

Preparing the Built Environment in Grenada for Future Sea Level Rise and Extreme Precipitation Events

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Executive Summary

Communities across the globe are being affected by climate change in numerous ways. However, those most often affected, especially by sea level rise, are those small island nations that are pressed for space already; this includes the island of Grenada. Grenada is located in the southern portion of the Caribbean and is bordered by the Caribbean Sea (West) and the Atlantic Ocean (East). The Planning and Development Authority (PDA) has been identified as the main stakeholder involved in this case study, but recommendations will be made to all parties involved to best accomplish our mission.

Key stakeholders were initially identified to cover all aspects of the system and were later placed into the decision making space. The decision space shows how the key stakeholders interconnect within the system. Participatory modeling normally includes the stakeholders, but when this is not possible, we use role playing to get an idea of what the actual stakeholders would say. Our role play meeting was collaborative, and gave us a better understanding of the decision space model. The decision space model explains the level of authority and interest of each stakeholder and correlates with the stakeholder meeting chart. The in-person participatory modeling was used to establish the goal statement, which we have identified as: A built environment in Grenada that enables the people to cope with the impacts of sea level rise and heavy precipitation by securing the safety and well-being of all and by distributing the risks equally while safeguarding the socio-economic and environmental system.

The wicked problem in our case is unique to the island of Grenada in that it is a community problem that involves all aspects of life on the island. And in order to conceptualize such a unique problem, several models have been developed to show relationships between all factors identified in the system. These models also help us to identify fragilities, including exposed assets, and those hazards, both endogenic and exogenic, that act on these fragilities.

From the fragilities, we were able to identify exposed assets, which can be defined as those assets which can be exploited by the hazards and potentially decrease in value. The exposed assets are organized into a chart, based on whether they are a part of the natural or built environment. The assets were chosen based on their importance to Grenada, and the hazards which impact them are identified in the tables.

Fragilities are factors in a system which can become affected by hazards and lead to the overall degradation of the system. For the purposes of this case study, fragilities have been organized into three categories, the built and natural environment, and the socio-economic sphere. Fragilities of the built environment involve where many population centers are located and the overall quality of the drainage and sewage systems. Fragilities of the natural environment include many biological factors such as the narrow range of tolerance of corals and mangroves and the growth periods of valuable crops, such as cocoa and nutmeg. Socio-economic

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fragilities more so include factors associated with supply chains, economic homogenization, and foundational societal practices.

For this study, numerous hazards were identified which encompass both endogenic hazards that originate from within the system, and exogenic hazards that originate from outside the system. These hazards are grouped into four hazard scenarios which are then used to design a spectrum of possible futures. These hazard scenarios include sea level rise, extreme precipitation events, hurricanes and storm surge, and droughts and heatwaves. For each of these hazards, a range of scenarios are established based on extensive literature reviews.

The hazard scenarios are used to sample the spectrum of possible futures and by doing so develop foresight. By examining multiple levels of action ranging from moderate, no-action, and comprehensive actions, a more detailed spectrum of possible futures can be established. Considering the benefits of stakeholder actions results in action-oriented trajectories resulting in four types of potential futures: continue, discipline, transformation, and collapse.

The risk assessment is the accumulation of the discussion of hazard scenarios and foresight. By synthesizing hazard probability and exposure of fragile assets, we can determine the futures of most concern to be addressed in by potential interventions. We assess the risk associated with the futures emerging for each hazard scenario: sea level rise, extreme precipitation events, hurricanes and storm surges, and drought and heat waves. The risks are visualized through the utilization of two differing assets. One is a graph to approximate the relativity of risk between the different future scenarios, and a matrix to tangibly quantify the probability and impact of each future scenario. The conclusions of the risk assessment provides guidance for the choice of interventions that are needed, and in what order, to minimize the risk faced by ensuring equitable distribution across the population.

Based on these findings, a broad range of interventions designed to avoid undesirable futures was considered. Interventions were split into five groups to encompass all areas of the goal statement. These groups include interventions for major stakeholders and societal areas who we identified could best address the implementation of these interventions. Each intervention was then ranked by listing the pros and cons to identify those that could be recommended to our stakeholders.

The recommendations recognize and acknowledge the limitations and challenges Grenada may face in addressing such concerns.

Recognizing that:

- Not one single stakeholder is responsible for making these decisions
- Grenada is running out of space for Grenadians
- Sea level rise is already causing flooding, increasing the severity of storm surges, causing erosion/ landslides, inundation etc.
- As the climate continues to change, we will experience a further increase in sea level rise, extreme precipitation events, and an increase in the severity of droughts and heatwaves.
- We do not exactly know the future of climate change and are unsure of what to expect

Acknowledging that:

- The Planning Development Authority is the main stakeholder dealing with this wicked problem
- The Planning Development Authority wants to do something but has limited resources/influence
- The Ministry of Agriculture is invested in the conservation missions being put forward with the Grenada fund for conservation
- The people are concerned about climate change

it is recommended that the:

Planning and Development Authority:

- Identifying Critical Infrastructure
 - Highlights high risk areas and buildings that can be targeted for moving
- Preparing built environment and people to move
 - Movement of population centers out of high risk areas
- Construction of Seawalls
 - Constructed in specific areas, around St. George's and Grenville, to keep out sea water
- Mapping and Preparation of Future Flood Zones
 - Increased mapping and data collection to identify future flood zones
 - Provides early warning system for high risk areas to begin moving out of flood zones

Ministry of Agriculture:

- Develop natural systems of landslide prevention
 - Planting of additional crops along river beds
 - Placement of native trees/shrubs along rivers in population centers
- Improvements to the storage of water
 - Larger containers to cope with longer dry seasons
- Development of rainwater capture systems
 - Reduced reliance on freshwater reserves
 - Efficient method of water capture

Grenada Fund for Conservation:

- Public education programs
 - Helps to inform public of issues regarding climate change
 - Generates public support

Education:

- Further education of climate change in schools
 - Variable education at each grade level
 - Mapping software taught at higher grade levels to better identify flood risk areas of Grenada

1 Introduction

1.1 The Challenge

Modern sea level rise has been predicted from historical trends and thermal expansion mirroring land subsidence in coastal areas impacted by interior land glacial melt. With uncertain predictions already from these factors, additional uncertainty is added to predictions for 2100 regarding the possibility of a glacial collapse in Greenland and West Antarctica (Vasskog et al., 2015). Nations such as Grenada have opted towards taking more conservative approaches to estimating sea level rise. In a 2015 report to the *United Nations (UN)*, the Government of Grenada commented on the maximum possibility of a 1.40 m sea level rise following thermal expansion and land glacial melt (Government of Grenada, 2017).

Contrarily, rainfall in the region is estimated to decrease with rising global temperature increases by 2100 (Almazroui et al., 2021). However, the frequency and concentration of these rainfall events and their coupling with other natural phenomena, including drought, can result in amplified reactions in natural and built environments. Such has been observed globally and along similar latitudes where persistent drought from decreased rainfall interrupted with heavy precipitation events results in worsened floods and landslides (Matanó et al., 2022).

1.2 Study Area - Grenada

Grenada is a small island nation in the Southern Caribbean and part of the Lesser Antilles island chain. Grenada itself is made up of three main sister islands, Grenada, the main island, and the smaller islands of Carriacou and Petite Martinique. The island is 344 square kilometers with a population of 116,600, around a third of which live below the poverty line and are concentrated along the coastlines. Grenada is of volcanic origin, and several major lakes across the island are volcanic craters. Coastlines primarily consist of sandy beaches and mangroves, with offshore reefs in shallow waters. Currently, Grenada's economy is heavily based on tourism and agricultural exports, which have given Grenada the nickname the "island of spice" due to its production of nutmeg and mace. Much like other islands of the Caribbean, Grenada experiences a hot and humid dry season and a cool, rainy season. But unlike other Caribbean islands, Grenada is at the southernmost point of the hurricane belt and, as a result, has only experienced three major hurricanes.

1.3 The Stakeholders

The people of Grenada are the most valuable stakeholders, and they are considered not only a stakeholder but an asset to Grenada. Kenrick Fullerton is the chairman of the Planning and Development Authority. The *Planning and Development Authority (PDA)* oversees proper development for locally owned and commercial businesses. This case study is written with the PDA in mind, considering the interests and authority of the following stakeholders. Parliament is a major stakeholder, and the Ministry of Agriculture is an important stakeholder, as food security is a priority for small developing islands. The Tourism Authority and Port Authority are stakeholders who hold little interest and authority in the case study; however, they are considered due to their importance to Grenada's economy. *Grenada Community Development Agency (GRENCODA)* is an important *Nongovernmental Organization (NGO)* that focuses on empowering Grenadians, but NGOs normally have little authority regarding policymaking. *Grenada Electricity Services Ltd. (Grenlec)* and *National Water and Sewage Authority (NAWASA)* are important utility companies in Grenada. As stakeholders, they both are relatively authoritative and interested in the case study. We had the opportunity to meet stakeholders in person and included their perspectives in our case study. The stakeholders whom we had the opportunity to meet with include the Project Manager at Ocean Spirits, the chairman of the PDA, the founder of the *Grenada Fund for Conservation (GFC)*, and the technology manager for the government of Grenada.

A role-playing exercise was done to understand this system's main stakeholders better (2.3). In addition to understanding the interests and goals of the stakeholders, role-playing was also helpful in drafting questions for the organized stakeholder meetings.

The stakeholders that were met with include the Project Manager at Ocean Spirits, Kate Charles, the chairman from the PDA, Kenrick Fullerton, founder of the GFC, Tyrone Buckmire, and the technology manager for the government of Grenada, Dave Baker. Kate Charles represented Ocean Spirits by showing Levera Ramsar Wetland, Levera Beach, and the new Grenada National Resort development in northern Grenada. Tyrone Buckmire represented the GFC by showing the hard work put in at the mangrove restoration site on Carricaou, Grenada's sister island. Kenrick Fullerton and Dave Baker also answered questions and represented the Grenadian Government in additional meetings.

1.4 Methods

1.4.1 MARI and the MCST

The mission of the *Mitigation and Adaptation Research Institute (MARI)* is to facilitate transformation towards sustainability and further the understanding of challenges posed by recent global changes to land use, biodiversity loss, extinction events, climate change, and sea level rise, and their impacts on the *Earth's life-support system (ELSS)*. The *MARI Case Study Template (MCST)* was developed in order to study wicked problems associated with modern global change and sustainability Plag (2024). These wicked problems refer to social or cultural problems that are difficult or impossible to solve because of incomplete or contradictory knowledge, many people and opinions involved, the financial burden associated with progress toward solutions, and the complexity of system interactions. The MCST emphasizes the importance of a transdisciplinary approach to ensure a well-rounded and unbiased outcome for the research and finalized case study. The MCST also respects the complexity of wicked problems while employing a system mapping and systems thinking mindset. It is broken into eleven sections: Introduction, Decision Space, Conceptual Modeling, Exposed Assets, Fragilities, Hazards, Foresight, Risk Assessments, Interventions, Discussion and Conclusions, and Recommendations.

An introduction is necessary to convey a general description of the system, such as its history or relevant geography, and jumpstarts the discussion of the wicked problem. Here, factors are considered, including what caused the wicked problem, who is affected, what is already being done to address the problem, and which societal agents will benefit from any proposed solutions.

The decision space further identifies which societal agents or stakeholders will ultimately make the decisions that impact the system. It allows for participatory modeling with active stakeholder engagement to create a formalized and shared representation of the system's current reality in a collective model that can be used to run scenarios and generate solutions for the decision space. In instances where participatory modeling with active stakeholders is not an option, role-playing can be utilized for proxy representatives of relevant stakeholders to formulate a set of values and desired outcomes from which the system's goal statement and model can be generated.

Conceptual modeling provides a more in-depth look at the wicked problem and system itself. Conceptual models are constructed based on prior inputs from research and stakeholders, and utilized to identify any relevant stocks, flows, and feedback loops while accounting for a relevant decision space.

Exposed assets refer to the physical assets or services with an associated financial value or importance to the system that is exposed to risk from hazards. These are cataloged and categorized to guide the formulation of the system's fragilities.

Fragilities are constitutional, process-related aspects of the system that can be considered 'fragile' or capable of breaking. The goal of formulating fragilities is to be able to better determine which of these inherent system processes can be reduced or compensated for via the adaptation of the system.

Hazards are both endogenic and exogenic threats to the system that can act on inherent fragilities and negatively impact a system's processes. These can range from ever-evolving global processes to minute, local changes, and each must be reasonably accounted for and explored using a range of hazard scenarios.

Foresight is crucial in modeling potential future outcomes for the system and relies on hazard scenarios as a baseline for running action-based simulations. It becomes necessary in complex systems to consider a wide-ranging spectrum of possible futures from which desirable futures can be imagined and used to inform future system response decisions.

Risk assessments are formulated using the equation: relationship of risk=hazard probability x fragility of assets related to this hazard x value of the exposed asset. They are assessed based on the spectrum of possible futures and provide guidance on where it would be most advantageous to focus interventions.

Interventions are developed based on which actions are necessary to influence the system's trajectory to align with the desirable future. Each is considered for its ability to increase the system's resilience and antifragility, and the advantages and disadvantages of each must be thoroughly explored.

Discussion and conclusions are a necessary reflection on the prior research and modeling and a reiteration of the wicked problem to create a cohesive narrative from which the recommendations can be informed.

Recommendations reflect the product of all prior work and inputs and address actionable, transformative interventions for specific stakeholders with the most significant capacity for positively influencing system change.

1.4.2 Planning, Research Trip, and Writing

The planning stage took approximately two and a half months, from January to March. It revolved around preliminary research into Grenada's history, geography, culture, and political climate. Once sufficient information was gathered, a list of relevant stakeholders was compiled and further researched. Those most relevant to Grenada's decision space were selected from this comprehensive list. A role-playing exercise was engaged via proxy representatives for each stakeholder based on values and priorities gleaned from research and interviews conducted with a few stakeholders. This exercise yielded a comprehensive goal statement created to encapsulate and satisfy the commonalities within the stakeholders' various missions and value sets.

From March 4th-11th, 2023, the Sustainability Leadership Team traveled to Grenada to conduct in-person interviews of stakeholders and pursue field surveys to understand the system better as it currently operates.

Upon returning to the States, each team member was assigned sections for which they were the lead author, responsible for managing contributions and ensuring sections were completed promptly. The writing of this document was a collaborative effort involving the seven undergraduates of the Sustainability Leadership Team and their supervisory professor.

2 Mapping the Decision Space and Role Playing

Mapping the decision space relevant for the case study was done in three steps: (1) Mapping stakeholders based on their interest in the challenge and authority to implement recommendations; (2) mapping rules and regulations based on their relevance and leverage; (3) a role playing exercise to derive a goal statement describing the desired future most stakeholders would agree to.

Mapping the decision space was a collaborative effort. By observing the attitude of all of the participants, the social links were revealed. Analyzing the social links, and the nature of the interactions, each proposal was justified by each party. These relations and social links were mapped along with the ethics, laws, regulations, and economic rules. The rules and regulations were mapped separately, but each component was used to create the decision space model.

