examples see: https://www.cmine.eu/topics/35391/page/contributing-projects-copy

Project	Period	Description and Relation to PARATUS
RASOR	2013 - 2016	Rapid Analysis and Spatialisation Of Risk (RASOR). Developed tools in the Caribbean https://cordis.europa.eu/project/id/606888
ANYWHERE	2016 - 2019	EnhANcing emergencY management and response to extreme WeatHER and climate Events. Developed a catalogue of hazard models http://anywhere-h2020.eu/
C2IMPRESS	2022 - 2025	Co-Creative Improved Understanding and Awareness of Multi-Hazard Risks for Disaster Resilient Society. Develop a novel integrated risk and resilience framework https://www.c2impress.com/
PARATUS	2022-2026	Promoting disaster preparedness and resilience by co-developing stakeholder support tools for managing the systemic risk of compounding disasters. Development of Disaster Risk Stakeholder Hub (http://drs-hub.eu) and open source tools for flood (http://fastflood.org) landslides (http://fastslide.org) and risk (http://riskchanges.org). https://www.paratus-project.eu/
MYRIAD_EU	2021 - 2025	catalyse a paradigm shift in how risks are currently assessed and managed, and co-develop the first harmonised framework for multi-hazard, multi-sector, and systemic risk management. Developed Gateway: https://disasterriskgateway.net/ https://www.myriadproject.eu/
DISTENDER	2022-2025	DISTENDER is an EU-funded project to establish new common ground for scientists and policy makers by developing actionable strategies for climate change mitigation and adaptation processes. https://distender.eu/
ICARIA	2023-2025	Improving ClimAte Resilience of crItical Assets will use asset-level modelling to understand climate-related direct and indirect impacts https://www.icaria-project.eu/
MEDIATE 2022 - 2025	2022 - 2025	MEDiate aims to develop a decision support system (DSS) for disaster risk management by considering multiple interacting natural hazards and cascading impacts using a novel resilient-informed, service-oriented, and people-centred approach that accounts for forecasted modification in the hazard and exposure. https://mediate-project.eu/
The HuT	2022 - 2026	promote a set of trans-disciplinary risk management tools and approaches that could be adopted and used in as many situations as possible. https://thehut-nexus.eu/

Annex 3: Examples of MHRA Work Done in Caribbean Countries

Country	MHRA examples
Jamaica	Jamaica has made notable progress in the field of MHRA through various projects aimed at improving disaster risk management. One key initiative is the Disaster Risk Management and Climate Change Adaptation Project, which seeks to establish a comprehensive risk assessment framework. This project incorporates community engagement, enabling local populations to contribute their knowledge and perspectives, leading to more effective assessments and strategies. Another example is the Climate Risk Atlas of Coastal Hazards and Risk in Negril. This publication by ODPEM (2011) identified the hazards, elements at risk and the projected impacts of the hazards for Negril, considering the specific climate scenarios and return periods. The climate threats under consideration in this publication are sea level rise, coastal erosion and storm surge. The Multi Hazard Risk Assessment for Annotto, St. Mary (ODPM, 2013) provides analyses and Assessment of four natural hazards in Annotto Bay Jamaica (Storm surges, coastal erosion, riverine flood and earthquakes). The maximum extent of flooding for each corresponding surge were estimated. The real extent of riverine flooding along with mapping of coastal erosion. Seismic analysis was done by rapid visual screening(RVS). A MHRA study in Falmouth Jamaica (ODPM, 2014) considered 3 hazards (Storm surge, Coastal erosion and earthquakes).
Trinidad and Tobago	In Trinidad and Tobago, the Office of Disaster Preparedness and Management (ODPM) has implemented assessments focused on flood and hurricane risks. The ODPM emphasizes the importance of integrating community inputs and local knowledge into risk assessments. Their approach includes the development of public awareness campaigns to educate citizens about disaster preparedness.
Dominica	A macroscale whole island analysis was used for the island of Dominica to develop susceptibility scenarios, triggered landslides and floods. This approach involved the incorporation of physical process parameters. These were then combined with vulnerabilty indcators to map spatial patterns of multi-risk. The analysis involved methods such as frequency ratio(FR), analytic hierarchy process (AHP), and geographic information system (GIS). A GeoNode deployment for sharing existing data launched in November 2012 and a full OpenDRI platform implementation took place in 2013.
Barbados	Barbados has established the Comprehensive Disaster Management Policy for Barbados, which outlines strategies for risk assessment and management. This policy places a strong emphasis on climate resilience, particularly concerning land use planning and infrastructure development. The government's efforts to implement comprehensive assessments have led to improved understanding of the vulnerabilities facing the island.

Annex 4: Examples of Disaster Risk Management legislative frameworks in Caribbean countries

Country	Disaster Risk Management legislative framework
Jamaica	the International Disaster Response Law (IDRL) in 2013, Disaster Risk Management (DRM) Act of 2021
Bahamas	Disaster Risk Management Act 2022, which also established the Disaster Risk Management Authority (DRMA)
St. Vincent and the Grenadines	National Disaster Plan, 2005, The Emergency Powers Act No. 45 of 1970, and the National Emergency and Disaster Management Act (2006), the International Disaster Response Law (IDRL) in 2017
Trinidad and Tobago	Environmental Management Act 2000
Dominica	Several disaster management acts, including the Climate Resilience Act, 2018, the National Disaster Plan 2001, and the Emergency Powers (Disaster) Act, 1987
Grenada	the International Disaster Response Law (IDRL) in 2018
Barbados	Emergency Management Act, 2006 and the Comprehensive Disaster Management (CDM) Policy, 2022
Antigua and Barbuda	the Disaster Management Act, 2002

Annex 5: Data types and availabilities in Caribbean countries

Types of Data Available

Humanitarian and Health Data

Humanitarian and health data availability also varies widely in the Caribbean. Nowadays, the humanitarian data exchange portal (HUMDAT, 2024) is an important data source, with >40 data layers for each country. Larger nations like Cuba and Jamaica have made significant strides in reporting health data, particularly concerning Non Communicable Diseases (NCDs). However, only a handful of Caribbean countries have established national reporting systems that include comprehensive indicators for NCDs and their risk factors. This lack of standardized data collection limits the ability to monitor health trends effectively and to implement targeted interventions. The disparities in health data availability are further exacerbated by underreporting issues, particularly in the context of infectious diseases such as dengue and chikungunya, where passive surveillance often leads to significant underestimation of disease burden.

Meteorological Data

In the Caribbean, meteorological data is collected through a combination of ground-based weather stations, satellite observations, and radar systems (UNDRR, 2023). Countries like Puerto Rico and the Dominican Republic have well-established meteorological networks that provide real-time data on weather conditions. However, smaller nations often lack the infrastructure to maintain such networks, resulting in gaps in data availability (UNDRR, 2023). In terms of environmental hazards, the Caribbean is particularly vulnerable to hurricanes, which have been shown to cause extensive damage to agriculture and infrastructure. Research indicates that comprehensive risk assessments are essential for understanding the potential impacts of hurricanes on the region's agriculture (Mohan, 2016; Mohan and Strobl, 2017). However, many Caribbean nations lack consistent data collection mechanisms, which hampers the ability to conduct thorough risk assessments. While some studies have utilized advanced modelling techniques to estimate hurricane risks and losses, the overall data landscape remains fragmented and inconsistent across different countries (Uitto et al., 2017; UNDP, 2023). There is also a wide range of satellite-derived meteorological datasets, such as CHIRPS, IMERG, GPM, GeoNetCast, SPIE etc.

Seismic Data

Seismic data is essential for assessing earthquake risks. The Caribbean region is seismically active, with several tectonic plate boundaries running through the area (UNDP, 2023). Seismic data is collected through networks of seismometers that detect and record ground motions. Puerto Rico and the U.S. Virgin Islands have extensive seismic monitoring networks, providing detailed data on earthquake activity. In contrast, many smaller islands have limited seismic monitoring capabilities, which restricts their ability to assess earthquake risks accurately (Bozzoni et al., 2011; Wright, 2013).

Hydrological Data

Hydrological data is vital for assessing flood risks, particularly in regions prone to heavy rainfall and hurricanes. This data includes information on river flow rates, rainfall patterns, and soil moisture levels. The Dominican Republic and Jamaica have developed comprehensive hydrological monitoring systems that provide valuable data for flood risk assessment. However, many smaller islands lack the resources to maintain such systems, leading to gaps in hydrological data availability (Cashman, 2014; Forde et al., 2024).

Topographic Data

Topographic data, including digital elevation models (DEMs) and detailed maps, is crucial for assessing risks related to landslides, flooding, and coastal erosion. European initiatives such as COPERNICUS (a collaboration between the EU and ESA) have provided good quality DEMs at 30 m resolution. High-resolution topographic data is available for some parts of the Caribbean, particularly in territories with strong international support. Also many smaller island states have now been able to acquire high resolution DEMs using LiDAR surveys (e.g. Dominica, Saint Lucia, Saint Vincent and the Grenadines, Grenada) (WorldBank, 2023).

Hazard Data

Hazard data characterize the type, frequency, intensity, and distribution of natural hazards in the Caribbean, serving as the foundation of any risk assessment. Some of the main datasets for various hazard types are:

- **Hurricanes and Tropical Storms**: The Caribbean Institute for Meteorology and Hydrology (CIMH) and the US National Oceanic and Atmospheric Administration (NOAA) through the National Hurricane Center (NHC) provide extensive data on hurricane paths, intensity, and frequency. These datasets have enabled the creation of regional models that simulate hurricane impacts on infrastructure, populations, and ecosystems (CIMH, 2022). The CHARIM Project provided data on hurricane risk assessment in the Caribbean. For example, the Project provided data on 1,829 events that occurred between 1988 and 2014. The Caribbean Hurricane Network (CHN) also provides climatological information on tropical cyclone characteristics, such as wind speed, paths and historical analyses (StormCarib, 2024). Also other services are available such as NOAA (2024) and Windy (2024)

- **Earthquakes and Volcanic Activity**: The University of the West Indies Seismic Research Centre (SRC) offers real-time data on earthquakes and volcanic eruptions in the Eastern Caribbean. SRC's seismic activity records allow for the assessment of seismic hazards, particularly in regions with active volcanoes such as Montserrat and Saint Vincent (SRC, 2022). The U.S. Geological Survey gives information on the Caribbean plate's convergence with the North American plate, which can cause earthquakes and tsunamis (Brink and Flores, 2018; Harbitz et al., 2012).

- **Floods and Droughts**: Flooding and droughts are increasingly critical hazards in the Caribbean, yet data availability varies. CIMH provides limited hydrological and meteorological data relevant to flooding, but flood maps and detailed data on drainage systems are lacking. CIMH also operates the Caribbean Flood Warning System (CFWS) and offers real-time rainfall data, flood forecasts, and risk mapping for member states. Historical data (1988-1014) are also available from the CHARIM Project. Drought data are more robust, with some monitoring and warning capabilities through the CIMH's

Caribbean Climate Outlook Forum (CariCOF) and the Caribbean Drought and Precipitation Monitoring Network (CDPMN), which monitors precipitation excesses and deficits and provides flood warnings, drought indices and forecasts for the region, but coverage across all territories remains uneven (CRCC, 2024). Some drought data (1970-2003) are also available from International Disaster Database, EM-DAT a global database on hazards. CDEMA through GeoCRIS provides hazard maps and vulnerability assessments, helping member states understand flood risks. For emergency and related situations NASA Earth Observing System Data and Information System (EOSDIS) offers satellite-based remote sensing data for precipitation, flood mapping, and drought monitoring. Likewise, European Space Agency (ESA) – Copernicus Emergency Management Service (EMS) provides satellite imagery and data for real-time flood monitoring and risk assessment.

Exposure Data

Exposure data detail the spatial distribution and characteristics of populations, infrastructure, and assets that may be impacted by natural hazards. This type of data is integral to assessing the potential scale and impact of hazard events (McDaniel, 2023).

- **Population and Demographic Data**: Census data, typically managed by national statistics agencies, provide population and demographic information across Caribbean countries. However, these data are not always current and can lack sufficient granularity for effective MHRA at the community level (McDaniel, 2023; Monteith, 2024; Jones, 2024).

- **Critical Infrastructure**: Data on infrastructure, including hospitals, schools, roads, and power facilities, are sparse and inconsistent (Becker er al, 2021). While some national agencies maintain infrastructure inventories, there is no standardized, region-wide database available for public access (Fernandez, 2008). This gap makes it challenging to assess infrastructure vulnerabilities comprehensively (Nash, 2021; Abdulkadri et al., 2016)

- **Economic Data**: Economic exposure data, such as income levels, employment statistics, and land use, are available from organizations like the Caribbean Development Bank and the World Bank. These data are essential for understanding potential economic losses due to hazards, though they are often aggregated at the national level and lack local specificity (Fernandez, 2008; Rozenberg et al., 2021).

Vulnerability Data

Vulnerability data highlight how various factors, including socio-economic status, construction standards, and environmental conditions, influence susceptibility to hazards. Vulnerability data are among the most challenging datasets to obtain due to their complex nature and the need for localized information.

- **Building Codes and Construction Standards**: While several Caribbean countries have national building codes, enforcement and data on compliance vary widely. Detailed information on building materials, structural conditions, and age of infrastructure is scarce, creating a significant gap in vulnerability data for structural assessment Rozenberg et al., 2021; ECLAC, 2004) .

- **Socio-Economic Vulnerability**: Poverty, health indicators, and social factors affecting vulnerability are partially covered by regional organizations like the Caribbean Public

Health Agency (CARPHA) and Economic Commission for Latin America and the Caribbean (ECLAC). However, these datasets often lack granularity, making it difficult to assess vulnerabilities at the neighbourhood or community level (Rhiney, 2015; Verrest, 2007; Pereira and Steenge, 2022). Some international agencies like the United States of America Overseas Security Advisory Centre and UN Office on Drugs and Crime also provided statistics and information on national socio-economic vulnerabilities (Ram et al., 2019). The Caribbean Catastrophe Risk Insurance Facility (CCRIF SPC) provides data on the economic impacts of disasters in the Caribbean.

- **Environmental Vulnerability**: Ecosystem health data, such as coral reef and mangrove coverage, are available through organizations like the Caribbean Natural Resources Institute (CANARI) CDEMA, Caribbean Community Climate Change Centre (CCCCC) and the United Nations Environment Programme (UNEP). Also, the United Nations Economic Commission for Latin America and the Caribbean (ECLAC) provides socio-economic analyses of disaster impacts, and risk assessments specific to the Caribbean region.. However, the frequency and consistency of these datasets vary, limiting their use in MHRA (UNEP, 2011; McMichael, 1997) .

Annex 6: Hazard Characteristics

Characteristic	Explanation
What?	What is the hazard type? What are the main **causes** of the event, what is the **trigger** of the event, and how is the event related to other events? This requires a good classification of events and their relationships.
How severe?	What is the expected **magnitude**, which is indicating the size and energy of the event (e.g. earthquake or volcanic magnitude, river discharge, landslide size). For this long time series of past events are extremely important, and the maintenance of hazard databases, that give information on the time and extent of the hazard events.
Where?	What is the **spatial extent** of the hazard, the so-called hazard footprint area, and the **intensity**, which is the spatial representation of damaging effects (e.g. ground shaking for earthquakes, water depth for floods). The **scale** of an event refers to the area affected which can range from local to global. This requires the mapping of past events and the modelling of future ones with hazard models.
How often?	What is the **frequency** or **probability of occurrence** of a given hazard magnitude/intensity. A **return period**, also known as a **recurrence interval** or **repeat interval**, is an average time between events with the same magnitude/intensity. The question is also: what is the relation between frequency and magnitude?
How long?	The **duration of the event** is important, also in relation to other events that might occur afterwards and cause a compounding (increasing) effect. Events may also have a rapid or slow onset.
What contributes?	There are **conditions that contribute** to the occurrence and the severity of the hazardous event, such as land use/ land cover, terrain, geology, human activities. These can be mapped as contributing or causal factors.
What triggers?	Hazardous events can be **triggered by specific extreme events**, of different origins, like geological (e.g. earthquakes or volcanoes), hydro-meteorological (extremes in rainfall and temperature) and anthropogenic activities (accidents)
How long before?	Are there any **indications or anomalies in time series** (e.g. of meteorological characteristics) that could be used to predict when, where and how severe the event will be? How long before the event can we know these? This is extremely important for **Early Warning** and Impact-Based forecasting.

Annex 7: Hazard interrelations

Table A7.1 : Subdivision of the main types of hazard type interrelations

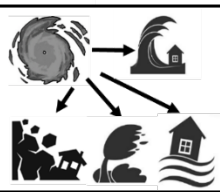
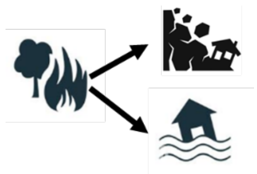
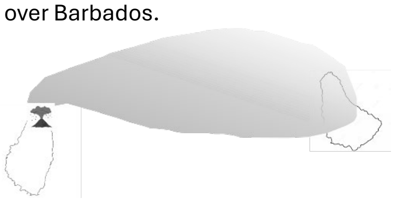
Hazard type interrelations	Description	Example	
Independent	Hazardous events that have no direct causal relationship and for which the hazard assessment can be carried out independently	Earthquakes and tropical storms have different trigger mechanisms	Haiti: Earthquakes (2010) and floods (e.g. 2016 Hurricane Mathew, which killed 580 people and left 35,000 left homeless) 
Triggering	Hazardous events might share the same trigger, occur simultaneously, and affect the same area.	Landslides and floods occur as a result of the same triggering rainfall event.	Dominica: 2017 Hurricane Maria caused extensive flooding, debris flows, wind and landslides. 
Cascading	These hazardous processes occur in sequence, where one process triggers the second and the second the third	An volcanic eruption may trigger a tsunami which causes coastal flooding	Grenada: In 1939 an eruption of the submarine volcano Kick-em Jenny caused tsunamis in Grenada and Saint Vincent and the Grenadines. 
Conditioning	These hazardous events change the conditions of the landscape in such a way that the susceptibility/likelihood and/or intensity of other hazardous processes increases substantially	Forest fires change the soil conditions, increasing the susceptibility to floods and landslides.	Cuba: Forest fire seasons in 2023 and 2024 followed by rainfall events, causing flooding in burned areas. 

Table A7.2 : Subdivision of the main types of spatial multi-hazard interrelations

Spatial interrelations	Description	Example	
Overlapping	The areas that might be affected by several types of hazards might overlap or partly overlap. Several types of hazards impact the assets.	During a hurricane the same area might be affected by different hazards (e.g. wind, storm surge and flashflood).	Dominican Republic: the same area was impacted by different hazards during two hurricanes (Irma and Maria) 
Source and spread	Hazardous events are spatially connected through a source and spread relation, where one is the source, and the other where a hazardous process or phenomenon spreads out to	A volcanic eruption can cause hazardous processes that reach areas far away from the volcano, such as ash fall and ash clouds that may impact air traffic .	The 2021 La Soufriere eruption in Saint Vincent, causing an ash cloud affecting air traffic over Barbados. 