2.1 Societal Agents

The main stakeholder being addressed is the PDA. In addition to working with the PDA to provide input for their plan for Grenada, it was essential to understand and consider the roles and interests of other parties/organizations involved in this system. The role-playing assisted in developing the decision space and choosing the stakeholders who are most relevant for the case study. Considering other aspects of the Grenadian environment and society, various stakeholders were included in addition to the PDA (Fig. 1). The additional stakeholders include the Ministry of Agriculture, Ports Authority, GRENCODA, Tourism Authority, NAWASA, Grenlec, GFC, Grenadian Parliament, and *Ther Ntaure Conservancy (TNC)*. Each

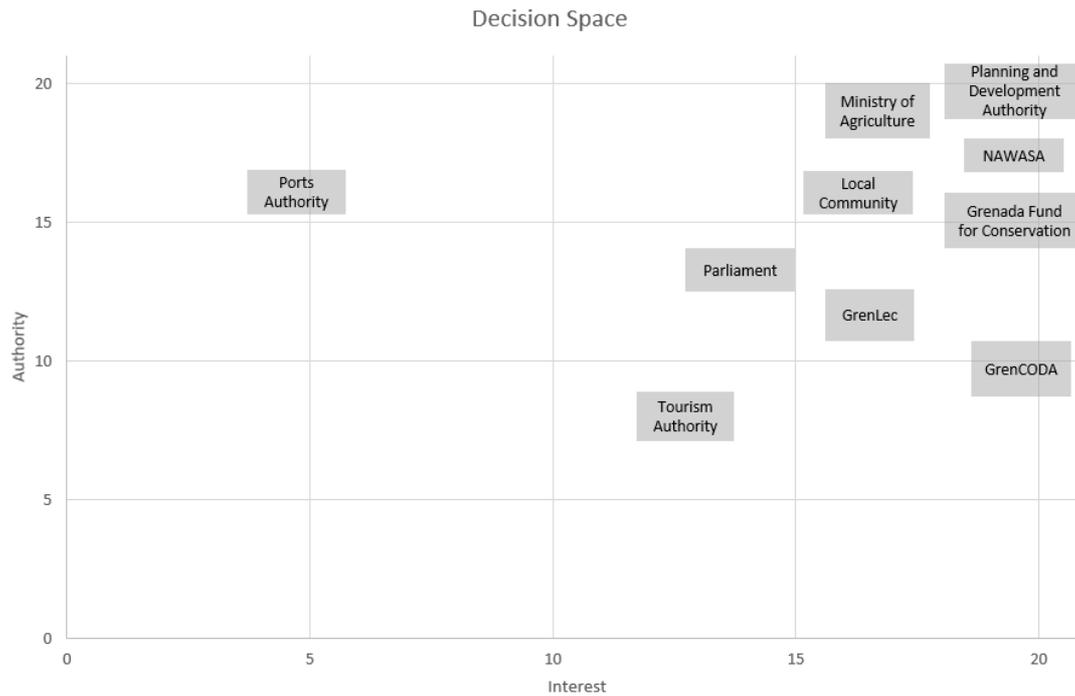


Figure 1. Mapping of stakeholders based on the authority and interest levels of these stakeholders.

stakeholder’s interests, influence, and authority are summarized in the decision space and role-playing sections below.

The stakeholders for this case study were chosen based on the role-playing experience (Section 2.3). The decision space relates the interests and authority of the stakeholders’ societal dynamics concerning mitigating and adapting for sea level rise and heavy precipitation. High authoritative stakeholders with the most interest are the PDA, Ocean Spirits, the GFC, NAWASA, and the Ministry of Agriculture (Tab. 1). The stakeholders with the least interest are the Port Authority and Tourism Authority. The non-governmental organization, GRENCODA, is a vital stakeholder interested in sea level rise and heavy precipitation, but GRENCODA has less authority. NGOs seem to gain more authority as socio-political issues worsen because GRENCODA significantly empowers local Grenadians.

The Grenadian Parliament is a governing body in Grenada that is currently divided among two opposing parties. The National Democratic Congress is the current ruling party that favors left-centered policies such as environmental protection. The New National Party is a conservative favored party that supports the transition to renewable energy and using the Green Climate Fund to upgrade water/sewage systems (Government of Grenada, 2022).

NAWASA is a significant stakeholder with high authority and interest. Grenada experiences dry and wet seasons, which negatively impacts freshwater availability. NAWASA provides water to most communities, with 90% being from surface water or rainfall (NAWASA, 2020). Funding and ownership of NAWASA is the government, and the people contribute through taxes or paying for water. Due to NAWASA servicing most of the island, the success of NAWASA significantly impacts other sectors and their availability of freshwater. That is why NAWASA is eager to adapt and mitigate sea level rise because of the challenges presented by climate change, sea level rise, dry/wet seasons, and saltwater intrusion, which impact the availability of freshwater (NAWASA, 2011).

The GRENCODA is a non-profit that strives to enhance the resilience of fisheries and community livelihoods to climate change impacts. GRENCODA focuses on rehabilitating and restoring watersheds and coastal resources, which are valuable assets for the island. This NGO receives funding from various places, for example, the *Caribbean Biodiversity Fund (CBF)*. GRENCODA participates in the

Table 1. Key Stakeholders.

Stakeholder	Interest Level	Interest	Level of Influence	Authority
GrenLEC	Moderate	renewable energy	High	services businesses + homes throughout Grenada
GrenCODA	High	equity / justice / inclusiveness	Moderate	NGO which is connected with local communities
NAWASA	High	provide water for citizens	High	Services communities through Grenada
GFC	High	raise public awareness & protect Grenada's natural environment	Moderate	NGO which has restorations throughout Grenada.
GTA	Low	development of tourism	High	Government Service
PDA	High	sustainable infrastructure	High	Government Service
Port Authority	Low	managing the port	High	Government Service
Ministry of Agriculture	High	sustainable farming practices to enhance food security	High	Government Service + Local Farms

Caribbean Community Climate Change Center (GRENCODA-CCCCC) and the *Caribbean Challenge Initiative (CCI)* projects, showing their high interest in mitigating and adapting to sea level rise and heavy precipitation (GRENCODA, n.d.).

The *Grenadian Ports Authority (GPA)* has more than three decades of service to the nation behind it; the GPA is now better equipped than ever to play a significant role in the nation's economy. Recent initiatives and investments by the GPA have been designed to boost Grenada's potential for cargo handling, the cruise sector, and tourism. All of these directly benefit the economy and the people of the country. The Grenada Ports Authority is principally responsible for the administration and operation of the Port of St. George's. It also has jurisdiction over Prickly Bay, St. David's Harbor, and Grenville, on the main island of Grenada, and Tyrrel Bay, the neighboring island of Carriacou. The GPA is a statutory organization controlled by the Minister of Finance, who appoints the Chairman and Board of Directors (Sánchez & Wilmsmeier, 2009). The functions of the Port Authority are to administer and operate Grenada's seaports, regulate and control navigation, maintain and improve, and regulate the ports and their services.

The GPA is a focal point for international organizations in maritime matters. They are represented in regional and international conferences in the Transport Committee, the Caribbean Memorandum of Understanding on Port State Control, the *International Oil Pollution Compensation (IOPC)* Funds, the *International Maritime Organization (IMO)*, and the Organization of American States Committee on Ports. The port authority will work with organizations and other ports to promote better commerce. Working with the Ministry of Finance, it draws up projects to develop the port and the environment, especially the coastal zone. The port authority recently became involved in an outreach program with the local community, such as the coastal zone management competition in primary schools. Also, they house regatta festivals and support the Grenada community development agency. They included a cruise terminal to develop the port authority's range of services. The first development in Carenage then followed the new development of the Melville Street Cruise Terminal. With the Melville Street Cruise Terminal, the GPA funded an operation to expand the bus terminal for more accessible transportation. The port authority's future vision is to continue bringing in tourism through cruises and build the economy. However, the GPA is not considering sea level rise, and the port is and will be negatively affected (Sánchez & Wilmsmeier, 2009).

The PDA was established as part of the new government and is in charge of all things related to physical development. The PDA has two main functions: development planning and development control. Specifically, their job is to ensure the implementation of stated objectives in the Physical Planning and Development Control Act 2002 (Government of Grenada, 2016). The goals are to ensure appropriate and sustainable use of all publicly and privately owned land for the public interest. The PDA wants to maintain and improve the quality of the physical environment to provide for the orderly sub-division of land and the provision of infrastructure and other services, maintain and improve the standard of building construction to secure human health and safety and to protect and conserve the natural and cultural heritage (Faldi & Macchi, 2017).

The *Grenada Tourism Authority (GTA)* is a national tourism organization of Grenada, primarily responsible for developing tourism in Grenada and its sister islands, Petite Martinique and Carriacou. Encouraging further development of destination management and marketing in Grenada, the GTA is a significant stakeholder interested in bettering Grenadians' well-being and potential success.

The Ministry of Agriculture, including land, forestry, and fisheries, was established to collectively control the natural resources and food production in Grenada. Currently, The Ministry of Agriculture has the set goal of increasing economic growth and sustainable development of Grenada, which is to be accomplished by agricultural development and increasing food security. Overall, the Ministry of Agriculture wants to revitalize the agricultural sector of the economy to better contribute to the country's socio-economic development (James, F., 2015).

There are two main legislative acts that the ministry operates off of: The National Agriculture Plan (2015-2030) (Government of Grenada, 2015) and The Revised Forest Policy for Grenada, Carriacou and Petite Martinique (Government of Grenada, 2018). The National Agriculture Plan aims to promote food security, generate income, and alleviate poverty. The National Forestry Policy aims to optimize forest resources for socio-economic development, conserve endemic and non-invasive species, and boost ecotourism and education on sustainable forestry (Government of Grenada, 2016). An ideal future for the agricultural sector of Grenada is to increase sustainable interaction with the natural world while also increasing the economic production of farms, fisheries, and ecotourism businesses.

The Transportation Sector is essential, as it provides a way to get around the entire island safely and efficiently. The current transportation situation involves nine zones and 44 total bus routes. This sector is managed by the Grenada Transport Commission, which receives funding from the Caribbean Development Bank, sourced via Agence Francaise de Development.

The Grenlec was established in 1960; Grenlec is Grenada's primary licensed electricity provider. With investments in community development, environment, and science and technology, Grenlec has high authority and interest in the wicked problem (Grenlec, n.d.).

2.2 Rule and Regulations

The rules and regulations model is sorted by relevance and leverage (Fig. 2). The National Forest Policy, alongside the land and agriculture policies, seems to have the most relevance and leverage. The least relevant policy, which does not have as much leverage, is Grenlec, transportation, and the NGOs code of conduct.

It is important to note that Grenada is a party to several international agreements, including Biodiversity, Climate Change, Climate Change-Kyoto Protocol, Climate Change-Paris Agreement, Comprehensive Nuclear Test Ban, Desertification, Endangered Species, Law of the Sea, Ozone Layer Protection, Ship Pollution, Wetlands, and Whaling. Therefore Grenada will be reporting to the *Intergovernmental Panel on Climate Change (IPCC)* and designating 30% of the island to be set aside for conservation (IPCC, 2023).

2.3 Role Playing

A role-playing exercise was completed with the goal to better understand the identified stakeholders' perspectives and values. Role-playing was used to develop the decision space. Each participant took

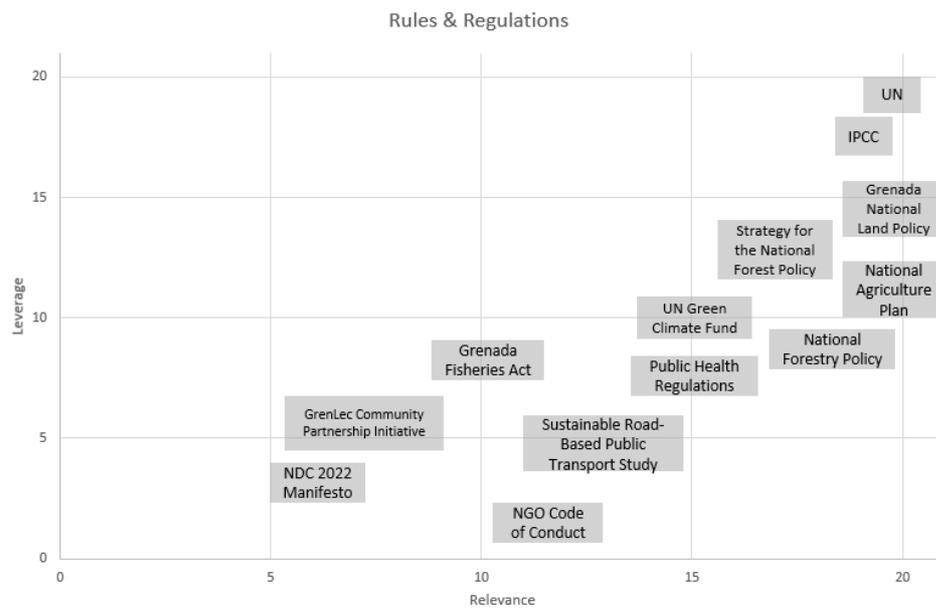


Figure 2. Mapping of rules and regulations in the system.



Figure 3. Stakeholder role playing exercise.

on the role of a specific stakeholder, doing independent research to embody each stakeholder's values regarding their organization and the country of Grenada. Based on each stakeholder's interests and authority, the goal is to have a built environment in Grenada that enables the people to cope with the impacts of sea level rise and heavy precipitation by securing the safety and well-being of all and by distributing the risks equally while safeguarding the socio-economic and environmental system. The resulting goal statement embodies the aspirations and ideal future for Grenada (see Fig. 4 below). The stakeholder role-playing event (Fig. 3) went as follows.

Planning and Development Authority [Jai Lewis]: The PDA, as established by the new government, is in charge of development in Grenada. The PDA has interests in sustainability, infrastructure, land use planning, and human health and safety. The main goal of this authority is to move Grenada in a sustainable direction that promotes the well-being of its people and preserves the beloved culture. A considerable concern of the PDA is maintaining Grenada's physical environment (beaches, for example)

in the face of sea level rise.

Grenada Ports Authority [Alivia Markham]: The GPA is responsible for the administration and operation of the port in St. George's, as well as Prickly Bay, St. David's Harbor and Grenville, and Tyrrel Bay (Carriacou). The GPA is also a focal point in all maritime matters, including cruises, cargo, and disaster relief. The GPA is actively involved with the community, helping sponsor events such as a Coastal Zone Management Competition in primary schools. There is a significant interest in coastal zone management and the cruise/tourism industry. The GPA is ready to help lead Grenada to a future with a robust and dynamic economy. However, one concern/issue for the GPA is the expansion of current ports and terminals.

Ministry of Agriculture [Rocco Boyd]: The Ministry of Agriculture is interested in seeing economic growth, agriculture development, increased food security, generation of income in rural communities, and alleviation of poverty. From this, the Ministry of Agriculture would like to see a future where there is revitalization of the agricultural sector, and incorporation of sustainability throughout the island. The concerns with making this future possible, include saltwater intrusion, heavy precipitation, and migration to rural areas.

The Grenada Electricity Services Ltd. [Blaizen Bloom]: Grenlec is the licensed provider of electricity in Grenada, Carriacou, and Petite Martinique. Since 1960, this company has provided integrated services of generating, transmitting, and distributing electricity to its customer base of 50,000+ citizens. Grenlec has always risen to the challenge of providing safe, reliable service through continuous investment into enhancing services, employees, infrastructure, and the community. The company's current objectives include moving toward renewable energy for Grenada, which will stabilize the cost of energy, reduce dependence on imported fuel, support economic growth, and protect the environment by increasing. One challenge that Grenlec may be faced with is maintaining energy efficiency in coastal areas that are vulnerable to sea level rise and heavy precipitation.