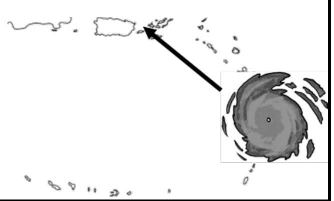
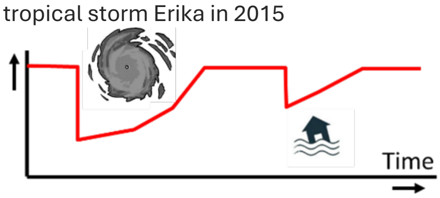
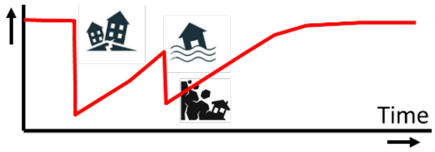
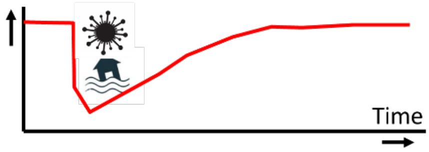
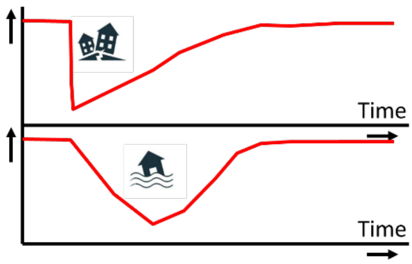
Cross-border	Hazardous events that cross different administrative borders. These can be within a country but can also be across different countries	Major hurricanes affect a number of countries and require collaboration for the hazard assessment	2024: Hurricane Beryl. 
Not-overlapping	The areas of different hazardous events do not overlap	Wildfires in one island, floods on another and drought on a third.	2009-2010 droughts 

Table A7.3 : Subdivision of the main types of spatial multi-hazard interrelations

Temporal hazard interrelations	**Description**	**Example**	
Events occur after a long time	the time period between two events is long enough so that the society or territorial system has fully recovered from the previous event	An hurricane of which damage is repaired within several years is followed by a flood after many years	Dominica: Hurricane David in 1979 and tropical storm Erika in 2015 
Consecutive events	Hazardous events may occur close to each other so that the damage of one is worsened by the damage of the other. Events occur in succession.	An earthquake is followed by a tropical storm occurring during the recovery period of the previous event.	 Haiti: The earthquake and tropical storm that affected the Southwest of Haiti in 2021
Simultaneous /Concurrent events	Independent events that are unrelated may occur simultaneously or very close to each other, , so the damage is due to the combined intensity of the hazard events.	The occurrence of simultaneous events, some with fast and other with slow onsets but compounding.	 Saint Vincent : 2021. Co-occurrence of COVID-19, coastal erosion, and volcanic eruption of La Soufriere
Onset speed	Hazardous events may be slow-onset events, which may cover months or years, or fast-onset events, such as earthquakes, storms, or flash floods.	Slow-onset: droughts or pandemics, Fast-onset ones: flash floods, earthquakes.	

Annex 8: Specific hazard types in the Caribbean context.

A8.1 Storms and associated hazards

Tropical cyclone related hazard sequences consider storm force winds, storm surge, thunderstorms, extreme rainfall, landslides, flood and debris flows each of which occur with varying spatial and temporal realities. Near real-time impacts can occur simultaneously or overlap (e.g. wind damage, storm surge) or in a cascading or consecutive manner (e.g. coastal inundation due to run up, urban and riverine flooding, landslides and debris flows following a period of intense rainfall. Typically, wind-related impacts precede rainfall related impacts. However, in some tropical cyclone systems, significant rainfall accumulations can occur on land prior to landfall. Wind related impacts are typically higher closer to the center of the system whereas high rainfall intensities are linked to the storm dynamics and vary spatially to the extent where, in the context of the Caribbean, rainfall- related impacts may be higher in one territory while wind related impacts are higher in another for the same system.

Hurricane hazard

The tropical cyclone hazard of the SPHERA loss model has two components: maximum wind speed and maximum storm surge. “Maximum wind speed” is the maximum velocity reached by the wind in a specific point during a tropical cyclone. The measure of wind speed used by the SPHERA model is the maximum averaged 1-minutes wind speed, in km/h. “Maximum storm surge” is the maximum level of water caused by the combined effect of a tropical cyclone (pressure drop and wind friction) and the astronomical tide at a specific location during a tropical cyclone, in m1. Both hazard measures are computed for a large set of locations through the use of mathematical models. The locations represent sites where one or more assets are located according to the exposure database (CCRIF, 2019).

Wind Hazard

A tropical cyclone is a rotating storm system characterized by a low-pressure centre and strong winds. Several types of mathematical models are available to reproduce this complex phenomenon and compute wind speed values over a large geographical domain, ranging from complex numerical weather model to simpler and faster parametric models. The wind component of the SPHERA model (CCRIF, 2019) is based on a modified version of a parametric wind model published by Silva et al. (2002) . This model is a modification of the Holland model (Holland, 1980), widely used in the field of tropical cyclone risk modelling. The model computes wind speed (and pressure) over a large domain, on the basis of input parameter values that can be usually found in the tropical cyclone best track database provided by all major national oceanographic agencies. These data include cyclone position, minimum sea level pressure, maximum wind speed and radius of maximum wind. The wind is computed as a function of the distance from the eye, the maximum wind speed and the Coriolis force parameter (dependent upon the latitude), and it is computed at every location of the domain. Then, the forward speed of the cyclone is also taken into account, as well as the rotational component of the cyclone movement. This operation is repeated at every time step of the cyclone, or at least at the time steps for which input information is available (usually every six hours), and at the end the maximum wind speed at every location over the domain is retained and used for loss computation purposes.

Storm Surge

Storm surge is a notable seasonal natural coastal hazard which exerts impacts to coastlines and associated infrastructure annually. Storm surge related coastal inundation typically results from increased water levels at the shoreline during the passage of tropical storms and hurricanes or distant swell events. The magnitude of the storm surge and extent of the coastal flooding is related to the intensity of the storm, trajectory, and velocity, the pressure setup, the wave processes and wave setup, the tidal elevation; and the wave runup and overtopping at the shoreline. Hurricane surge assessment is used as a tool to develop the associated wave, surge and flood levels for synthetic hurricane events. The overall process consists of the following:

- Screening synthetic hurricane events to identify the storms corresponding to the desired return period events.
- Simulating these identified storms using more detailed models
- Extracting wave and water level conditions near the shoreline
- Running these extracted conditions through an empirical profile model to estimate wave runup and overtopping.
- Flood elevation and inundation zones are then identified from this information.

In this regard, a computational screening tool (i.e., Numerical Modelling) is used to rapidly simulate the synthetic hurricanes. The Government of Barbados (i.e., via the Coastal Zone Management Unit in association with Baird) has used the MIKE21 Spectral Wave model (MIKE21-SW) to model wave characteristics in nearshore locations. The MIKE21 Flexible Mesh Hydrodynamic model (MIKE21-FM) is used to evaluate wind setup as a function of onshore windspeed and direction. The WAVAD model has been used to model wave characteristics in offshore locations. Understanding wave runup onto the shore is an important step to completing the computational screening tool. In this regard, EurOtop is used to estimate wave runup. Wave runup was selected for this screening tool, rather than overtopping volume, due to the highly nonlinear characteristics of wave overtopping.

Model validation is undertaken in two phases: between modelled and recorded data, and between modelled data from WAVAD (screening tool) and the MIKE21-SW simulations.

Validation is also completed for the measured and modelled surge values. Shore-linear flooding is characterized by flooding that is roughly linear along the shoreline. Meanwhile, overtopped water remains near the shoreline or drains back down the beach face. Therefore, coastal flooding can be approximated by a line that extends along the coast that will approximately follow existing contour lines. Hazard maps are produced based on the computations completed at discrete profile locations around the coastline, and some interpolation between profiles is required.

A8.2 Coastal hazards

Coastal flooding

Coastal high-hazard areas are defined as areas where wave action and/or high velocity water can cause structural damage to buildings during the design storm event. The landward extent of the overtopping flow is calculated using a modified form the Cox-Machemehl (1986) equation which relates the decrease in flow depth with distance from the shore crest. The rate at which a bore loses energy as it moves inland depends on various site-specific factors. FEMA (2005) recommends calculating the initial landward bore propagation distance for a Froude number of

1.8. The calibration factor should be adjusted if this distance does not appear reasonable or match observations. No information on wave overtopping distances from historical hurricanes is available for many countries. Guidance in FEMA (2005) suggests that significant building damage occurs when the product of the flow depth and velocity squared exceeds 5.7 m3/s2 (200 ft3/s2); however, recent post-hurricane damage assessments have identified significant damage outside of coastal high-hazard zones where conditions are predicted to be less severe (FEMA, 2009). For this reason, additional zones have also been defined that are adjacent to coastal high-hazard zones, where some additional caution may be required. The methodology to map where coastal high-hazard zones occur was based on the location of the eroded beach line. The process to create the coastal high-hazard zones is described as follows:

- The eroded beach line defines the position of the 0.6 m elevation beach face. Using a 7:1 beach slope, an eroded beach crest position is determined.
- The eroded beach crest position was then trimmed to the position of the hard-shore line. This means that if the beach face was projected to extend through a revetment or a wall, it was limited to the revetment/wall position.
- The distance of the coastal high-hazard zone was extended inland from the trimmed position described above to a distance defined for each profile from the EurOtop (2016) method.

Manual adjustment is often needed to respond to specific site characteristics. The coastal high-hazard zone may include houses that are protected by walls or the presence of other buildings. The damage level of these buildings will be outlined in the risk assessment.

Flooding due to storm surge is a highly complex process that has many different variables that could impact the results. Some of the key uncertainties are as follows:

- Overtopping and runup estimates: There is significant discrepancy between different methods when assessing runup elevations, particularly overtopping values on more complex profiles. Differences between methods for overtopped volumes of one order of magnitude or more are not unusual. The natural complexity of this process is high, and the uncertainty is significant.
- Beach Profiles: It was assumed that beach profiles are static. No attempt made to predict how a beach berm could build or breach in response to an event, or how the beach may have been altered by the time an event occurs.
- Lateral Variation: Profiles have been extracted at representative locations; however, lateral differences in bathymetry and topography exist, impacting the extent of the runup and overtopping relative to the representative profile.
- Structure Details: In some regions, some walls will impact how water moves inland and flows back to sea. Walls may be solid or have drainage through or under the wall. This level of detail has not been considered.
- Duration of Storm: Key storm events were identified based on their maximum runup and overtopping potential. Some storms may have had lower overtopping, but may have continued for longer for a larger total volume. This could be important to flooding in lower backshore regions and can make some lesser events more important in specific regions.
- Land-side flow paths: Details of how water spreads on the land will affect flooding in some regions. Attempts are made to identify major flow paths, but drainage systems, walls, building and other features will impact how water moves.

- Land-side drainage: Details of the landside drainage were not included in this modelling and concurrent flooding due to other factors such as heavy rainfall and storm water runoff will impact the water depths on land.
- Channels back to the sea: large channels such as Holetown Lagoon can have a large beach berm blocking them. It is reasonable to assume that some level of berm will be present at the start of the storm and/or during the storm. It cannot be assumed that a channel will be clear and operating efficiently during a storm.

Coastal erosion

Shoreline fluctuations are naturally occurring processes that, in and of themselves, are not hazards, and only become hazards when human activities and development encroach within the shoreline. In some instances, these human activities may accelerate the severity of the resulting hazards. Given the naturally complex and dynamic nature of beaches, determining hazard susceptibility of a given beach requires careful assessment of a wide range of parameters. Over the short-term, beach environments, impacted by flood and erosion processes, may undergo alternating periods of erosion and accretion as they attempt to achieve a dynamic equilibrium with the forces acting upon them. Over the long term, beaches experiencing a positive sediment budget (i.e., more sand and gravel incoming than outgoing) are generally accreting shore forms while those experiencing a negative sediment budget are eroding. Considering the future, sea level rise is generally expected to cause shoreline recession as resulting greater depths would allow more wave energy to reach the shoreline. As such, the depiction and evaluation of the hazard susceptibility of beaches in Barbados should be dependent on information and understanding of short-term fluctuations as well as long-term beach sediment budget including potential sea level rise impacts.

The beach erosion hazard assessment relies heavily on historical data to understand how beaches respond to storms within the context of the natural conditions of each beach. There are many beaches that do not have recorded profile data, which necessitates professional judgment to define the erosion hazard. The numerical modelling completed by Baird for the Coastal Risk Assessment and Management Programme (CRMP) work (Baird, 2016) provided insight into beach response in Barbados and sea level rise impacts. Local knowledge of beaches in Barbados and the common underlying cobble layer was important to finalizing an approach for undertaking this study. Erosion rates can be based on historical data (airphotos and satellite images), and through more detailed LIDAR imagery (Pelydryn Ltd. 2015).

The erosion hazard zone was defined based on interpolation of recent historical erosion/accretion trends obtained from profile survey data. While this is believed to be a reasonable approach, the results are expected to be more reliable for beaches located near profile survey stations (i.e., less impacted by the interpolation process). Furthermore, analysis did not explicitly consider the impact of very strong storms that could damage the structures that presently limit beach erosion potential. Without accurate subsurface information, it is impossible to know the exact response of a beach to a very severe storm and how the underlying cobble beach could be changed.

The analysis did not include an assessment of the condition of coastal walls and other defenses that would limit the beach erosion in most developed areas of the coast. The assumption is that these walls, revetments or other structures would be maintained (or rebuilt) to “hold the line” against long term erosion trends. The trimmed hazard zones reflect our knowledge of local structures and how erosion may be limited, but were not based on structural assessments.

Coastal cliffs may be impacted significantly by waves. This may result in significant volumes of water being directed up the cliff's face and even onto the cliff's top and inland via its own momentum and/or via the assistance of wind. In some cases, the force of the up-rushing water may entrain rock from the seabed or cliff face, creating a more serious hazard. The overtopping rates predicted from EurOtop are based on physical model experiments and include splash and spray at vertical walls (such as caisson breakwaters), but do not include the effect of wind on overtopping volumes. Spray may cause additional hazards such as the deterioration of building materials. A building setback is recommended around all coastal cliffs but given the very site-specific nature of the hazard the setback needs to be evaluated on a case-by-case basis (Baird, 2017).

Once all the required information from profile survey stations were mapped and subsequently modified for long-term beach erosion and sea level rise effects, the data was extended through interpolation to cover all the beaches around the island. For this purpose, the existing 0.35 m Lamont Datum (LD) Mean Sea Level (MSL) shoreline was used as a reference line. The line was divided into approximately 3,000 segments of approximately 45 m length each in ArcMap. Interpolated values (i.e., distances of the inshore and seaward limits of the erosion hazard zone from the existing MSL shoreline) were assigned to each segment. Two buffer zones were created, one inshore and the other one seaward of the reference line, for each shoreline segment using the assigned values. Finally, all the buffer zones were merged to create a continuous erosion hazard zone. Finally, the resulting island-wide erosion hazard zone was reviewed for quality control and consistency with the understanding of the beaches in Barbados. Adjustments (e.g., revisions to long-term erosion rates based on more recent trends in beach behaviour) were applied at a few locations until a reasonably acceptable island-wide hazard zone was achieved.

A8.3 Drought-related hazards

Droughts are increasingly significant threats to the Caribbean region, where many states rely heavily on agriculture, tourism, and water resources that are sensitive to climate variability. Fundamentally, drought occurs when there is an extended period of deficient rainfall, which leads to reduced water availability for ecosystems, agriculture, and human consumption. In the Caribbean, climate change and climate variability have exacerbated drought events' frequency, duration, and intensity, making implementing robust drought risk assessment methods essential. These methods are critical in identifying vulnerable areas, guiding water management strategies, and informing mitigation efforts. This section explores various drought risk assessment methods used in the Caribbean, focusing on meteorological, hydrological, agricultural, and socio-economic assessments.

Meteorological Drought Assessment

A prolonged deficit in rainfall characterizes meteorological droughts compared to normal conditions. Several indices are used to assess meteorological drought in the Caribbean. One widely applied tool is the Standardized Precipitation Index (SPI), which measures precipitation deviations from the historical average over multiple time scales, ranging from a few months to several years. The SPI is widely adopted in the Caribbean due to its flexibility and effectiveness in capturing short-term agricultural droughts as well as long-term hydrological droughts

(Centella-Artola et al. 2020; Ayala and Heslar 2019; Beharry et al. 2019). The SPI has also been used in drought projections in the Caribbean. See (Chaulagain et al. 2023; Depsky and Pons 2020; Joyette 2018).

Another critical tool is the Palmer Drought Severity Index (PDSI), which considers precipitation and temperature to estimate soil moisture conditions and drought severity. The PDSI has been employed in the Caribbean to understand drought persistence over a range of time periods. However, the PDSI has limitations in tropical climates, such as the Caribbean, due to its reliance on fixed soil moisture and temperature conditions, which are more applicable to temperate regions. However, the index has been used by several authors, including (Moraes, Mote, and Seymour 2022; Herrera et al. 2018).

Additionally, the Caribbean Drought and Precipitation Monitoring Network (CDPMN), launched by the Caribbean Institute for Meteorology and Hydrology (CIMH) in 2009, provides real-time monitoring of precipitation and drought conditions across the region (Trotman, Mehdi, et al. 2008). The CDPMN monitors drought and precipitation on two scales: (i) regional, encompassing the entire Caribbean basin and (ii) national, using several indices and indicators, and uses various drought indices, including SPI, Deciles to identify emerging drought conditions and inform policymakers (Farrell, Trotman, and Cox 2010). Other indices are also utilised to provide information on normal or abnormal soil moisture, using PDSI, and Crop Moisture Index, CMI or the status of vegetation using the Normalised Difference Vegetation Index. In addition to these drought and precipitation status observations, short-term and medium-term seasonal precipitation projections of future drought and excessive precipitation.

Hydrological Drought Assessment

Hydrological drought occurs when surface and groundwater supplies are deficient, often resulting from extended meteorological droughts. The Caribbean's small island nations are particularly vulnerable to hydrological drought due to their dependence on surface water, groundwater, and limited storage capacity (Piasecki and Harmsen 2022; Beharry et al. 2019).