National Water And Sewage Authority [Adelle Novak]: NAWASA services the businesses and homes throughout the island. NAWASA provides water for citizens and is interested in keeping a good supply of water for Grenadians. A desired future for NAWASA is for there to be infrastructure upgrades, increased water availability and reduced saltwater intrusion. Saltwater intrusion is a concern of NAWASA and Grenada has seasonal droughts which affect the water supply. NAWASA would ideally receive more funding for these upgrades to support the livelihoods of Grenadians.

Grenada Community Development Agency [Adelle Novak]: As part of the umbrella body of *The Inter-Agency Group of Development Organisations (IAGDO)* in Grenada, GRENCODA is interested in boosting justice and inclusiveness throughout Grenada via empowerment and support, specifically for low-income, rural communities. A desired future which GRENCODA would support, would be a future where Grenadians have equal distribution of risk where mitigation and adaptation is feasible for all Grenadians. Concerns related to sea level rise and heavy precipitation, is human safety and health, water quality and food security which will be negatively influenced by sea level rise and heavy precipitation.

Grenada Fund for Conservation [Meagan Duncan]: The GFC is a registered non-profit, non-governmental organization that was established in 2008. The main goal of this organization is to help promote and protect Grenada's natural environment and respect the balance between natural resources and human needs by ensuring that people can benefit from conserving resources sustainably. The GFC does considerable advocating and lobbying for legislative changes to help and protect endangered national and transboundary species. There are also efforts to undertake nationwide activities at the school and community level to raise public awareness of Grenada's natural environment.

Grenada Tourism Authority [Ashawne Edwards]: The GTA was established in 2013 and is responsible for the development of Grenada's, Carriacou's, and Petite Martinique's tourism sector via marketing and management. In 2023, the chairman of the GTA was Barry Collymore, who has recently approved the Grenada National Resort. This organization aims to achieve satisfactory traveler experiences while promoting sustainable, environmentally responsible growth that benefits the people of Grenada. A big problem this organization is experiencing is a reduction of beachfront attractions due to rising sea levels and coastal erosion.

Table 2. In-Person Stakeholder Meetings.

Stakeholders	Main Focus	Authority & Interest	Participatory Model
Tyrone Buckmire [Grenada Fund for Conservation]	Conservation & Culture	- Moderate Authority - High Interest	Mangrove Conservation & Culture. Insight on Carriacou.
Kenrick Fullerton [Planning & Development Authority]	Community, Infrastructure & Education	- High Authority - High Interest	Education & Development Risks
Davon Baker [Technology Manager for Gov't of Grenada]	Conservation & Innovation for applied sustainability for local communities	- High Authority - High Interest	Strategic Planning for Sustainable Communities
Kate Charles [Ocean Spirits]	-Levera Ramsar Wetland -The National Resort -Conservation	- Moderate Authority - High Interest	Community Involvement & Commercial Development

2.4 In-Person Stakeholder Meetings

After gaining experience through the role-playing exercise, real stakeholder meetings were conducted (Tab. 2). Some of the contacted representatives do not represent a listed stakeholder, but their insight about Grenada and the natural environment was beneficial. The representatives that were involved in the meetings include:

- Kate Charles [Ocean Spirits] - Kate Charles is a marine biologist and project manager for Ocean Spirits. Kate was informative on the Levera Ramsar Wetland, home to mangroves, reefs, beaches, and forests. Levera Ramsar Wetland is located in the northern parts of Grenada and serves as a park for locals and tourists to experience Grenada in its natural form. Kate brought attention to the new National Resort being built next to Levera and explained the side effects of changing the island's native flora and fauna.
- Tyrone Buckmire [GFC] - Tyrone represented the GFC, a non-profit, non-governmental organization to increase awareness about climate change, coastal resilience, and mangrove restoration, turtle conservation, and various other important topics related to the environment. Tyrone presented the mangrove restoration project up close, including the original mangroves and the new mangrove nursery. The airport was shown to be affected by erosion by the current sea level, and the expansion of the airport combined with sea level rise will negatively affect the mangroves. Tyrone was adamant about the outcomes of privatization being merely for profit and having negative consequences on the mangroves.
- Kenrick Fullerton [PDA] - Kenrick Fullerton is the chairman of the PDA. By addressing the development of local homes and businesses and authorizing the planning of commercial businesses, the PDA has the opportunity to have a high interest and the authority to prepare Grenada for sea level rise and heavy precipitation. Kenrick explained that encouraging the youth to embrace their culture and enhance education on climate change could contribute to empowering the livelihoods of young adults.
- Joey [Data Analysis] - The meeting with Joey was informative and gave an inside look at what Grenada means to the local people. Joey is a data analyst and a contact from Kate Charles. Joey

explained the importance of preserving Grenadian culture while encouraging climate change and conservation education. Attention was brought to the commercial businesses, resorts, and golf courses that exploit the land. Commercial businesses seem to help the economy but negatively influence the local people, culture, and natural environment. Grenadians rely heavily on the island's natural beauty, providing resources for people. The big commercial businesses which don't consider the livelihoods of the local people by not providing opportunities for jobs or empowerment seem to influence the island people negatively.

- Andre Joesph Witzig [TNC] - Andre represented TNC and discussed the work being done for Grenada. Two significant projects for TNC are the Caribbean Regional Oceanscape Project and the Resilient Island Program. The World Bank funds the Caribbean Regional Oceanscape Project. It encourages a blue economy, meaning it focuses on sustainably using the ocean's resources for economic growth and to improve Grenadians' livelihoods. The Resilient Island Program aims to implement ecosystem-based solutions to advance climate adaptation, to create more resilient islands. Attention was brought to the salinity levels, quality of soil conditions, and hydrology obstacles affecting the mangroves. TNC brought awareness to the importance of the mangroves and their plans for restoring them, specifically in the northern part of the islands, as well as the value of sea turtle conservation.
- Davon Baker [Ministry of Fishery and Carricaou NGO] - Davon Baker represented the Government of Grenada and partnered with Tyrone Buckmire to show us the mangrove restoration. Davon Baker was informative and gave insight into the strategic planning for a sustainable community and green infrastructure while updating us on the innovation occurring throughout governmental projects.

2.5 Goal Statement

The goal statement was formulated based on the conclusions gathered during our role-playing exercise about the values and missions of each of our relevant stakeholders (Fig. 4). A clear understanding of a mutual, underlying goal was agreed upon during the exercise, and the resultant goal statement authored:

A built environment in Grenada that enables the people to cope with the impacts of sea level rise and heavy precipitation by securing the safety and well-being of all and by distributing the risks equally while safeguarding the socio-economic and environmental system.

It represents a collaborative effort between our proxy representatives conducting a participatory modeling exercise on behalf of their active counterparts to discern the nature of the system, its decision space, and a collective desired outcome. To further this aim, we will now look at various conceptual models that were mapped out as a result of additional efforts to understand the system of Grenada.

3 Characterizing the Wicked Problem and Modeling the System

3.1 Preparing the Built Environment in Grenada for Climate Change: A Wicked Problem

Finding pathways to the future described by the goal statement constitutes a wicked problem. The concept of considering social planning problems as wicked problems was introduced by Rittel & Webber (1973). The problem of reaching the desired future described by the goal statement meets all ten criteria identified by Rittel & Webber (1973) that characterize a wicked problem. In particular, although many small island states face similar problems in their preparation for the anticipated and potentially surprising impacts of modern climate change, the situation in Grenada is a unique combination of hazard exposure, topography and geology, ecosystems, population and culture, political system, economy, and dependencies on the regional and larger environment. Tackling the wicked problem therefore cannot be based on importing approaches from elsewhere. The unique problem needs to be understood and specific interventions need to be tailored for the unique circumstances in Grenada. Wicked problems do not

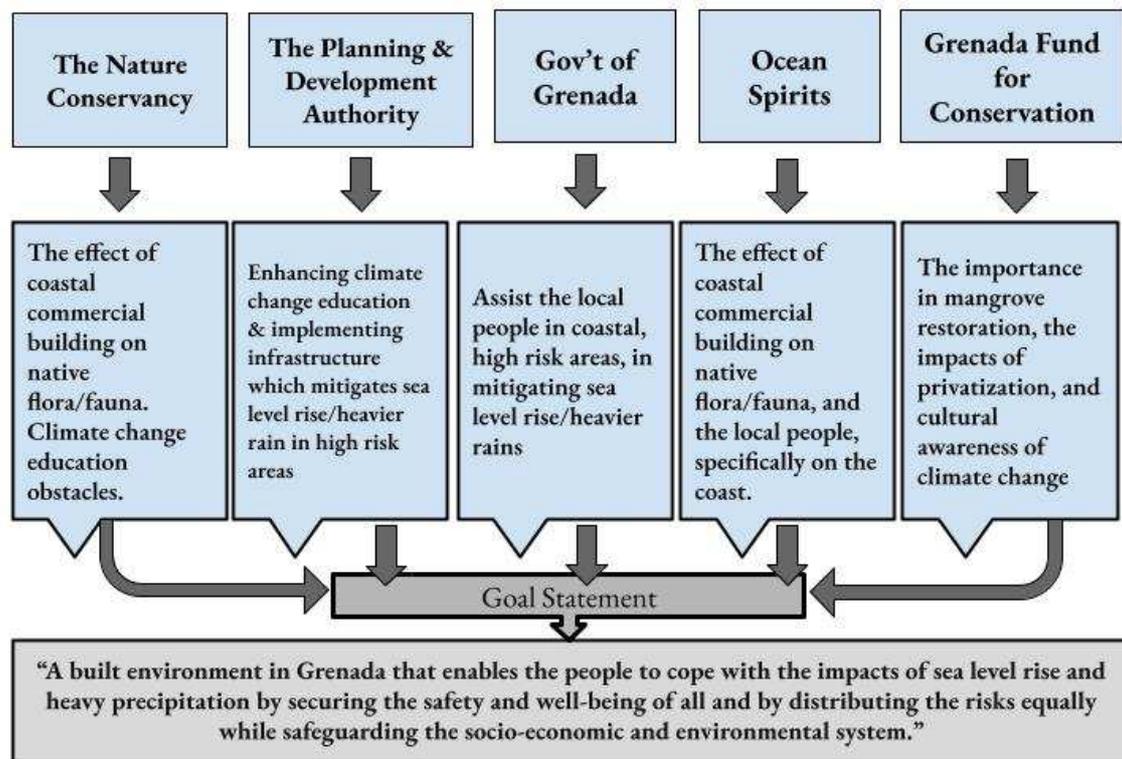


Figure 4. Deriving the Goal Statement from Stakeholder Perspectives.

have solutions but require a constant effort to monitor and improve the situation. This requires a deep understanding of the system and the major feedback loops.

In order to understand the challenges in reaching this desired future and to be able to identify necessary and sufficient intervention, the system representing the goal statement needs to be modeled and investigated. Having a comprehensive conceptual model of the system will allow us to identify the exposed assets and system fragilities. Including the system's environment in our conceptual model will provide insight into the hazards that could originate in this environment and impact our system.

3.2 Conceptual Model for Grenada exposed to Climate Change Hazards

At a high level, Grenada can be considered as composed of land areas consisting of several islands of varying size and the territorial waters surrounding these islands. This system is embedded in an environment consisting of the high seas, i.e., the open ocean, the continents and the coupled atmosphere-ocean system. For the purpose of this case study, it is helpful to consider the global biosphere and the global climate system as part of the environment of the system Grenada.

The islands that compose the land area of Grenada harbor several intertwined sub-system (Fig. 5). The terrestrial, freshwater and coastal ecosystems are intertwined with a growing built environment providing a home to an also growing social fabric. These systems are embedded in the territorial waters of Grenada. Overlain to this physical system is the economic system of Grenada. These interconnected and to some extent interdependent systems are embedded in the larger environment composed of the global ocean and the continental systems. This larger environment also includes the global climate system and global biosphere.

The system of Grenada is coupled to the environment through many interdependencies, feedback loops and hazards that originate in the system environment. For the goal statement, hydrometeorological hazards are of particular interest (purple arrows in Fig. 5). These hazards not only impact Grenada

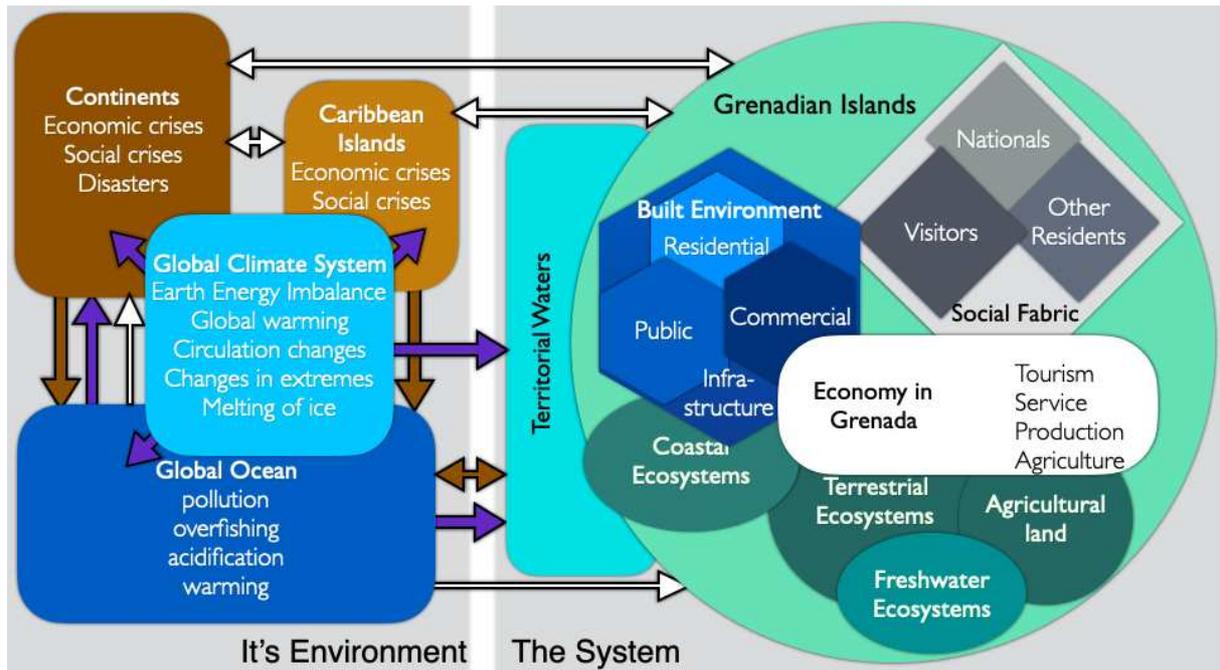


Figure 5. Conceptual Model for Grenada under Climate change. The system model for Grenada comprises the islands and the territorial waters. The system of the islands are composed of subsystems including the natural environment composed of coastal, terrestrial, and freshwater ecosystems as well as agricultural land, the built environment integrating residential, commercial and public buildings with service infrastructure, and the social system integrating nationals, other residents and visitors. Economy is a system overlaying all these other systems. The environment of Grenada is composed of the other Caribbean countries, the global ocean, and the global set of continents. The global climate system is overlaying these elements of the global environment. The arrows indicate economic relationships or dependencies (white), pollution (brown), and hydrometeorological hazards (purple).

directly but can also impact subsystems in the system environment in ways that change the economic relationships and dependencies (white arrows in in Fig. 5). Importantly, the hazards can also trigger changes in pollution that impact the global ocean as well as the terrestrial waters of Grenada (brown arrows in Fig. 5).