Streamflow monitoring and groundwater assessments are utilised to assess hydrological droughts (Trotman, Mehdi, et al. 2008). The Standardized Streamflow Index (SSI), similar to the SPI, tracks deviations in streamflow levels and is particularly useful for understanding the temporal and spatial patterns of hydrological drought. In regions like Jamaica and Barbados, where surface water resources are crucial, monitoring streamflow has proven essential in managing water resources during drought conditions (Cashman et al., 2010).

Groundwater assessments in the Caribbean are more complex due to the limited data available on aquifers. Remote sensing technologies, such as satellite-based Gravity Recovery and Climate Experiment (GRACE) data, have been employed in recent years to estimate groundwater storage changes, although their application in the Caribbean is still developing (Longuevergne, Scanlon, and Wilson 2010). These assessments are crucial for managing the region's water supply, particularly in countries like Antigua and Barbuda, where groundwater is the primary source of potable water (Boger and Perdikaris 2022).

Agricultural Drought Assessment

Agricultural drought, which occurs when soil moisture levels are insufficient to support crop growth, is a significant concern in the Caribbean due to the region's reliance on agriculture for food security and economic stability (Barker 2012; Simpson, Scott, and Trotz 2011). Several drought risk assessment tools are used to gauge the impact of drought on agricultural productivity.

The Normalised Difference Vegetation Index (NDVI), derived from satellite imagery, monitors vegetation health and stress by measuring the difference between near-infrared and red-light reflectance from plants. In the Caribbean, NDVI has been successfully used to track vegetation changes during drought periods, such as in the drought-prone regions of Haiti and the Dominican Republic, providing an early warning system for agricultural stress (Alexander and Thongs 2023; Elusma, Tung, and Lee 2022; Barker 2012).

Additionally, soil moisture monitoring is critical to agricultural drought assessment. The Crop Moisture Index (CMI), an offshoot of the PDSI, assesses short-term moisture conditions affecting crop yields. The CMI is particularly useful in the Caribbean for predicting immediate crop conditions and guiding irrigation planning in the agricultural sectors of islands such as Cuba and the Dominican Republic (Singh 1997).

Socio-Economic Drought Assessment

Socio-economic drought results from the complex interplay between natural drought events and human systems, affecting water availability, food production, and livelihoods. Assessing socio-economic drought in the Caribbean requires integrating data on water demand, agricultural dependence, economic factors, and community vulnerability.

Vulnerability assessments incorporating socio-economic indicators, such as income, employment in agriculture, and access to water resources, are increasingly used in the Caribbean to understand how different communities are impacted by drought (Pulwarty, Nurse, and Trotz 2010). For example, vulnerability assessments in St. Vincent and the Grenadines have helped prioritise water distribution efforts during prolonged droughts by identifying the most at-risk populations (Scott, Simpson, and Sim 2012).

Additionally, Integrated Drought Management Programs (IDMP), led by the CIMH and other regional bodies, are increasingly focusing on the socio-economic impacts of drought. These programs aim to create a holistic drought management framework by combining meteorological, hydrological, agricultural, and socio-economic data to inform decision-making and reduce the risk of drought-related crises (Trotman et al. 2021; Moore, Elliott, and Lorde 2017; Rhiney 2015; Farrell, Trotman, and Cox 2010).

Conclusion

Drought risk assessment in the Caribbean is multi-dimensional, involving meteorological, hydrological, agricultural, and socio-economic methods (Joyette 2018). While traditional tools like the SPI and PDSI are widely used for meteorological assessments, advances in satellite technology and remote sensing enhance hydrological and agricultural assessments. Additionally, socio-economic assessments are critical for understanding the broader impacts of drought on vulnerable populations and guiding resource allocation. As drought risks increase due to climate change, integrating these assessment methods will be vital for developing effective drought management and mitigation strategies across the Caribbean at the local and regional levels.

A8.4 Geological Hazards

The Caribbean region is highly susceptible to geological hazards due to its location at the intersection of several tectonic plates, including the Caribbean, North American, South American, and Atlantic plates. These tectonic interactions give rise to frequent earthquakes, volcanic eruptions, and the potential for tsunamis. Understanding these hazards is crucial for assessing risk and implementing strategies for disaster risk reduction in the Caribbean (WorldBank, 2018).

Earthquakes

The Caribbean is part of an active seismic zone, with tectonic activity resulting from the movement of the Caribbean Plate. Earthquakes in the region are typically caused by subduction zones, transform faults, and other tectonic boundaries, making many Caribbean islands particularly vulnerable. The most seismically active areas include Puerto Rico, the Dominican Republic, Haiti, and the Lesser Antilles arc.

Notably, Haiti experienced a devastating earthquake in 2010, which resulted in significant loss of life, widespread infrastructure damage, and long-term socio-economic impacts. Seismic activity continues to pose a threat to urban centers in the Caribbean.

Earthquake preparedness in the Caribbean includes building codes to improve structural resilience, public education campaigns on earthquake safety, and seismic monitoring systems to provide early warnings and better preparedness. Detailed seismic hazards maps for the Easter Caribbean have been developed by the UWI Seismic Research Centre and can be found at the link: https://uwiseismic.com/downloads/seismic-hazard-map/

Tsunamis

Tsunamis are often triggered by underwater seismic activity, landslides, or volcanic eruptions. In the Caribbean, the potential for tsunamis is significant due to the region's seismic activity and underwater volcanic eruptions. Though not as frequent as other hazards, the destructive potential of tsunamis necessitates comprehensive risk assessments and preparedness.

The Eastern Caribbean islands lie in a setting where major structural changes are occurring in the Earth's crust. All known sources capable of causing tsunamis (that is, earthquakes, volcanic eruptions, landslides) occur within striking distance of the Eastern Caribbean, and there are also distant sources across the Atlantic. Since the islands lie in an area of relatively high earthquake activity for the Caribbean, the most likely tsunamis to affect the Eastern Caribbean are those which can be triggered by shallow earthquakes (less than 50 km depth), in the region, greater than magnitude 6.5.

In the past 500 years there have been ten confirmed earthquake-generated tsunamis in the Caribbean Basin with four causing fatalities. There have been several tsunami events in the Caribbean, such as the 1946 tsunami in the Dominican Republic, which caused widespread flooding and casualties. The historical record suggests that potentially destructive tsunamis occur at an average rate of 1-2 per century in the Caribbean. The recurrence rate for tsunamis in the Caribbean is approximately: 1 destructive tsunami per century for local earthquakes and 1 destructive tsunami per 200 years for distant earthquakes. It should be noted that these recurrence rates are small, but not negligible.

Tsunamis caused by large volcanic eruptions at or below sea level also pose a threat to the Eastern Caribbean. The submarine (underwater) volcano Kick-‘em-Jenny located 9 km north of Grenada erupts on average every 11 years. At least two of those eruptions, in 1939 and 1965, generated small tsunamis that were witnessed on the north coast of Grenada.

The International Tsunami Information Center - Caribbean Office (ITIC-CAR) supports domestic and international tsunami warning services and programs in the Caribbean and adjacent regions. The office focuses on strengthening and sustaining the tsunami observational system as well as the continued enhancement of tsunami outreach, education and readiness, including the implementation of the TsunamiReady® and international Tsunami Ready Programs. If an earthquake occurs that can or has triggered a tsunami that may affect the Caribbean, the Pacific Tsunami Warning Center (PTWC) will send a bulletin to Tsunami Warning Focal Points – the official agency responsible for receipt of the warning message in each Caribbean country. Communicating this warning to the public is the responsibility of the national disaster management agency in each country.

Volcanoes

The Eastern Caribbean, particularly the Lesser Antilles, is home to several active volcanic systems. Islands such as Montserrat, Dominica, St. Vincent, and Martinique are at high risk due to active volcanoes like the Soufrière Hills and Mount Pelée. Volcanic eruptions can lead to pyroclastic flows, ashfall, and lahars, which can devastate communities, agriculture, and infrastructure. Details of volcanoes and volcanic hazard assessments can be found in Lindsay et al. (2005).

The eruption of Soufrière Hills in Montserrat (1995-present) displaced much of the island's population and rendered parts of the island uninhabitable. It serves as a stark reminder of the long-term effects of volcanic activity. More recently the 2020/2021 eruption of La Soufrière volcano, St. Vincent is a reminder of the hazards that volcanoes pose and the impacts that can affect neighboring islands (Joseph et al., 2022).

The Seismic Research Centre (SRC) at the University of the West Indies monitors volcanic activity in the region, providing early warning and coordinating evacuation plans. Continued investment in volcanic monitoring and emergency response is essential to mitigate risks. Detailed volcanic hazard maps are available from the UWI SRC’s website at the link: https://uwiseismic.com/downloads/volcanic-hazard-atlas-of-the-lesser-antilles/

Interrelation of Geological Hazards

Geological hazards such as earthquakes, tsunamis, and volcanic eruptions are often interrelated. For instance, undersea earthquakes may trigger tsunamis, while volcanic activity may lead to seismic unrest. Multi-hazard risk assessments must consider these interconnected risks to develop more robust preparedness and response strategies.

Risk Reduction Strategies

Efforts to reduce geological hazard risks in the Caribbean focus on a combination of structural and non-structural measures:

- **Structural**: Strengthening building codes, retrofitting vulnerable structures, and designing tsunami barriers in high-risk areas.

- **Non-Structural**: Public education, early warning systems, and evacuation plans are crucial in reducing the loss of life during these events. Regional collaboration on seismic and volcanic monitoring further enhances the preparedness and resilience of Caribbean nations.