In the context of the goal statement, the *Global Climate System (GCS)* connects to the other subsystem in the system environment and the system itself via hydrometeorological hazards. In Fig. 5, the purple arrows represent these hazardous connections. The GCS is characterized by a currently very large Earth Energy Balance (EEI) of 320 TW, with most of this energy being stored in the ocean (Trenberth et al., 2016; Cheng et al., 2022; Trenberth & Cheng, 2022; von Schuckmann et al., 2023). Among others, ocean warming impacts ocean circulation (e.g., Li et al., 2023), the marine biosphere (e.g., Pinsky et al., 2019) and the frequency and intensity of tropical cyclones (e.g., Balaguru et al., 2018; Trenberth et al., 2018). It also leads to so-called steric changes in the sea surface height (e.g., Levitus et al., 2012) and changes in the dynamic sea surface topography, which both impact local sea level. The exogenic hazards relevant for the goal statements and the endogenic hazards potentially triggered by these hazards are considered in more detail in Section 3.5. Section 6 presents possible scenarios for these hazards that are used in Section 7 to explore the spectrum of possible futures.

The hazards emerging from a changing GCS increasingly have impacts on the global social and economic systems, as well as the availability of resources. Other hazards such as food shortages, economy downturns, pandemics and wars can severely impact the economic and social systems in the environment. Because of the important economic dependencies of Grenada on the system environment (indicated by the white arrows in Fig. 5), these crises in the economic and social subsystems in the environment can

easily result in significant hazards for the economy and the social fabric of the system Grenada.

The hydrometeorological hazards impact the system both in the territorial waters and directly on the land areas. These hazards can have significant impacts on the built environment with consequences both for the social fabric and the economy.

Pollution is an important hazard, too, with potentially severe consequences for the health of humans and the wildlife. Activities on land in Grenada can increase the pollution of the territorial waters and the high seas. Water exchange between the territorial waters and the high seas transports pollution in both directions. Pollution in the adjacent ocean enters the territorial waters and adds to the pollution there.

In particular, pollution of the surface microlayer (SML) between 1 μm and 1000 μm is of increasing concern, and it is found to be on the order of 500 times more than for the rest of the ocean (Dryden & Duncan, 2022). Limited sewage capabilities in Grenada, as well as many other parts of the globe result in a contribution to this pollution. Increased runoff during extreme precipitation events in many countries amplifies the problem. Within the environment of our system, pollution is added from land to the sea with a range of novel substances including PFAS (e.g., Cousins et al., 2022) and plastics (e.g., Meijer et al., 2021). While the health impacts of PAFS are well known and widely acknowledge (e.g., Temkin et al., 2020), health impacts of plastics and microplastics were not understood until very recently (Landrigan et al., 2023). Considering the rapid growth of the urban coasts globally, it can be expected that increased extreme precipitation events and coastal hazards will lead to many event with high flows of polluting material into the ocean (e.g., Plag et al., 2021).

3.3 Interdependencies between the System and its Environment

There is a multitude of interdependencies and interactions between the system conceptualized in Fig. 5 and its environment. Economically, Grenada depends on many supply chains of material, energy, people, and knowledge. It also depends to some extent on a market for products produced in Grenada and services offered. Many of these supply chains are precarious and can easily be interrupted or delayed.

Grenada is in a transition from an agriculture-based economy to a service industry-based economy, with inbound tourism being a main pillar of the service industry. This transition generates new built environments predominantly in areas that are exposed to hydrometeorological hazards. Often, the new buildings are in ecologically highly valuable areas or impact such areas. The degradation of these areas is in conflict with declared goals of protecting core ecosystems. The transition also creates new dependencies on supply chains from the system environment that are fragile with respect to the hydrometeorological hazard.

3.4 System Components and Feedback Loops

In order to better understand the assets and fragilities of the system representing the goal statement, a system model with higher resolution is depicted in Fig. 6. The terrestrial waters are home to a rich marine ecosystem. The transition zone for these waters to the land area, the coastal zone, also host viable ecosystems. Large parts of the land areas are still forested and other parts provide space for agriculture and human settlements.

The territorial waters of Grenada harbor abundant marine ecosystems, including a number of coral reefs. For the people in Grenada, these waters are a food resource. In the transition zone between the territorial waters and the terrestrial areas, mangroves, wetlands and beaches host rich and valuable ecosystems.

Most of the land areas not transformed for human purposes are forested. In 2018, an estimated 50% of the land area were forested Central Intelligence Agency (2023). The freshwater ecosystem include numerous rivers that have in many cases created deep valleys with steep slopes in the volcanic geology. A number of lakes and a few geothermally active springs and pools are part of the freshwater system.

The land areas transformed for human purposes include agricultural lands in form of pastures and rangeland for livestock and cropland. In 2018, an estimated 32.3% of the land was in use for agriculture with 8.8% arable land, 20.6% for crops, and 2.9% for pasture Central Intelligence Agency (2023).

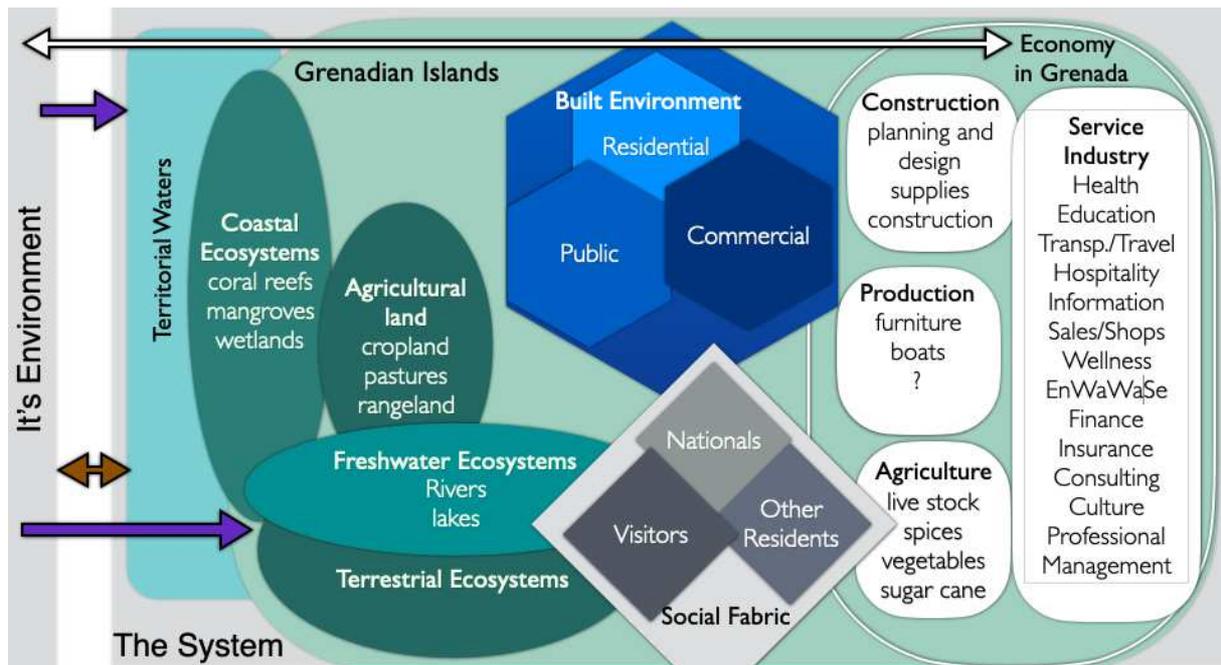


Figure 6. Higher resolution model for the system representing the goal statement. The interdependencies of the subsystems are discussed in the text. EnWaWASe: Energy/Water/Waste/Sewer services.

A large fraction of the built environment is in or near the coastal zone. Urban population accounts for roughly 37% of the population, with most of that population being in the capital St George's Central Intelligence Agency (2023). In particular, many of the commercial buildings are in areas with less steep topography closer to the coast lines. Hotels and other hospitality-related buildings are preferably next to beaches. Residential buildings are spread out and increasingly encroaching into hitherto undisturbed ecosystem. In the past, many of the smaller islands provided basically undisturbed habitats for birds and other animals. In recent years, an increasing fraction of these islands have been put in private hands for development, with the built environment there often close to sea level.

The social fabric is composed of a large fraction of nationals and a smaller fraction of other residents. Nationals are both those who have citizenship by birth as well as a growing fraction of immigrants having obtained citizenship. The population growth rate is small (estimated to be 0.29% in 2023, Central Intelligence Agency, 2023), which is to some extent due to a negative net migration rate Central Intelligence Agency (2023). Other residents are to some extent retirees from other countries, and a significant foreign student body studying at St George's University. Visitors include tourists as well as people with special skills needed for certain work to be carried out.

The economy of Grenada is a small OECS service-based economy with a large tourism section. Other significant sectors include construction, transportation and education Central Intelligence Agency (2023). Grenada is major spice exporter. Export commodities include nutmeg, tuna, cocoa beans, fruits, nuts, toilet paper, acrylic paints, and beer (estimated for 2021, CIA, 2023). While shrinking, the public debt is still high. The economy depends on many supply chains and local infrastructure that are fragile with respect to hurricanes.

In 2017 the service sector accounted for an estimated 77.7% of the economy, while industry accounted for 15.5% and agriculture for 6.8% Central Intelligence Agency (2023). Agricultural products include bananas, watermelons, sweet potatoes, sugar cane, tomatoes, plantains, coconuts, melons, cucumbers, and cabbages Central Intelligence Agency (2023).

Industry is composed food and beverages, textiles, light assembly operations, tourism, construction, and education and exhibits a significant production growth rate of estimated 15% in 2021 Central Intelligence Agency (2023). In 2008, the largest fraction of the labor forces of 69% was in services while only

20% were in industry and 11% in agriculture. Most likely, in 2023, the fraction in service has increased.

More than 95% of the population have access to electricity. Most of the electricity is produced with imported fossil fuels (total installed capacity estimated at 98.3% in 2020; CIA, 2023) while solar and wind currently account for only 1.7% of the estimated total capacity Central Intelligence Agency (2023). The electrical grid exhibit fragilities to tropical storms and hurricanes.

Access to improved drinking water is available to roughly 97% of the population. Water supply is also fragile and can be out of operation due to hurricanes for extended periods of time.

While an estimated 94% of the population had access to sanitation facilities in 2020 Central Intelligence Agency (2023), the level of waste water treatment is in most areas not very high and it can be expected that plastics and other novel substances in most cases are not captured. Much of the grey water is not treated besides grease traps. Storm water treatment is not developed.

3.5 Exogenic and Endogenic Hazards

As indicated above, hydrometeorological hazards relevant to the for the goal statement originating in the system environment are of paramount importance. These exogenic hazards can trigger many endogenic hazards (Fig. 7), depending on where assets are exposed and what fragilities these assets exhibit.

The climate-change related exogenic hazards indicated in Fig. 6 impact the system in many ways and lead to a number of endogenic hazards depending on what system fragilities are explored by these exogenic hazards. The main endogenic hazards include:

- Coastal flooding and inundation: storm surges associated with tropical storms and hurricanes come with significant coastal flooding impacting major roads and coastal buildings and leading to erosion. Local sea-level rise over the last 50 years has lead to a slow progression of the coast line inland an a significant loss of land areas (see Section 6).
- Increased heavy precipitation events result in large river floods, often as flashfloods.
- The destruction of commercial buildings and infrastructure as well as the disruption of supply chains leads to economic and social problems.
- Land loss and increasing exposure to coastal and river hazards creates migration out of the growing flood zones.
- Environmental degradation results from both the coastal and river flooding and the increase in pollution caused by flooding events.

The assets exposed to climate-change-related and other hazards include the ecosystems, the human built environment, the social fabric as well as the economic productivity (Section 4).

Realizing that the extent to which the hazards impact the system depends on system fragilities points to a pathways for preparation through adaptation that removes or reduces these fragilities. Understanding the fragilities is at the core of successful adaptation planning (Section 5). Combining the assets, the fragilities, and the hazards (Section 6) provides a path to a better understanding of the spectrum of possible futures (Section 7) and a thorough assessment of the risks (Section 8).

4 Exposed Assets

Assets are valuable resources which provide financial, social, or physical growth to a system. Exposed assets are those which have hazards that will potentially decrease their value or production. Exposed assets can be used to determine which resources should be prioritized when considering plans of mitigation or adaptation.

Mangroves serve as an asset for Grenadians in many ways. Mangroves protect inward land from natural disasters by blocking the coast with their hardy wood material. Mangroves serve as a biodiversity nursery, providing a safe space for new vegetation to grow. By being a resource, and also providing

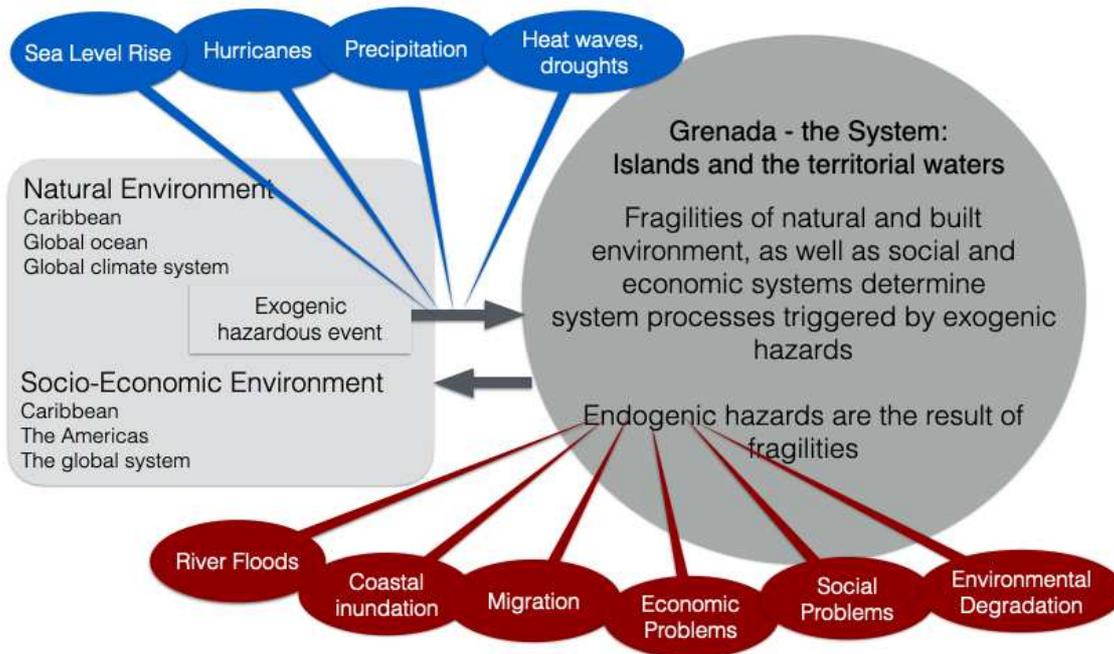


Figure 7. Exogenic and Endogenic Climate-Related Hazards to Grenada.

different resources, mangroves are vital to the natural and built environment. Mangroves are excellent at filtering out pollutants, which is valuable for other coastal species and neighboring communities. Overall, mangroves are an important asset for Grenadians to allow the island's natural beauty to thrive. The associated hazards include sea level rise, ocean warming, coastal expansion, sea walls/dikes, lack of local awareness and overconsumption of resources. Limited finances influence overconsumption, as locals are compelled to cut down mangroves for their own benefit.

4.1 Natural Environment

Grenada has a rich non-human environment with many assets (Tab. 3). Mangroves serve as an asset for Grenadians in many ways. Mangroves protect inward land from natural disasters by blocking the coast with their hardy wood material. Mangroves serve as a biodiversity nursery, providing a safe space for new vegetation to grow. By being a resource, and also providing different resources, mangroves are vital to the natural and built environment. Mangroves are excellent at filtering out pollutants, which is valuable for other coastal species and neighboring communities (Beck & Menéndez, 2020, e.g.). Overall, mangroves are an important asset for Grenadians to allow the island's natural beauty to thrive. The associated hazards include sea level rise, ocean warming, coastal expansion, sea walls/dikes, lack of local awareness and overconsumption of resources (Herrera-Silveira et al., 2022). Limited finances influence overconsumption, as locals are compelled to cut down mangroves for their own benefit.

The well-recognized sandy beaches of Grenada are a major source of income for franchises and local businesses. These beaches are a major part of the local culture, and the dependency on foreign investment appears to dwindle the local representation. The building of hotels and resorts on the ocean fronts is limiting access for locals and changing the natural landscape Grenada is known for. Coastal erosion is a main hazard for these beaches, and the continued placement of tourist hotels and restaurants increases the rate of erosion. These areas of attraction include light pollution, which is known to disrupt sea turtle nesting habitats. Sea turtles require the beaches of Grenada to nest, and the turtle populations in Grenada play critical roles for the wildlife populations throughout the island.

Coral reefs provide food and protection to Grenadians. Reefs serve as wave breakers to protect the coast from tropical storms and save the island's natural beauty from destruction. Coral reefs are home for numerous aquatic species, such as fish, shellfish, and other invertebrates. These species serve as

income for fisheries and food for the local people. Seafood is a majority of the food being eaten on the island, and hazards such as ocean eutrophication, warming, and acidification will negatively impact this. Expansion of tourist attractions results in heavy sedimentation and pollution from coastal construction and expansion. Sea level rise will increase the rate of sedimentation, impacting these coral reefs. Coral reefs are also tourist attractions due to snorkeling, scuba diving, and boat tours. The mentioned hazards will reduce the flow of funds in regard to tourism, impacting the economy of the local Grenadians.

Local fish populations are a source of income and nourishment for Grenadians. Food security will be threatened by hazards such as ocean acidification, warming, and eutrophication because fish require certain demands for homeostasis, such as pH or salinity levels. Sea level rise and climate change will impact these, reducing food security for Grenadians. Overfishing is happening and will continue, especially if fish populations decline more rapidly. This will impact the economy of local Grenadians and further push the coral reefs into an un-returnable state, impacting the entire island of Grenada.

The tropical forests making up Grenada's steep topography play several vital roles in the success of the island. The forests are home to a large portion of the island's wildlife, resulting in vast biodiversity throughout the island. Forests are known to be large carbon sinks, which is helpful in the face of human-induced rapid global change. This is threatened by construction expansion due to deforestation.

Many construction resources are found within these forests, resulting in overconsumption and leading to more deforestation. Poverty levels influence overconsumption because many locals are compelled to cut trees for their own benefit. There has been evidence of locals using mangroves to prop their houses up when faced with heavy storms or flooding.

4.2 Built Environment

The built environment relies heavily on the harbor and port authority for various functionalities (Tab. 4). The average GDP value for exports of goods and services is 60% and on average, 393.766 million dollars are from exports Central Intelligence Agency (2023). Grenada is known as the spice isle, and many apicultural products such as nutmeg, tuna, cocoa beans, fruits, and nuts are major exports. Imports of goods and services is -55%, and about 650 million are for imports Central Intelligence Agency (2023). Major imports are normally aircrafts, poultry meat, cars, refined petroleum, and food preparation materials. The major trading partners for imports are the United States(35%) and Canada(24%). The major trading partners for exports are the United States (40%), and various other countries.

Airports are vital for Grenadians' island lifestyle. Airports bring in tourists which is a major source of income. Grenada relies on the success of the airports for not only tourists, but also exports, imports, medical services, sister island transportation, and various economic values. In regards to medical assistance throughout the Caribbean, many Grenadians travel to Trinidad or the USA where specialized medical services are available. Airports bring in tourists which is a major part of Grenada's economic system.

Roadways are the main form of transportation throughout Grenada. The roads are being overloaded with a growing population and the growing popularity of cars as transportation. An increasing amount of cars are being imported into Grenada, and there is a lack of planning for flooding or heavy precipitation. The roads among the coast, specifically the east coast facing the Atlantic Ocean, are at the most risk to sea level rise and erosion. Grenville is a well-known city that is already under pressure from flooding and erosion.

Energy facilities, specifically oil, fuels the entire island, with some energy, such as petroleum, being imported. Erosion, storm surges, tidal flooding, sea level rise, and heavy precipitation will affect the success of the energy facilities. If Grenada can't fulfill the island's energy requirements, Grenada will become more dependent on other countries.

There are several hospitals throughout the island; however, the main hospital is the St. Georges hospital. Located below Fort George, this hospital has a lot of history, making it a valuable historical asset. Grenada has free healthcare for its citizens, and there are clinics and health centers all around the island. Major impacts to the hospital include sea level rise, landslides, tidal flooding, tropical storms, erosion, and landslides.

Table 3. Natural Assets.

Assets	Service	Value	Associated Hazard
Natural			
Mangroves	<ul style="list-style-type: none"> Protects inland from natural disasters Serves as a nursery for several species Value to other Ecosystems Resources Filter pollutants from water 	Mangroves have great value as they protect the built and natural environments around the island. Mangroves protect over billions of dollars of global flooding damage every year(2022, Michael Beck and Pelayo Menéndez).	<ul style="list-style-type: none"> Sea level rise Ocean Warming Unchecked Expansion Sea Walls/Dikes Inequitable Wealth Distribution
Sandy Beaches	<ul style="list-style-type: none"> Public Access Recreation (community hot spot) Value to other Ecosystems Turtle nesting habitat (critical) 	Beach restoration is very expensive, if feasible at all (2018, Song)	<ul style="list-style-type: none"> Dependency on foreign investment Construction Coastal Erosion
Coral Reefs	<ul style="list-style-type: none"> Source of income Value to other Ecosystems Wave Breakers / protect coast Critical fisheries habitats Filtrate pollutants from water 	The cost of reef restoration is expensive, if feasible. The economic cost of reefs is worth about 375\$ billion each year (2021, NOAA).	<ul style="list-style-type: none"> Ocean Eutrophication Ocean Warming Ocean Acidification Expansion (pollution/construction) SLR
Local Fish Populations	<ul style="list-style-type: none"> Food Security: decreases demand on imports Taxes tourism Industry: Snorkel, Scuba Diving, Boat Tours 	Fisheries are a big income source. Impacts of SLR and heavy precipitation will be greatly affected, and the economy will face consequences (2019, World Bank)	<ul style="list-style-type: none"> Ocean Acidification / Eutrophication Overconsumption Waste management Climate Change
Forests	<ul style="list-style-type: none"> Value to other Ecosystems Integrate bamboo root system that helps prevent landslides Carbon sink 	Ecosystems are of great value, and will greatly affect other sectors. Disregarding the forests will result in more financial burdens. (Schmitz, 2023)	<ul style="list-style-type: none"> Expansion Climate Change Overconsumption of natural resources

Local hotels/ business are apart of the Grenadian economy and culture. Local homes and businesses are responsible for the livelihoods of the local people, and can be empowering for many by providing jobs and shelter. Local homes and businesses on the coast attract lots of customers however sea level rise and extreme precipitation is a concern.

4.3 Production

Cocoa and nutmeg are some of Grenada’s most popular spices and the most popular exports (Tab. 5). Grenada is known as the spice island, and spices are a major export which produce on average about 393 million, therefore these spices are a valuable asset Central Intelligence Agency (2023). Cocoa and nutmeg trees will be greatly affected by climate change, extreme precipitation and sea level rise as spice trees often times require specific conditions which will be affected by extreme conditions.

Table 4. Built Environment Assets.

Built			
Harbor / Port	<ul style="list-style-type: none"> • Tourism • Food/Supply lines/Imports • Transportation 	The Port Authority brings in around 5 million in revenue. Grenada is heavily dependent on the port authority (UN, 2009)	<ul style="list-style-type: none"> • SLR • Storm Surge • Tidal Flooding • Expansion
Airports	<ul style="list-style-type: none"> • Tourism • Material [import/export] • Transportation 	The only international airport in Grenada, Maurice Bishop, contributes 23 million to the economy, and provides 1,700 jobs. (Oxford Economics, 2009)	<ul style="list-style-type: none"> • Expansion (Carriacou) • Dependency on Tourism • SLR • Tropical Storms
Roadways	<ul style="list-style-type: none"> • Transportation • Integral for island functioning 	The cost to build roads is already very expensive. To maintain or restore a road, would cost even more, when dealing with implications that arise from rapid climate change (2019, BigIslandNow)	<ul style="list-style-type: none"> • Erosion • Tidal Flooding • Storm Surge • Landslides • Mudslides • Heavy Precipitation • SLR • Tropical storms/hurricanes
Homes / Housing	<ul style="list-style-type: none"> • Living space • Shelter/Safety • Culture (sense of identity) 	70th percentile globally for quality of living index (2023, GCS)	<ul style="list-style-type: none"> • Sea Level Rise • Coastal Expansion • Erosion • Landslides
Energy Facilities	<ul style="list-style-type: none"> • Responsible for vast majority of energy production in the nation 	Annually 1.8 billion goes into energy per year (2020, U.S. Department of Energy)	<ul style="list-style-type: none"> • Sea Level Rise • Storm Surge • Tidal Flooding • Tropical Storms • Erosion • Landslides
Hospital	<ul style="list-style-type: none"> • Provides medical care for most of the citizens within the nation • Sense of security 	The total cost to build the hospital in St. Georges was ~ 34,000,000 EC. It can be expected that repair or restoration will be costly (2013, Johns)	<ul style="list-style-type: none"> • Sea Level Rise (st.Georges) • Landslides/Mudslides • Heavy Precipitation
Local Hotels / Business	<ul style="list-style-type: none"> • Forms the backbone of the tourism economy. Without this, there is no tourism. \$ taxes 	Coastal businesses are at risk from natural disasters, potentially requiring billions of dollars to recover (2021, UN)	<ul style="list-style-type: none"> • Sea Level Rise • Heavy Precipitation • Tidal flooding • Upscaling

Food security is important for small developing islands because of their reliance on imports. Agricultural land is a valuable asset which will be impacted by climate change and landslides. Just 11% of the labor force is from farmers, and locally owned farms are an important way to empower the local people, specifically in low-income communities Central Intelligence Agency (2023). Agriculture will be exposed by climate change, and the affects will affect the economy and the people which rely on it.

Agriculture is a huge asset to Grenada, and so are the bananas. Grenada exported 4.02k in bananas, mostly to the United States and Montenegro in the past years (OEC, 2021). Bananas are a major part of the export trade, as well as, the economy of Grenada, making bananas a valuable asset which will be exposed by climate change.

Table 5. Production Assets.

Production			
Cocoa / Nutmeg Trees	<ul style="list-style-type: none"> • Economy (major export) • Food Security • Culture • Tourism 	The natural environment is at risk, and products which rely on it will face serious consequences if preventative measures aren't taken (2021, UN)	<ul style="list-style-type: none"> • Tropical Storms/Hurricanes • Heavy Precipitation • Sea Level Rise
Agriculture	<ul style="list-style-type: none"> • Economy • Food Security 	As an island, Grenada is already naturally dependent on imported food. Local farms empower local people, but it is common for farmers to not have access to innovative, sustainable farm practices. Current farm practices will become more difficult as climate change creates a harsher environment, directly impacting the livelihoods of many. The cost of food security may be expensive now, but the cost to have food insecurity is much higher as imports increase (2023, Global Communities)	<ul style="list-style-type: none"> • Tropical Storms/Hurricanes • Heavy Precipitation • Sea Level Rise • Flooding • Landslides
Banana Trees	<ul style="list-style-type: none"> • Economy (major export) • Food Security 	Banana trees require a lot of moisture, which will be impacted as climate change makes dry seasons become hotter, and longer. The limitations and sensitivity of bananas, will impact production, and as a result the supply chain will also be impacted (Turner, 2008)	<ul style="list-style-type: none"> • Tropical Storms/Hurricanes • Extreme Precipitation • Sea Level Rise

Table 6. Core Asset.

Core Assets			
The Local People	<ul style="list-style-type: none"> • Economy • Culture • Source of value for all other assets (Core Asset) • Cost of human life 	Natural disasters enhanced by rapid climate change will cost trillions of dollars (UNDRR/CRED, 2020)	<ul style="list-style-type: none"> • All Hazards

4.4 Grenada's Core Asset

Local Grenadians are the most valuable asset (Tab. 6), which is impacted the most by the hazards discussed above. The value at risk is the life of the people, and the risk is not equally distributed. Disasters caused by natural hazards enhanced by rapid climate change will cost trillions of dollars (UNDRR and CRED, 2020). Future climate change comes with a risk which the Grenadian Government will need to consider when planning for sea level rise and heavy precipitation.

5 Fragilities

A fragility is a constitutional system property that can lead to degradation of the system's functioning or to significant changes in the system if exposed to external or internal hazards. This section describes the fragilities of the built, natural and social economic systems of Grenada. This system's fragilities were analyzed based on the goal statement of the case study. The understanding of these fragilities and other sections of this case study are needed to be able to see a change in the system. The continuation of sea level rise and increased precipitation will exacerbate the hazards and fragilities of Grenada.

5.1 Fragilities of the Built Environment

Grenada has very mountainous topography combined with low-lying valleys. This can make the steep topography fragile, less stable and more susceptible to displacements (Ternan et al., 1989). For example, when increased precipitation is present, settlements and infrastructure of Grenada are susceptible to landslides or mudslides. This will threaten towns, farms, and future and current infrastructure. Additionally, the topography is exposed to coastal erosion. Houses built along these coasts are at risk. The steep mountains further inland make arrears of Grenada more prone to floods and damage from these landslides.

The low lying areas of Grenada are very susceptible to sea level rise (Tab. 7). These are the very first areas impacted when flooding occurs and has a decreased drainage capacity. When sea level rise, storm surges, and increase in intensities of these hazards, these low lying areas will become inundated by the sea water thus damaging the built environment and local communities.

The built infrastructure of sewage systems in Grenada are not fully complete. Thus, when sea level rise will inundate these low lying areas and the sewage system (Compton & Forde, 2020). When the streets flood many of the sewage will flood into the street as well. This will lead to severe health hazards to the local Grenadines that will have to walk through these waters as well as potential mixing with the ocean causing further pollution.