Volcanic risk management planning and awareness activities are the primary volcanic hazard mitigation strategies implemented by UWI-SRC for the Caribbean. These activities include the preparation of volcanic hazard maps for the Antilles region and the volcanic hazard atlas of comprehensive geological and volcanological data for each volcanic island (Lindsay et al 2005), as well as the development of volcanic alert-level systems for each island (Joseph et al 2022).

A8.5 Environmental and health hazards

The Caribbean region, characterized by its unique geography and climate, faces a multitude of environmental and health hazards that significantly impact its population. These hazards include diseases, epidemics, and pollution, which are exacerbated by various socio-economic and environmental factors. This section aims to explore these challenges, to provide an overview of the situation in the Caribbean.

Environmental Pollution and Its Health Impacts

Air pollution is a critical concern in the Caribbean, with various studies highlighting its detrimental effects on public health. The region experiences high levels of particulate matter (PM), nitrogen oxides (NOx), and ozone (O3), primarily due to industrial activities, vehicular emissions, and seasonal dust intrusions from Africa (Husaini et al., 2022; Baboola et al., 2019). For instance, the presence of African dust has been linked to respiratory diseases, exacerbating conditions such as asthma and chronic obstructive pulmonary disease (COPD) (Plocoste et al., 2018; Euphrasie-Clotilde , 2017). The Statistical Air Pollution Index (API) for Trinidad and Tobago indicates that air quality is significantly affected by both local and transboundary pollution, leading to increased respiratory and allergic responses among the population (Plocoste et al., 2018).

Moreover, the health implications of air pollution are profound. Long-term exposure to PM2.5 and other pollutants has been associated with increased mortality rates from cardiovascular diseases and lung cancer (Yu et al., 2021; Johnson, 2015). A systematic review of air pollution and public health in Latin America and the Caribbean found that vulnerable populations, particularly those in lower socio-economic strata, are disproportionately affected by these health risks (Vinck et al. 2021; Machin et al., 2019). This disparity underscores the need for targeted public health interventions and policies aimed at reducing pollution levels and protecting at-risk communities.

Water Quality and Vector-Borne Diseases

Water quality is another significant environmental health issue in the Caribbean. The region faces challenges related to the contamination of freshwater sources due to agricultural runoff, inadequate wastewater management, and the presence of persistent organic pollutants (POPs) and heavy metals (DeVito et al., 2022). These contaminants pose serious health risks, including gastrointestinal diseases and other waterborne illnesses. The reliance on rainwater harvesting systems further complicates the situation, as the microbial quality of harvested water often remains unmonitored (Hajat et al., 2015).

In addition to water quality issues, vector-borne diseases (VBDs) such as dengue, chikungunya, and Zika virus pose substantial public health challenges in the Caribbean. The region's tropical climate creates ideal conditions for the proliferation of mosquito populations, which are responsible for transmitting these diseases (Hajat et al., 2015; George et al., 2019). The health systems in many Caribbean nations are often ill-equipped to handle outbreaks of VBDs, leading to increased morbidity and mortality rates (George et al., 2019). Strengthening health systems and enhancing surveillance capabilities are critical for managing these diseases effectively.

The Impact of Climate Change

Climate change exacerbates existing environmental health hazards in the Caribbean (e.g., heatwaves increasing vector-borne diseases). Rising temperatures and changing precipitation patterns contribute to the increased frequency and intensity of extreme weather events, such as hurricanes and floods, which can disrupt healthcare services and lead to outbreaks of infectious diseases (Johnson, 2015). The 2017 hurricanes that struck Puerto Rico and other islands highlighted the vulnerabilities of the region's health infrastructure and the need for comprehensive disaster preparedness and recovery plans.

Furthermore, climate change influences air quality by increasing the concentration of ground-level ozone and other pollutants, which can trigger respiratory problems and other health issues (DeVito et al., 2022). The interplay between climate change, pollution, and health outcomes necessitates a multi-faceted approach to environmental health in the Caribbean, incorporating strategies for mitigation and adaptation.

Socioeconomic Factors and Health Disparities

Socioeconomic disparities play a significant role in shaping health outcomes in the Caribbean. The region is characterized by high levels of poverty and inequality, which limit access to healthcare services and resources necessary for maintaining good health. Migratory patterns of health professionals seeking better opportunities abroad further exacerbate the challenges faced by local health systems, leading to shortages of qualified personnel. Research indicates that Caribbean-born individuals diagnosed with prostate cancer in the region face significantly higher mortality rates compared to those diagnosed in the United States, highlighting the disparities in healthcare access and quality (Mutetwa et al., 2010). Addressing these disparities requires targeted interventions that focus on improving healthcare access, enhancing the quality of services, and addressing the social determinants of health.

The Caribbean faces a complex interplay of environmental and health hazards that significantly impact its population. Pollution, water quality issues, vector-borne diseases, climate change, and socioeconomic disparities all contribute to a challenging public health landscape. Addressing these issues requires a coordinated effort involving policy changes, community engagement, and investment in health infrastructure. By prioritizing environmental health and addressing the underlying social determinants, the Caribbean can work towards a healthier future for its inhabitants. It is important here to highlight initiatives like the Caribbean Public Health Agency (CARPHA) and their role in addressing multi-hazard health risk.

A8.6 Anthropogenic hazards

The Caribbean region, characterized by its unique geographical and socio-economic landscape, faces a multitude of anthropogenic hazards that significantly impact its communities and ecosystems. These hazards can be broadly categorized into three main types: accidents, civil unrest, and transportation hazards. Each of these categories presents distinct challenges that require comprehensive understanding and strategic management to mitigate their effects.

Accidents in the Caribbean often stem from industrial activities, environmental mismanagement, and infrastructural inadequacies. The region's vulnerability to such accidents is exacerbated by its economic reliance on tourism and agriculture, which can lead to neglect in safety regulations and environmental protections. For instance, the accumulation of hazardous waste, particularly electronic waste, poses severe health risks to local populations, as highlighted by (Turner et al, 2021). The presence of heavy metals and other contaminants in the environment can lead to chronic health issues, particularly among children who are more susceptible to environmental toxins. Furthermore, the historical trajectories of disaster risk in Caribbean nations, as discussed by Barclay et al. (2018), reveal a pattern of short-sighted policy decisions that have increased exposure to industrial accidents and environmental hazards. Oil spills can have a devastating impact on Caribbean coastlines and associated Blue Economy sectors such as Coastal Tourism, Fisheries, etc. This threat esists due to numerous oil tankers that traverse the Caribbean sea and the emerging threat from offshore oil exploration. Map of Oil Tanker traffic: https://blog.refinerymaps.com/2016/01/oil-tanker-ocean-traffic-maps.html

Civil unrest in the Caribbean is often fueled by socio-economic disparities, political instability, and environmental degradation. The region has witnessed numerous protests and uprisings, particularly in response to government policies perceived as detrimental to public welfare. The interplay between environmental hazards and civil unrest is significant; for example, the lack of adequate responses to natural disasters can lead to public discontent and unrest, as communities feel neglected by their governments Barclay et al. (2018). Moreover, the economic instability resulting from reliance on tourism and external financing can exacerbate tensions, leading to civil disturbances that further complicate disaster response efforts (Liu et al., 2022).

Transportation hazards in the Caribbean are particularly concerning due to the region's reliance on maritime and aerial transport for both tourism and trade. The impacts of climate change, including rising sea levels and increased frequency of severe weather events, pose significant risks to transportation infrastructure. Lempert el at. (2021) emphasize the need for risk management frameworks that can address the vulnerabilities of transportation systems in the face of climate-related hazards. Additionally, the Caribbean's geographical isolation complicates logistics and emergency response, making it imperative to develop resilient transportation networks that can withstand environmental shocks (Amat et al., 2022). The integration of climate risk assessments into transportation planning is essential for enhancing the resilience of these critical infrastructures (Hoagland-Grey , 2015).

The intersection of these anthropogenic hazards reveals a complex web of vulnerabilities that Caribbean nations must navigate. For instance, the environmental impacts of industrial accidents can lead to public health crises, which in turn may fuel civil unrest as communities demand accountability and action from their governments. Similarly, the degradation of transportation infrastructure due to climate-related hazards can hinder emergency response efforts during accidents or civil disturbances, exacerbating the overall impact on communities.

In addressing these challenges, it is crucial for Caribbean nations to adopt a multidisciplinary approach that incorporates environmental science, public health, and socio-political analysis. The integration of disaster risk reduction strategies with sustainable development goals can foster resilience against both natural and anthropogenic hazards. For example, the implementation of stricter regulations on hazardous waste management, as suggested by Oliveira et al. (2023), can mitigate the risks associated with industrial accidents while also promoting environmental sustainability.

Furthermore, enhancing community engagement in disaster preparedness and response can empower local populations to take proactive measures against civil unrest and accidents. Kelman (2017) highlights the importance of community-driven initiatives in building resilience, particularly in island contexts where traditional top-down approaches may fall short. By fostering a culture of preparedness and collaboration, Caribbean nations can better equip themselves to handle the multifaceted challenges posed by anthropogenic hazards.

In conclusion, the Caribbean region faces a myriad of anthropogenic hazards that necessitate a comprehensive and integrated approach to risk management. By understanding the interconnectedness of accidents, civil unrest, and transportation hazards, stakeholders can develop effective strategies to mitigate their impacts. The path forward requires collaboration among governments, communities, and international partners to build a resilient Caribbean that can withstand the challenges of the 21st century.

Annex 9: Climate change and hazards in the Caribbean context.