Beaches and mangroves of Grenada are very important for the built environment. The inability of these two things to migrate will lead to erosion of the coastline and further expose the coast to sea level rise. With increasing sea level rise the beach will be continuously pushed inland and to the sides and will eventually fully erode and mangroves will eventually be no longer.

5.2 Fragilities in the Non-Human Environment

Coral reefs are delicate ecosystems with many inherent fragilities that can be acted upon by a variety of hazards (Tab. 8). For example, sea level rise would increase the depth at which the stationary coral reefs are submerged. This deeper depth would result in less light reaching the corals thus decreasing their rates of photosynthesis. Additionally, the rising waterline will start to annex more expansive inland areas than before, thereby increasing the levels of polluted runoff that is produced from heavy precipitation events. This resultant runoff has the potential to not only cloud coastal waters, further obscuring how much light makes it to the reefs, but it could also change the chemical composition or PH levels within the water itself (Enochs et al., 2020), possibly pushing the reef system outside of the narrow window of conditions in which corals thrive.

The natural mangroves of Grenada currently act as a buffer between wave action, storm surge, and the coast. However, they grow slowly and require specific conditions regarding salinity and salt water inundation in order to thrive. With limited space to migrate and sea levels quickly rising, mangroves do not have enough time or space in order to successfully adapt to changing conditions.

Cocoa and nutmeg, both major exports for Grenada, naturally have long growth periods before they are capable of bearing fruit. For nutmeg trees it takes at least eight years to yield fruit and for cacao it will take about five. Increased storms, heavier rains, and sea level rise can damage these trees and potentially put farmers out of work for several years. This would stall the agricultural sector of the economy and place a strong limiting agent on the threshold for resilience present within these communities.

Table 7. Fragilities of the Built Environment.

Built		
Fragilities	Hazards	Explanation
Steep topography is less stable (more prone to displacement) than level ground	Erosion, Landslides/mudslide, Heavy Precipitation, Land Capacity	The volcanic composition of Grenada exposes many of the coastal areas to erosion. Houses built along these coasts are at risk of collapsing under their own weight. The steep mountain faces inland also make several areas in Grenada prone to floods and damage from landslides and mudslides.
Low lying areas have decreased drainage capacity, first areas impacted during flooding	SLR, Storm Surges, landslides/mudslides, heavy precipitation, Tidal floods	As sea level rise increases, lower lying areas will become inundated by sea water, damaging the built environment and local communities.
Incomplete sewage system	Tidal flooding, saltwater intrusion, Disease/ injury, Storm surge, pollution	As an increase in sea level rise and flooding from high precipitation, the community will be inundated causing the water to mix in with sewage. This can cause health issues when the people in the community walk through these waters. Thus, having sewage in the ocean will further pollute it.
Inability of beaches and mangroves to migrate horizontally	SLR, erosion, Land Capacity	SLR and erosion both affect beaches which have been limited in migratory capabilities. This often results in the beach face being pushed to the sides, and eventually, completely eroding.

5.3 Socio-economic Fragilities

Low-Income households are considered fragile because they typically lack the necessary financial means required to successfully recover from loss or damage (Tab. 9). For example, it would be far more difficult for individuals with low-income to be able to migrate inland than those with more financial security because they lack the capital for rebuilding their homes. Also, if they have to move further away from their workplace, the burden of a longer commute could put them at even greater risk from the impact of a hazard. In Grenada 40% of people are below the poverty line (Commission, 2022). Due to this economic standing, sea level rise will impact many Grenadians who will be unable to afford moving inland or replacing their belongings. Much of Grenada's populace currently face social vulnerabilities, such as unequal distribution of risk, socio-economic status, and access to information. These factors all contribute to the degree of which the impacts will be felt. Lack of access to resources such as education, healthcare, and economic relief will result in an increasing number of people retreating to live in unstable or unsafe regions. Those who are currently low-income, will be the most effected by hazards associated with sea level rise and heavy precipitation and any low-income household that currently resides on the

Table 8. Fragilities of the Non-human environment.

Natural		
Fragilities	Hazards	Explanation
Coral reefs narrow range of tolerance	Ocean warming, eutrophication, acidification, SLR	Reefs are heavily affected by factors of climate change, such as ocean warming, acidification, and eutrophication. These factors often affect the biological process that these organisms conduct. With sea level rise, coral reefs will see an eventual decrease in photosynthesis.
mangroves ability to vertically migrate	Ocean warming, eutrophication, acidification, SLR	Mangroves are affected by factors of climate change. SLR, if it occurs too fast, can also be damaging as mangroves would not be able to keep up with the rising sea.
Long growth period of cocoa and nutmeg	Tropical Storms / Hurricanes	Two of the major crops on Grenada, cocoa and nutmeg, both take long durations to actually grow and produce fruits/nuts. Increased hurricane activity can keep the farms that produce such plants in a constant state of no production .

coast, specifically in Grenville and St. George, should be given extra consideration by the government when implementing mitigation efforts.

Lack of foresight/education in current developments is a major fragility among low-income, or poverish communities. A majority of Grenada, is not made aware of current issues such as sea level rise due to the lack of education and public awareness about the causes and possibilities which will arise from climate change impacts. Although about 98% of the population above 15 years old is literate and about 3.6% of the total GDP is spent towards education, education regarding climate change is far and few between and there is oftentimes misunderstanding of the science behind climate change Central Intelligence Agency (2023). Without education and foresight about climate issues such as sea level rise, these communities cannot begin to prepare for the potential serious damages of sea level rise and heavy precipitation can bring (IPCC, 2023). The Grenadians in low-income, poverish communities do not have the same access to education as others, and this contributes to formation cognitive biases which limit the understanding of climate change (Faldi & Macchi, 2017). Low-income communities are often in the front lines of experiencing the impacts of climate change, and it results in these communities being fragile against climate change impacts. This is a clear sign of unequal risk distribution, and this is a result of not only poor economic opportunities, but also lack of education on important issues such as climate change (Nations, 2021).

The dependency on the supply chain will impact Grenada's economy, as the hazards associated with climate change will negatively impact the ports internationally. The island of Grenada relies heavily on external imports for things such as building supplies and certain food sources. Major exports are a major part of the economy of Grenada. Exported goods and services make up 60% of the total GDP of Grenada Central Intelligence Agency (2023). The reliance on the supply chain as income for the economy, Grenada is made fragile against the possible outcomes of sea level rise and extreme precipitation (IPCC, 2023). Sea level rise and heavy rainfall affecting the flow of the ports in Grenada, will affect the ability of the Grenadian system to continue growing. The built environment heavily relies on imports for construction, therefore as climate change impacts the supply chain, the infrastructure will be directly weakened (Nations, 2021). The extremity of the impacts will depend on whether the Grenadian Port

Table 9. Socio-economic fragilities.

Socio-economic		
Fragilities	Hazards	Explanation
Inequitable/polarized wealth distribution (in terms of overall economic standing and ability to move/replace)	Disease, SLR	SLR, storm surge, and hurricanes are all factors that can lead to the destruction of the built environment, something that many of the people of Grenada cannot afford.
Lack of foresight/education in current developments	SLR, Erosion, Tidal Flooding, Storm Surge	Due to the lack of education and foresight, issues such as sea level rise etc are not made aware to locals. Without these Grenada cannot prepare for the future disasters.
International supply chain	SLR, tropical storms/ hurricanes	In Grenada, the supply chain is a major factor in daily life and one that can be easily disrupted. Landslides, storm surges, and mudslides can block roadways or collapse bridges, and SLR and storm surges can damage boats and destroy ports.
Limited capacity of healthcare	Disease, SLR	Floods/SLR are often a major contributor to the spread of diseases as it often brings up raw sewage and hazardous debris. The increased amounts of tidal flooding and flooding from rain events would put extreme strain on the poor healthcare system on the island.
Economic homogenization (tourism dependent economy)	Expansion, Excess Land Division	Grenada is completely dependent on tourism now which means that is their main source of income. With sea level rise and others, Grenada will lose a lot causing less tourists to be able to get into Grenada or refrain from coming.
Food security relies heavily on supply lines/imports	SLR, tidal flooding, storm surges, expansion, heavy precipitation, overconsumption, Climate change	Since a lot of agriculture is in small backyard farms, they are at serious risk from heavy precipitation and groundwater intrusion causing the destruction of food. Sea level rise will also impact imports from coming in thus furthering their loss of food.
Diminished availability of land (due to Foreign Land Ownership/CBI program)	Unsustainable Expansion, Excess Land Subdivision	Construction destroys natural habitats, contributes to loose soil→ erosion, degrades/diminishes the land available for potential migration. With only a finite area to expand in, the built infrastructure of Grenada will eventually run out of room.

Authority will make strategic plans for sea level rise and heavy precipitation. However, the dependency on imports, exports, and the international supply chain will serve as a fragility for Grenada as the impacts of climate change become hazards.

As a small, developing island state Grenada relies on much of its economy on tourism, but also on foreign investors through the Citizenship by Investment Program. While it provides the opportunity for increased economic opportunity and development, an issue that has arisen with this foreign-focused economic model is the purchasing of interior lands by non-Grenadian citizens or full-time residents. With the inevitable rise of sea level, the privatization of elevated lands poses an equity issue which also poses an issue for potential migrations in the future.

Although considered one of the best healthcare systems in the Caribbean, Grenada's healthcare capacity remains limited especially when confronted with issues of sea level rise and extreme precipitation events. Totalling only four large hospitals across three islands within the nation, many within even the most generous rises in sea level the future capacity of these institutions remains in peril. Furthermore, the health hazards posed by the potential illnesses that may be exposed to the citizens of Grenada through these crises, such as pollution of sewage, could very well cause increased demand for a hospital system already under normal capacity from sea level rise and flooding. Take for example the hospital in

St. George's, in which some portions border the coastline at present-day sea level which remains an exquisite example of those implications.

As stated by many of the stakeholders interviewed, tourism is a major source of income on island. With sea level rise and heavy rainfall damaging infrastructure such as hotels and natural ecotourism sites, Grenada has the potential to lose a large portion of its tourism generated income. Beaches around the island are also impacted to a great extent. Not only are beaches such as Grand Anse hot spots for tourists and locals alike, but these areas are prime real-estate for many of the island's hotels. Unfortunately, these low-lying areas are susceptible to even small progressions of sea level rise, such as one meter. Because most of the island's hotels are located on or near the coast, they are at greater risk from hydrometeorological storms such as hurricanes. The rapid intensification of these storms poses a severe threat to tourism-dependent islands such as Grenada. Hurricanes can cause millions in repairs, and predicting when a storm will hit has become increasingly difficult (Balaguru et al., 2018). Other hazards, such as extreme flooding events, can also negatively impact tourism on the island by obstructing roadways and severing supply routes used by hotels and other tourism-dependent facilities.

Food security is one of the major concerns for the Ministry of Agriculture. Local/backyard farms are at serious risk from heavy rainfalls, landslides/mudslides, and groundwater intrusion, which could put the people of Grenada in a situation where they are without food. Hydrometeorological hazards such as hurricanes, which can lead to storm surges, devastate agricultural land all over the island, especially those by the coast. Coastal ports are also at risk because of hazards such as sea level rise. The damages caused by these hazards are a detriment to imported goods. In addition, human presence in the coastal zone is growing, resulting in equally rapid growth in consumer goods in these areas (Plag et al., 2021). Unfortunately, some of these areas are not located in the most ideal locations. This transition has landed a large majority of agricultural land in flood zones, negatively affecting food security.

As referenced earlier, the Citizenship by Investment Program is a huge source of revenue and investment for the government of Grenada. However, this recent institution and growing independence in tourism poses a risk for the future of Grenada. If the beaches were to be lost and the coastal resorts flooded, all without proper preparation the Grenadian economy would be devastated. This especially remains true as much of the current economic development and expansion of Grenada relies upon the destruction of the remaining coastal ecosystems that provide numerous, natural resources to the Grenadian people including water filtration and storm surge protections. The issues combined with a potential decrease in easily developable lands is an important consideration for a sustainable Grenada moving forward.

6 Scenarios for Hazards to the Built Environment

6.1 Introduction

Grenada is exposed to a range of exogenic and endogenic hazards resulting from modern global change (Fig. 7 in Section 3.5), ranging from threats to global food security, limited access to resources, new biological hazards, and reduction or loss of tourism to more frequent and more intense hydrometeorological hazards impacting the country. The latter include sea level rise, longer and more intense droughts, more frequent, longer and more intense heat waves, more frequent and stronger hurricanes, and extreme precipitation events (Fig. 9). For food security, crop vulnerability to climate change and extreme weather events is a growing concern (Monteleone et al., 2023), and the loss of food security can impact both imports of food to Grenada as well as the local production and exports of agriculture products. Wild fires are already increasing in geographical distribution, frequency and intensity causing increasing concerns for human health and wildlife.

Social planners are challenged with the trade-off between precautionary preparing society for future potentially extreme hazards at high costs for the present population and limiting preparations to the more probable but limited hazards. Kemp et al. (2022) point out that in many assessments of climate change impacts the worst cases are ignored and emphasize the high risk of societal collapse this approach is associated with. Typically, for a given hazards the so-called long-tail of the *Probability Density Function*

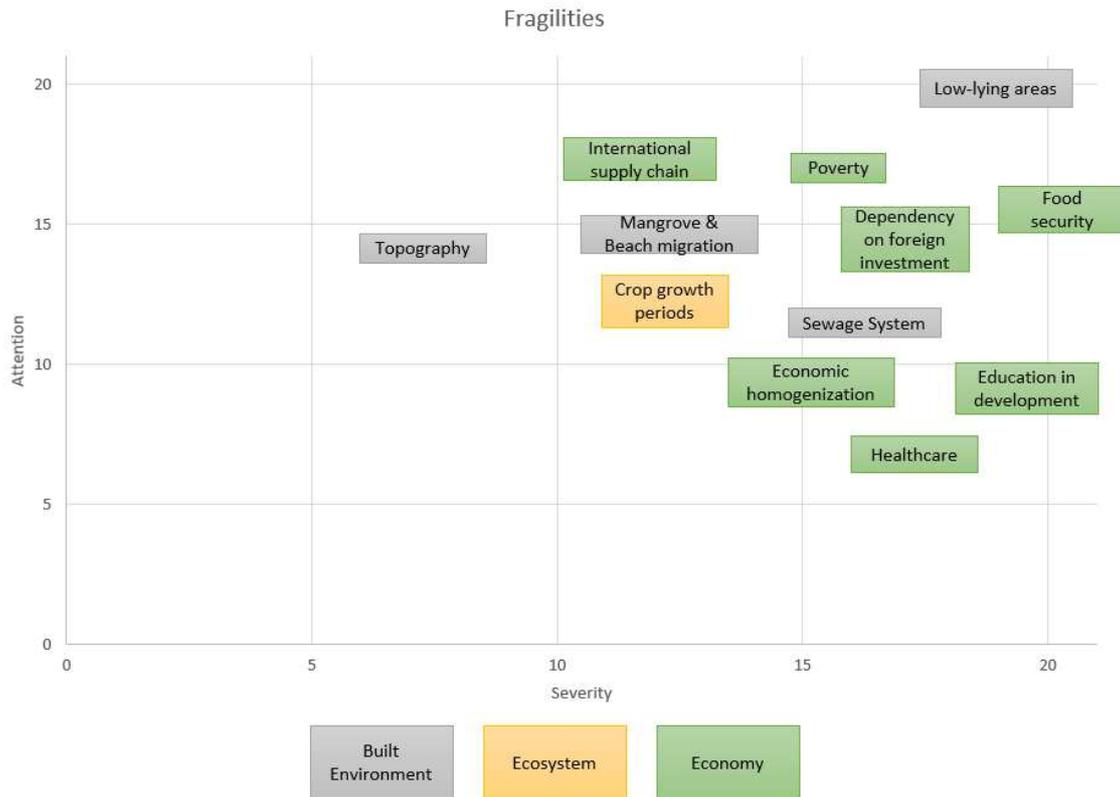


Figure 8. Mapping of the severity and attention drawn to fragilities in the system.