Hurricanes and Tropical Storms

The Caribbean is highly susceptible to hurricanes and tropical storms, which are expected to become more intense due to climate change (Cavallo *et al.* 2024; Hernández-Delgado *et al.* 2024; Vosper et al., 2020; Fuller et al., 2020). While the frequency of hurricanes may not significantly increase, the intensity of storms, especially Category 4 and 5 hurricanes, is expected to rise due to warmer ocean temperatures (Knutson *et al.* 2015). Warmer sea surface temperatures provide more energy to fuel tropical cyclones, making them more powerful and causing higher wind speeds, heavier rainfall, and more significant storm surges (ELeader 2024; Knutson *et al.* 2021; Jagessar, 2023).

Recent hurricanes, such as Hurricane Irma, Maria (2017) and Hurricane Dorian (2019), demonstrate the devastating potential of stronger storms in the region. Irma caused widespread destruction across several Caribbean islands, including Barbuda, Anguilla, and the Virgin Islands, while Dorian devastated parts of the Bahamas (Eppinga and Pucko 2018; UN 2018). Assessing the risks posed by hurricanes under climate change requires advanced climate models that account for projected sea surface temperatures and atmospheric conditions. When combined with satellite imagery and global climate models, historical data help forecast future hurricane behaviour and inform preparedness efforts (NOAA 2020).

Sea-Level Rise and Coastal Erosion

Sea-level rise is one of the most significant impacts of climate change in the Caribbean. The IPCC projects that global sea levels could rise by as much as 1 meter by 2100 if greenhouse gas emissions continue unchecked (Masson-Delmotte *et al.* 2021). For the Caribbean, this severely threatens coastal communities home to a significant portion of the region's population (Martyr-Koller *et al.* 2021; Scott, Simpson, and Sim 2012). Coastal cities, tourism infrastructure, and ecosystems such as mangroves and coral reefs are at risk of inundation and erosion (Soanes *et al.* 2023). Rising seas exacerbate storm surges during hurricanes and tropical storms, increasing the risk of flooding in low-lying areas.

Coastal erosion is another primary concern, as rising sea levels and stronger wave action gradually wear away shorelines, endangering human settlements and critical ecosystems (USGCRP 2018; Simpson *et al.* 2012). Assessing the risks of sea-level rise involves mapping coastal vulnerabilities, using satellite data to monitor shoreline changes, and modelling future scenarios of sea-level rise and coastal impacts (USGCRP 2018). Countries like Jamaica and Barbados have implemented coastal zone management plans that include regular erosion and flood risk assessments, but more comprehensive, region-wide approaches are needed to address the scale of the threat (Thomas *et al.* 2019).

Flooding and Changing Precipitation Patterns

Climate change is altering rainfall patterns across the Caribbean, leading to increased flooding risks and more prolonged periods of drought. Increased temperatures intensify the hydrological cycle, leading to more extreme precipitation events. This can result in flash floods, landslides, and river flooding, especially in areas where drainage systems are inadequate to handle sudden increases in water volume (Mycoo 2018).

Assessing flood risks under climate change requires detailed hydrological modelling to account for changes in rainfall intensity, duration, and frequency (O'Shea *et al.* 2024). In the Dominican Republic and Saint Lucia, climate models indicate that more intense rainfall events are likely to increase in frequency, making urban and agricultural areas more prone to flash flooding (Karmalkar *et al.* 2013; Taylor *et al.* 2012). Remote sensing technologies, such as satellite-based monitoring and ground-based observations, help provide real-time data on rainfall patterns and flood risks .

In addition to flash flooding, sea-level rise exacerbates the risk of coastal and urban flooding (Mycoo 2018). Saltwater intrusion into freshwater aquifers is another challenge associated with rising seas, particularly in island nations that rely heavily on groundwater for their water supply (CCCCC 2020).

Droughts and Water Scarcity

While some areas of the Caribbean are becoming wetter, others are experiencing more prolonged and severe droughts. The Caribbean has always been prone to droughts (Joyette 2018), but climate change is expected to exacerbate these conditions by increasing temperatures and changing rainfall patterns. Islands such as Barbados, Antigua and Barbuda, and Saint Vincent and the Grenadines have experienced severe droughts in recent years, affecting agriculture, water resources, and energy production (Trotman *et al.* 2017; Joyette 2015; Farrell, Trotman, and Cox 2010).

Drought assessments rely on climate models that simulate precipitation changes and soil moisture levels under different climate scenarios. The Standardised Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI) are commonly used to assess drought severity and monitor long-term trends. In the Caribbean, the Caribbean Institute for Meteorology and Hydrology (CIMH) plays a crucial role in tracking and predicting drought conditions (Trotman *et al.* 2017). However, the region requires more robust early warning systems to provide timely information on impending droughts and water scarcity (Ward *et al.* 2020; CIMH 2019).

Annex 10 Overview of Earth Observation datasets for exposure analysis

Land Cover
• ESA CCI Land Cover (provided by Copernicus C3S service) https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-land-cover?tab=overview • Copernicus CLMS Dynamic Land Cover https://land.copernicus.eu/en/products/global-dynamic-land-cover • Google Dynamic World https://developers.google.com/earth-engine/datasets/catalog/GOOGLE_DYNAMICWORLD_V1 • Esri Land Cover https://livingatlas.arcgis.com/landcover/ • ESA World Cover https://esa-worldcover.org/en • UMD GLAD https://glad.umd.edu/projects/global-land-cover-and-land-use-monitoring-support-environmental-sustainability • GLC_FCS30D https://gee-community-catalog.org/projects/glc_fcs/ • CORINE Land Cover (only Europe) https://land.copernicus.eu/en/products/corine-land-cover
Crop Information
• WorldCereal https://esa-worldcereal.org/en • Landsat-derived global rainfed and irrigated-cropland https://lpdaac.usgs.gov/products/lgrip30v001/ • Plantations https://doi.org/10.1038/s41597-022-01332-3 • Global Agro-Ecological Zones (AEZ): Actual yields and production https://gaez.fao.org/pages/theme-details-theme-5 • Global Yield Cap Atlas https://www.yieldgap.org/web/guest/coverage-and-data-download
Livestock
• Gridded Livestock Density https://dataverse.harvard.edu/dataverse/glw_4
Built-up area
• GHS built-up surface grid https://human-settlement.emergency.copernicus.eu/ghs_buS2023.php GHS building height https://human-settlement.emergency.copernicus.eu/ghs_buH2023.php GHS Settlement Characteristics https://human-settlement.emergency.copernicus.eu/ghs_buC2023.php • Google Open Buildings https://sites.research.google/open-buildings/#download https://developers.google.com/earth-engine/datasets/catalog/GOOGLE_Research_open-buildings_v3_polygons • Bing Global Building Footprints https://github.com/microsoft/GlobalMLBuildingFootprints
Infrastructure
• Essential services, transportation infrastructure, artificial waterways https://www.hotosm.org/ • Facilities GRID3 (Africa) https://data.grid3.org/search?sort=Date%20Created%7Ccreated%7Cdesc&tags=POI
Population
• WorldPop https://www.worldpop.org/ • GHS population grid multitemporal https://human-settlement.emergency.copernicus.eu/ghs_pop2023.php • Gridded GDP Projections https://doi.org/10.3389/fbuil.2021.760306 • Global population age https://doi.org/10.1038/s41597-024-03864-2 • Travel time to healthcare facilities https://doi.org/10.1038/s41591-020-1059-1

- Projected Population and Poverty https://datacatalog.worldbank.org/search/dataset/0065627/Climate-Change-Knowledge-Portal--Projected-Population-and-Poverty-0-25-degree
- NASA nighttime lights: https://www.earthdata.nasa.gov/learn/backgrounders/nighttime-lights

Building data can be obtained from a number of global datasets, such as through crowdsourcing (OpenStreetMap[2]), Artificial Intelligence (Microsoft Building Footprints[3], Google Open Buildings[4], OpenBuildingMap[5]), and Built-up area from Satellite data (World Settlement Map[6], Global Human Settlement Layer[7]). Population data can be obtained from a number of international data sources - LandScan[8] , WorldPop[9] , GHS[10] , Gridded Population of World Version 4 (GPWv4)[11], and META High-resolution population Density Maps[12]. Population

characteristics can be obtained from the PopGrid intiative[13] Land use/land cover data can be obtained from a number of global data sources, such as Global Forest Cover [14], Copernicus Land cover [15], CORINE Land Cover (CLC)[16], GlobCover (from ENVISAT, MERIS)[17], ESA WorldCover[18]. See also Table 6.3.

[2] https://www.openstreetmap.org/#map=10/42.7289/41.4349

[3] https://planetarycomputer.microsoft.com/explore?c=34.9555%2C30.1416&z=1.11&v=2&d=ms-buildings&m=Global&r=Default&s=false%3A%3A100%3A%3Atrue&sr=desc&ae=0

[4] https://sites.research.google/open-buildings/#explore

[5] https://www.openbuildingmap.org/

[6] https://geoservice.dlr.de/web/maps/eoc:wsfevolution

[7] https://ghsl.jrc.ec.europa.eu/data.php

[8] http://www.ornl.gov/sci/landscan/

[9] http://www.worldpop.org.uk/

[10] https://ghsl.jrc.ec.europa.eu/data.php#GHSLBasics

[11] https://sedac.ciesin.columbia.edu/data/collection/gpw-v4

[12] https://dataforgood.facebook.com/dfg/tools/high-resolution-population-density-maps

[13] https://www.popgrid.org/high-resolution-gridded-population-datasets-latin-america-and-caribbean-using-official-statistics-0

[14] https://www.globalforestwatch.org/

[15] https://lcviewer.vito.be

[16] https://land.copernicus.eu/pan-european/corine-land-cover

[17] http://due.esrin.esa.int/page_globcover.php

[18] https://esa-worldcover.org/en

Figure 6.1: Available building data for Roseau (Dominica). Left : Microsoft AI generated building footprints. Right: OpenBuildingMap with occupancy classes generated through AI (source: GFZ)

Annex 11 Methods for generating vulnerability curves

Group	Method	Description
Empirical methods	**Analysis of observed damage**	Based on the collection and analysis of statistics of damage that occurred in recent and historic events. Relating vulnerability to different hazard intensities (Fuchs et al., 2007)
	Expert opinion	Based on asking groups of expert on vulnerability to give their opinion, e.g., the percentage damage they expect for the different structural types having different hazard intensities. In order to come to a good assessment of the vulnerability, many experts have to be asked, and this is time-consuming and subjective in general. Re-assessments of vulnerability after building upgrade or repair are difficult to accommodate (Godfrey at al, 2015)
	Score Assignment	The method uses a questionnaire with different parameters to assess the potential damages in relation to different hazard levels. The score assignment method is easier to update e.g., if we think about earthquake vulnerability before and after the application of retrofitting (Papathome-Kohle et al., 2019).
Analytical models	**Simple Analytical models**	Studying the behavior of buildings and structures based on engineering design criteria, analyzing e.g., seismic load and deriving the likelihood of failure, using computer-based methods from geotechnical engineering. Using e.g. shake tables and wind tunnels, as well as computer simulation techniques (Gentile et al, 2022)
	Detailed Analytical methods	Using complex methods. It is time-consuming, needs a lot of detailed data, and will be used for the assessment of individual structures (Galasso ret al., 2021)

Annex 12: Overview of software tools for Multi-Hazard Risk Assessment

Description and relevance for PARATUS	Evaluation
CAPRA (Probabilistic Risk Assessment: https://ecapra.org/ The CAPRA) Platform was an initiative of the World Bank GFDRR that aimed to develop a multi-hazard risk assessment tool to strengthen the institutional capacity for assessing, understanding, and communicating disaster risk, with the ultimate goal of integrating disaster risk information into development policies and programs. Under the CAPRA platform, government, institutions, private companies, and other agencies address specific development challenges and meet disaster risk information needs through specialized software applications, extensive documentation, consultancy and advisory services, hands-on practical training, and other complementary services. The CAPRA suite of standalone tools offered a range of tools for probabilistic hazard modelling, an exposure module, a vulnerability database module, and the CAPRA-GIS for probabilistic risk assessment.	Unfortunately, the tools are no longer updated and many of them do no longer function.
HAZUS: https://www.fema.gov/flood-maps/products-tools/hazus  HAZUS is a standardized methodology developed by the Federal Emergency Management Agency (FEMA) in the USA. The freely available software package called HAZUS-MH (for Multi-Hazard) gives users access to FEMA's models for estimating potential losses from earthquakes, floods, and hurricanes. The software package uses Geographic Information Systems (GIS) technology to estimate physical, economic, and social impacts of disasters. It graphically illustrates the limits of identified high-risk locations due to earthquake, hurricane, and floods. Users can then visualize the spatial relationships between populations and other, more permanently fixed geographic assets or resources for the specific hazard being modelled, a crucial function in the pre-disaster planning process.	Extensive documentation It runs under ARCGIS, and requires expertise in GIS analysis. Method should be adjusted to Caribbean situation.
RiskScape: https://riskscape.org.nz/ RiskScape is an open-source spatial data processing application used for multi-hazard risk analysis. It is highly customisable, letting modellers tailor the risk analysis to suit the problem domain and input data being modelled. It provides a flexible data processing framework for building and executing geospatial risk models, and can take a variety of input layers and geospatially stitch them together. For example, RiskScape can take a building portfolio and a flood hazard map and analyse the flood depth (if any) that each building was exposed to. It is expected that CLI users have a working knowledge of the command line for the operating system they are using. Commands and examples used in this documentation are all used from a Unix terminal and tested using Windows PowerShell. The system has been completely redeveloped recently.	The software itself is written in Java. There is no Graphical The software requires knowledge of the RiskScape Command Line Interface (CLI). User should have programming background
OpenQUAKE: https://www.globalquakemodel.org/ openquake The OpenQuake Engine is the Global Earthquake Model Foundation's (GEM) state-of-the-art, open-source software collaboratively developed for earthquake hazard and risk modelling. It runs on operating systems such as Linux, macOS and Windows; and can be deployed on laptops, desktops, standalone servers, and multi-node clusters. The functionality to analyse hazard and risks at specific site, city, country, or regional level makes the OpenQuake Engine a powerful and dynamic tool for assessing the potential impacts of earthquakes at any location in the world.	It only addresses earthquake hazards. Has very good tools and documentation

SaferPlaces: https://saferplaces.co/ SaferPlaces Global Platform AI-based Digital Twin Solution for Flood Risk Intelligence. Geospatial, Satellite, Climate Data and AI-based models combined into a cloud computing environment provides incredible insights in terms of flood risk intelligence. SaferPlaces leverages the increasing availability of high resolution geospatial and climate open data from Google Earth Engine (GEE), Open Street Map (OSM), Microsoft Planetary, AMAZON and Copernicus which are integrated automatically	Focuses only on flooding. A commercial solution, ranging between 3-20 Euro/km^2/year.
CLIMADA: https://wcr.ethz.ch/ research/climada.html a Python-based software tool that allows to estimate the expected economic damage as a measure of risk today, the incremental increase from economic growth and the further incremental increase due to climate change. It provides global coverage of major climate-related extreme-weather hazards at high resolution via a data API, namely tropical cyclones, river flood, agricultural drought, winter storms and wildfires, all at 4km spatial resolution. For all hazards, historic and probabilistic event sets exist, for some also under select climate forcing scenarios (RCPs) at distinct time horizons (e.g., 2040). CLIMADA is developed, maintained and available open-source in Python 3.x Free use and access under GNU GPL3 GitHub made. Data freely available under CC BY 4.0 via the CLIMADA data API (application programming interface, metadata provided).	Very good solution, but doesn't have a Graphical User Interface. Users should know Python.
INFORM Risk https://drmkc.jrc.ec.europa.eu/ inform-index/INFORM-Risk/Methodology INFORM RISK A global, open-source qualitative tool for risk assessment for humanitarian crises and disasters. It has three dimensions: hazard & exposure, vulnerability, and lack of coping capacity. Each dimension encompasses different categories, which are user-driven concepts related to the needs of humanitarian and resilience actors. In order to accommodate the INFORM Risk methodology, where the vulnerability variable is split among three dimensions, the equation is updated to: Risk = Hazard & Exposure 1/3 × Vulnerability 1/3 × Lack of coping capacity 1/3. It is a multiplicative equation. A composite index is typically a compromise between a data driven and a user driven model. There are always some components which existing data cannot describe, especially if the demands for quality of data are very high.	The tool is most used globally for prioritizing administrative areas with respect to DRR programmes. Provides no quantitative estimate.
VIGIRISKS: https://www.vigirisks.fr/ vigirisks natural hazards FLOOD EARTHQUAKE LANDSLIDE Vigirisks is a French scientific service platform that enables users to access and run calculations, processing operations or modelling simulations concerning natural risks, while also ensuring the traceability of the data. Designed by BRGM but also open to a wider community. Used also in French Caribbean. Users can access the data available at BRGM as well as external reference data to which they can add their own project data (e.g. time-scale, rainfall, etc.).	Not freely available. Only for organisations that work with the French BRGM.
INSAFE : http://www.inasafe.org InaSAFE www.inasafe.org initiated as a partnership between the World Bank, GFDRR, the Australian Government and BNPB Indonesia, is being adopted by DRR practitioners around the world. It provides a platform for users to reproduce historical scenarios or use predictive or probabilistic to investigate the potential impact. The software can freely be copied and shared (along with QGIS, its underlying platform), making the barrier to entry very low for use of the tool by DRR practitioners. The open nature of the software and the specific architectural approach allow it flexibility and easy customization to the specific needs of a geographic region, institution, or government agency.	It works with QGIS. However, it seems recent development is less.

RiskChanges: https://riskchanges.org/ An open-source web-based Spatial Decision Support tool for the analysis of Dynamic Multi-Hazard risk. The system is developed for local authorities to evaluate the current multi-hazard risk situation , analyze how this will change under future scenarios, and compare risk reduction alternatives. Users can work with any hazard and asset data, either from internet sources or uploading them. The systems also has a build-in vulnerability curve database. Cost-Benefit analysis and multi-criteria module are available in the near future.	Open source and freely available. Is still under development, and some issues remain.
SPHERA: https://www.ccrif.org/publications/technical-paper/evolution-ccrifs-parametric-insurance-models  The Caribbean Catastrophe Risk Insurance Facility (CCRIF) has recently developed a new in-house System for Probabilistic Hazard Evaluation and Risk Assessment (SPHERA). The models are designed to evaluate the risk to windstorms (stormsurges and wind damage) and earthquakes. The EQ hazard module uses a probabilistic seismic hazard assessment (PSHA) technique that combines the frequency of occurrence of future earthquakes in time and space and the evaluation of the ground motion random fields generated by each event. The TC hazard module was designed to statistically estimate the impact of future tropical cyclones, storms, and tropical depressions either by-passing or making landfall in any of the countries considered.	Proprietary model developed by and owned by CCRIF.