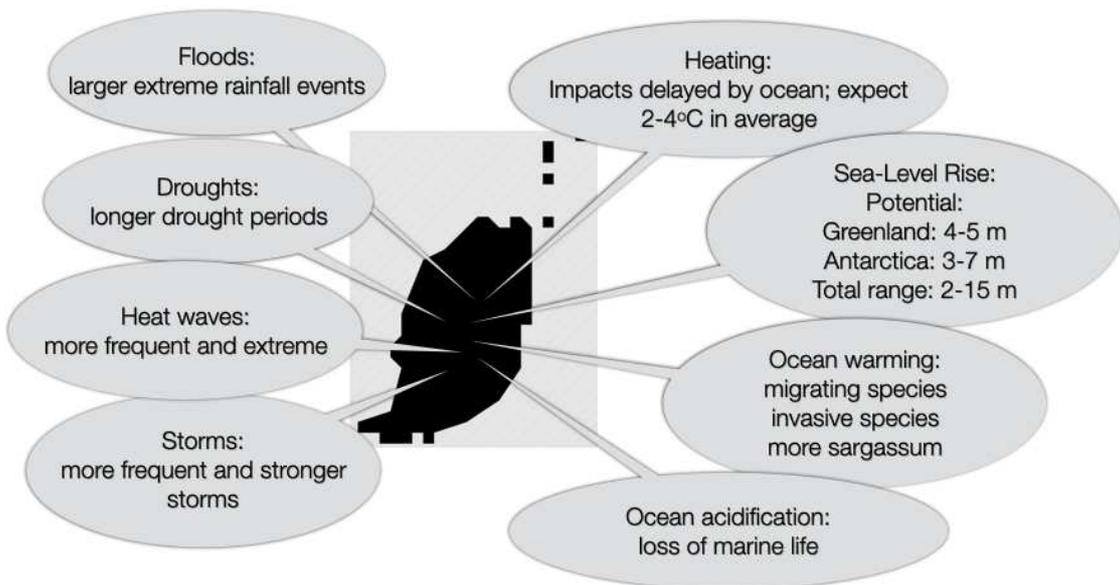


Figure 9. Climate-Change Related Hazards to Grenada.

(PDF) of a hazard comes with a much higher risk than the more probable lower-impact middle range of the PDF.

IPCC (2023) points out that the impacts of climate change future generations will have to deal with depends on the decision being made today and in the near future (Fig. 10). This also applies to all other threats that combine into the complex Anthropocene Risk (Keys et al., 2019) associated with the triple crises of climate change, biodiversity loss, and pollution. These threats are no longer decoupled. The

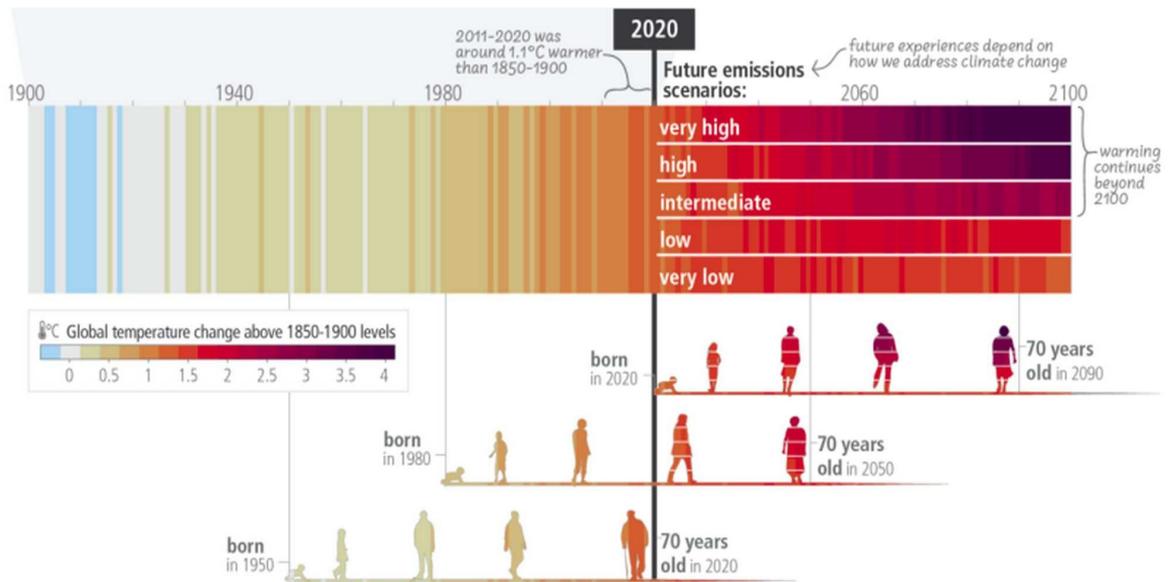


Figure 10. The extent to which future generations are impacted by climate change and the resulting hazards depends on decisions made now and in the near future. From IPCC (2023).

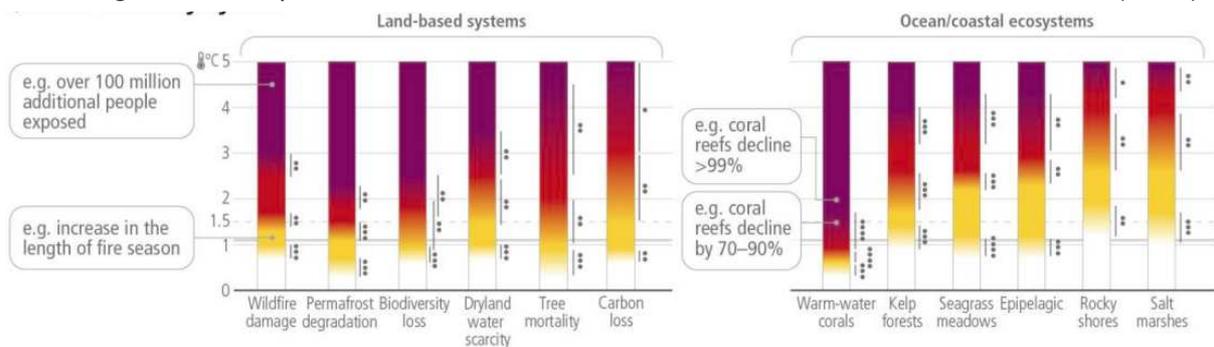


Figure 11. Risks for different ecosystems depending on mean global air temperature increases. From IPCC (2023).

syndrome of modern global change combines to a complex and existential challenge to humanity from local to global scale (Plag, 2020).

A major challenge is in the fact that in each of the triple crises, the visible impacts are lagged and occur often decades after the causing processes have occurred. For example, the increase in global air temperature to the equilibrium temperature for current atmospheric Greenhouse gas contents is delayed by many decades because of the very high volumetric heat capacity of water compared to air (Plag, 2020). This results in the ocean absorbing more than 90% of the energy the planet is currently storing (von Schuckmann et al., 2023). Biodiversity loss caused by climate change is delayed because of ecosystem processes (Fig. 11), and lags are on the order of 10 years for birds and more than 40 years for larger animals Cornford et al. (2023). Pollution in the ocean is lagged with respect to the pollution entering the environment due to the time it takes for the pollution to reach the ocean. In the case of plastics, the accumulation of plastics in the coastal built environment can lead to significant pollution in the ocean with a time lag of up to a century Plag et al. (2021). This delayed evidence of impacts has a severe impact on risk perception and can easily lead to an underestimation of the threats a system is exposed to.

Risk assessments have to consider that in the future copying capacity may be limited because several hazards occur simultaneously. Among others, the risk of losing species and reduced food productions, as well as risks for humans health resulting from high heat-humidity conditions are expected to increase regional differences in risk, with the Caribbean exhibiting high risks in all these areas (IPCC, 2023).

While the full impacts of hydrometeorological hazards may be delayed, it is very likely that copying capacity may be needed for the broad spectrum of challenges and not be available for adaptation to increased flooding and inundation. Adaptation therefore should aim to change planning already today with the goal to ensure that current actions do not increase future risks under worst case scenarios.

For the built environment, sea-level rise, hurricanes, and extreme precipitation events are the most impactful hazards. Importantly, a rising sea level also increases the maximum flood levels of the storm surges associated with a hurricane of a given strength. Events that were in the past 1-in-100 year events could easily happen in the future at annual or interannual frequencies (IPCC, 2023).

In the following, we make an effort to consider the full PDF for the climate-change related hazards that could impact the built environment in Grenada. The hazards that can directly impact the built environment include sea level rise, tropical storms and hurricanes, and extreme precipitation events. For some hazards, the impacts can be reduced through adaptation of the built environment. These hazards include droughts and heat waves.

6.2 Local Sea Level Rise Scenarios

Local Sea Level (LSL) changes are the difference of changes in the height of the sea surface and the land surface. In general, for Grenada, land surface changes are on the order of 1 mm/yr as indicated by two permanent GPS sites in Grenada and Carriacou (see Hamond et al., 2023). Land surface changes are impacted by mass changes on the Earth's surface resulting among others from the melting of glaciers and ice sheets (e.g., Plag & Jules-Plag, 2013). However, since Grenada is in the far-field of the ice sheets, this contribution is small and accounted for in estimates of local sea-level change caused by melting of land-based ice.

The main contributions to changes in sea surface height result from change in the ocean heat content and changes in the mass balance of the ocean. Changes in ocean circulation also impact the dynamic sea surface topography and these changes can result in LSL changes of a few decimeters. Changes in atmospheric circulation can change the average air pressure and wind fields, and this has an impact on LSL. The possible contributions are on the order of a few centimeters.

Changes on ocean heat during the 21st Century are estimated to result in steric *Global Sea Level (GSL)* rise of 0.3 to 1.2 m (IPCC, 2023), depending on how fast the ocean is warming. The current *Earth Energy Balance (EEI)* is on the order of 320 TW, and most of this energy is absorbed by the ocean (von Schuckmann et al., 2023). This high amount of energy absorbed by the ocean points towards the upper end of the range for the steric GSL rise and LSL rise.

Glaciers are already contributing to GSL rise. It can be expected that this contribution will remain at the same level or increase during the 21st Century (IPCC, 2023).

The potentially largest contribution to GSLR could come from the large ice sheets in Greenland and Antarctica. Recent findings have indicated that the *Greenland Ice Sheet (GIS)* could become unstable within this century (Reyes et al., 2014; Morlighem et al., 2014; Box et al., 2018; King et al., 2020; Boers & Rypdal, 2021). Ocean waters around Greenland have been found to warm rapidly (de Steur et al., 2023). Submarine valleys reaching far inland under the GIS could lead for warm water to reach deep under the ice sheet. A rapid disintegration of large parts of the GIS can not longer be ruled out. The GIS holds water equivalent to about 4.5 m in GSL rise. Disintegration of one third would lead to 1.5 m of GSLR. Similarly, the *Antarctic Ice Sheet (AIS)* also could contribute to rapid increases in GSL (Weber et al., 2014). The *West Antarctic Ice Sheet (WAIS)* has already entered a state of disintegration (Rignot, 2002; Sumner, 2014; Mouginit et al., 2014), but it is not clear how fast this process will lead to a complete melting of the WAIS. In the end, this process will result in roughly 4 m of GSL rise (Joughin et al., 2014) and we can not exclude that one or two meters of that will be contributed in the 21st Century.

A large epistemic uncertainty relates to the speed of the retreat of the grounding line of ice sheets (Joughin et al., 2014). A recent study aiming to address this uncertainty found that during the last deglaciation rapid grounding-line retreat at rates ranging from 55 to 610 m/day took place (Batchelor et al., 2023).

While the total LSL rise in the 21st century is of importance for the challenges Grenada faces, of equal

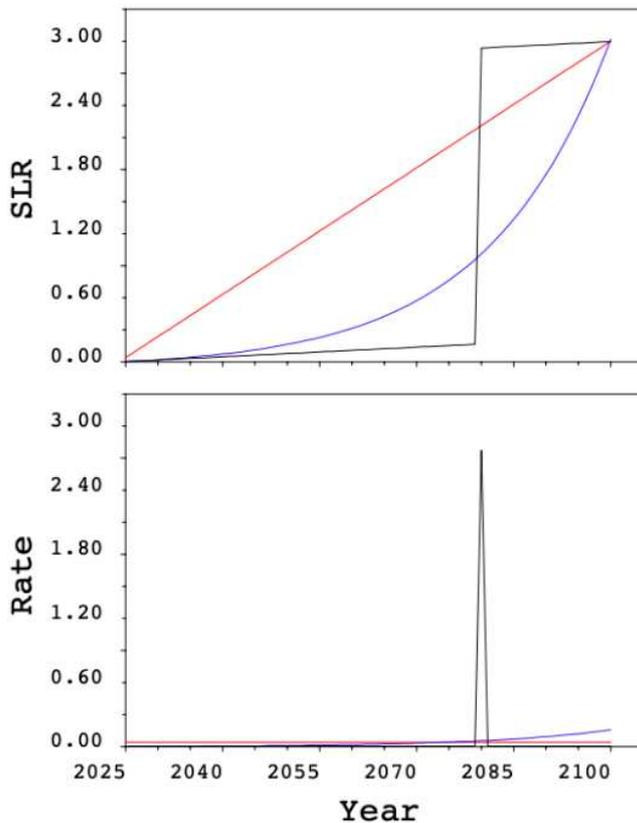


Figure 12. Archetypical LSL rise trajectories. Perception of the risk associated with LSL rise and willingness to adapt and mitigate impacts can be expected to depend on the rise trajectory. Lower diagram is the rise rate and upper diagram is the actual rise. The red trajectory is for a high constant rate of LSL rise, the blue trajectory for an exponentially increasing rate, and the black curve for a low rate combined with a sudden step-like rise. Rate is in m/yr and LSL rise is in m.

importance for the possible futures the LSL rise might create is the actual LSL rise trajectory. Different trajectories will impact risk perception and willingness to respond and adapt very differently. Three archetypical trajectories are depicted in Fig. 12:

1. Constant LSLR rate: A more or less linear increase will impact society with a slowly increasing risk perception and develop the understanding that adaptation is required early on.
2. Exponentially increasing LSLR rate: more exponential increase in the rate of LSLR will delay the realization that adaptation is necessary and delay serious adaptation. When the rate of LSLR is much larger than the current rate, direct damage to buildings will increase rapidly and economic activities will be hindered through increasingly frequent and more severe flooding. Copying capacities will be strained towards the end of the 21st Century.
3. Low constant LSLR rate followed by a rapid, step-like increase: If the rate of LSLR remains low over several decades, risk awareness will also remain low and significant adaptation of the built environment will most likely not take place. If this low rate is followed by a rapid, almost step-like increase, the built environment will not be prepared and copying capacity will not be sufficient to facilitate rapid adaptation. The social and economic consequences of such a scenario would be difficult to tackle.

Note that the most recent analyses of GSL rise in the last three decades provides solid evidence for a increase of the rate of GSL rise from 2.3 mm/yr in the decade starting in 1993 to 4.6 mm/yr in the decade starting in 2013 (Fig. 13). This gives a high probability to Scenario 2. The most likely trajectory is one that combines Scenarios 2 and 3, i.e., an exponential increase of the rate of GSL rise with one or more rapid, step-like increases due to disintegration of one or more parts of the GIS and WAIS.

Another reason for larger rates of GSL rise and LSL rise is in the speed of climate change. During the last two deglaciations after the ice ages, atmospheric carbon dioxide increased over 10,000 years from a low level near 170 ppm at the maximum of the ice ages to roughly 300 ppm at the warm periods (Fig. 14). Over the last 120 years, an increase from 300 ppm to almost 420 ppm was roughly 100 times faster. Likewise, the increase in the average global surface temperature atmospheric was on the order

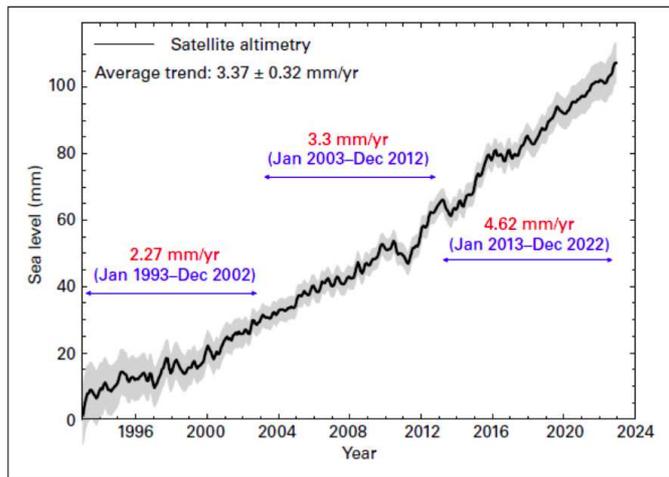


Figure 13. GSL change from January 1993 to December 2022 (black curve) with associated uncertainty (shaded area) based on satellite altimetry. The horizontal blue lines indicate the average linear trends over three successive time spans. Source: Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS): data from AVISO, altimetry (<https://www.aviso.altimetry.fr>).

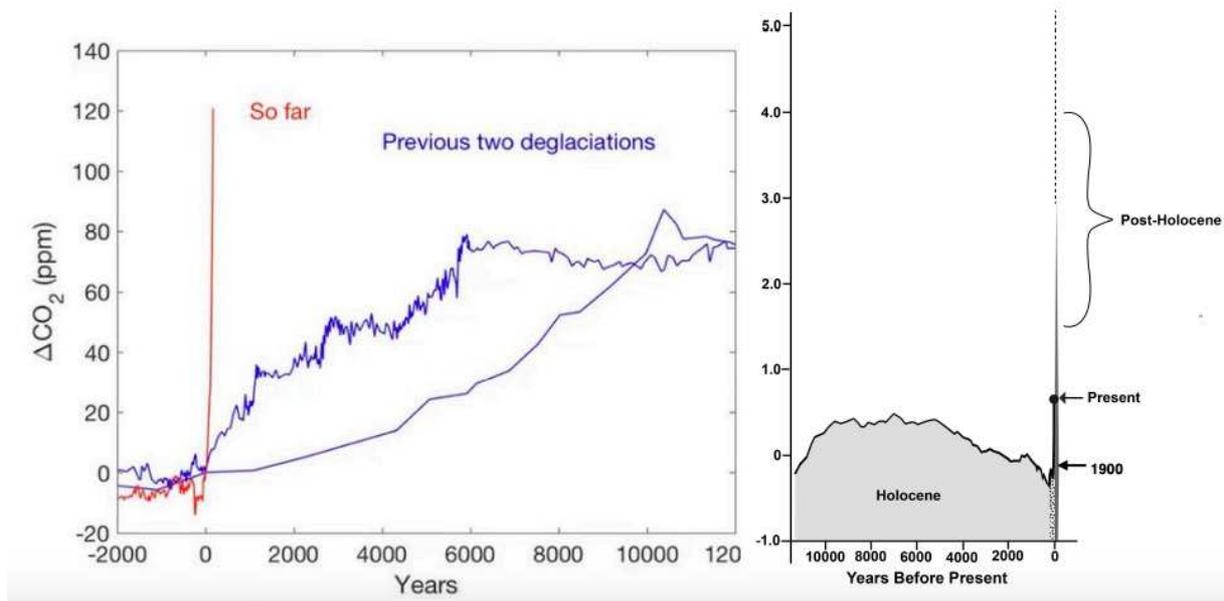


Figure 14. Glaciation Periods. From Plag (2023, personal communication).

of 170 times faster than the changes in mean global temperatures were during the last few deglaciations (Gaffney & Steffen, 2017). The extreme rates of change in many climate-relevant parameters signal a high degree of disequilibrium and instability. A rapid disintegration of large part of the remaining ice sheets there is a possible consequence.

It is important to note that over the last 20 years scientific knowledge related to GSL rise and LSL rise has evolved rapidly. While at the beginning of the 21st century, most experts considered a very rapid and large GSL rise highly unlikely (e.g., Church et al., 2001), many experts agree now that there is no scientific basis to exclude large rises. The most likely PDF for total GSL rise in the 21st Century now has a long tail including values of 5 to 10 m and more (see Fig. 18 below). The government of Grenada used in a 2017 report (Government of Grenada, 2017) a predicted LSLR for Grenada of about 0.5 m (Fig. 15) and indicated that 1.4 m could be possible. These scenarios are very likely far too optimistic. Using them as a planning guide for the adaptation of the built environment to LSLR will very likely lead to severe impacts on the people, built environment, and economy of Grenada in the second half of the century.

Recent assessments of GSL rise still are in the range from 0.5 m to 1 m by 2100 if increased contributions from the large ice sheets are not included (Fig. 16). While there is consensus that the land-based ice masses are in a disequilibrium with the current and expected future temperatures, the epistemic uncertainty concerning the processes that will lead the ice sheets to melt prevent solid assessments of how large the contribution to GSL rise could be in this century. There is, however, no scientific basis to ex-

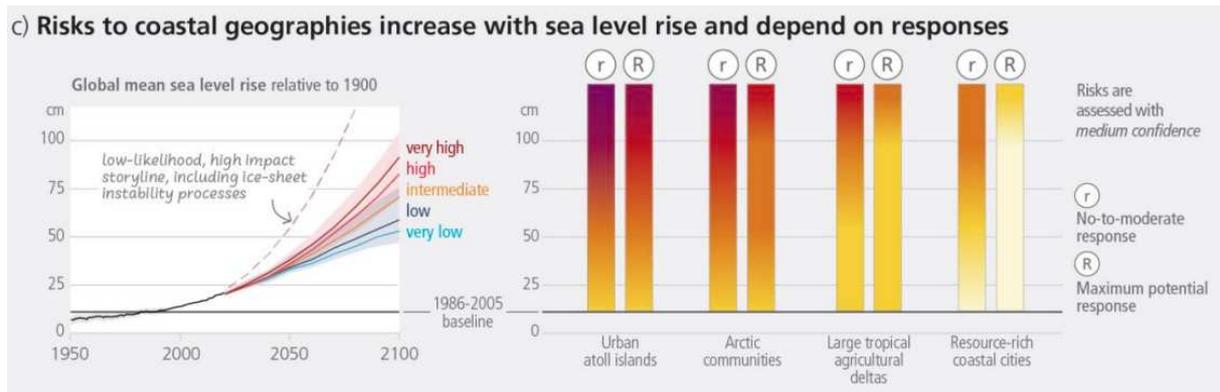


Figure 15. Scenario for LSL rise around Grenada considered for planning purposes by the Government of Grenada. From Government of Grenada (2017).

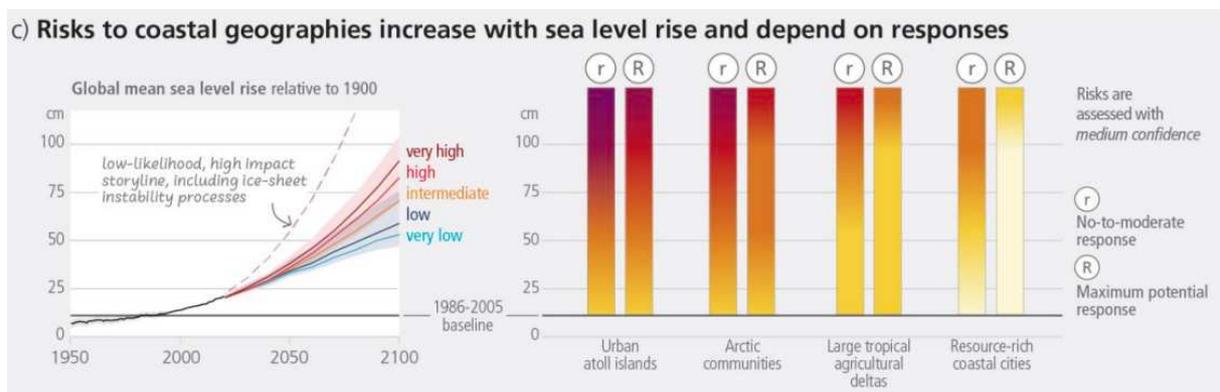


Figure 16. Global Sea-Level Rise in the 21st Century and impacts on different geographical location. From IPCC (2023).

clude the possibility of very rapidly increasing contributions from the ice sheets already in this century. The IPCC (2023) assesses the probability of instability as low but because of the high impact large GSL rise on the order of several meters would have, the risk associated with the long-tail of the PDF of the GSL rise in the 21st century exceeds the risks associated with the lower GSL rise values.

Comparing the PDF for global air temperature rise by 2100 to the PDF for century-scale temperature changes over the last 800,000 years (Fig. 17) then it is obvious that the 21st century PDF is far outside the 800,000 year PDF. On the other hand, the PDF for century-scale changes in GSL in Fig. 17 covers a range from -6.3 m to 6.3 m, a range much larger than estimates for the 21st Century indicated.

Based on recent assessments discussed above, a possible PDF for the 21st century GSL rise is indicated in Fig. 18, but this PDF may turn out to be too optimistic. Particularly the low probability-high impact long-tail may exhibit higher probability and stretch to larger GSLR values. The long-tail of the PDF as well as the risk associated with that long-tail depends on a range of factors, including the actual emissions trajectory, the response of the climate system to these emissions, and the rate at which ice sheet are losing ice or disintegrating. More recent studies concluded that the risk associated with the long-tail of this PDF may be larger than previously thought. For example, the West Antarctic Ice Sheet could be more prone to melting than previously thought, and this could result in a total rise by 2100 of ≈ 3 m (DeConto & Pollard, 2016). While this estimate is among the more extreme scenarios, it demonstrates the potential for the long-tail of PDF being associated with the largest risk for coastal communities.

Sea-level is an output of the global climate system and sea-level rise is a complex and uncertain phenomenon. There are many processes on local to global scale that create a wide range of possible outcomes. Therefore, on a global scale, it is crucial to have sufficient and continuous monitoring and modeling systems that can detect the onset of more rapid GSL rise and/or significant processes in the

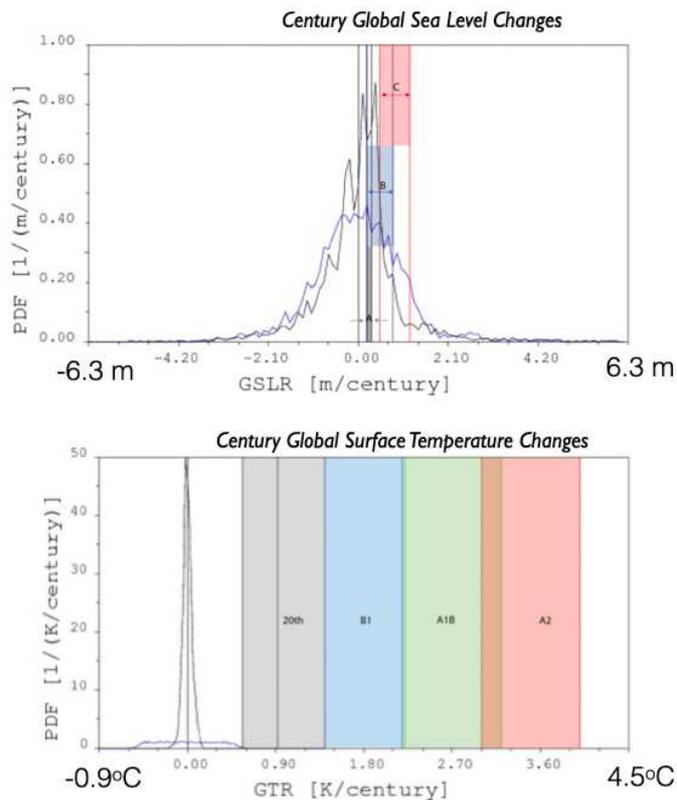


Figure 17. PDF for century-scale changes in global mean temperature and GSL for the last 800,000 years. From Plag & Jules-Plag (2013).

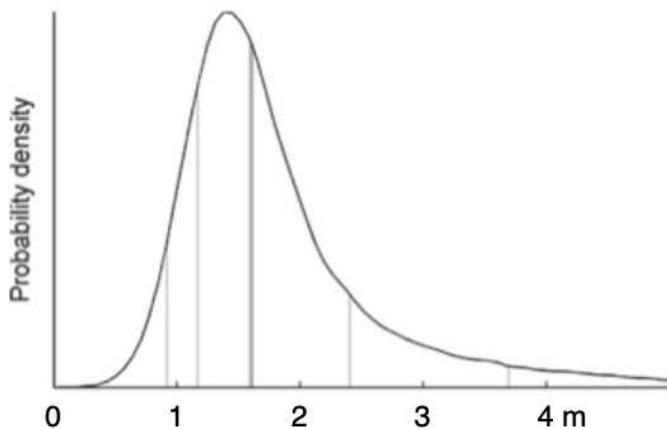


Figure 18. A possible PDF for GSL rise in the 21st Century. Considering that the PDF for global mean temperature rise is far outside the PDF for century-scale changes in global mean temperatures for the last million years, this PDF may be far too optimistic.

large land-based ice sheets and forecast sea level rise on decadal time scales ((Plag et al., 2010; Ponte et al., 2019). Likewise, research need to continue to improve the understanding of the processes that drive sea-level rise in order to better assess the associated risks. Based on any “early warning” from such an operational forecasting system, adaptation actions can be accelerated.

Activities aiming at the monitoring and forecasting of sea-level rise as well as research of the system processes that control sea-level rise are on-going at international levels. Given the challenge of a trade-off between preparing sufficiently for low probability-high impact events and keeping adaptation costs and socio-economic impacts at a responsible level, it will be important to for Grenada to monitor the development of knowledge. For example, five year assessments of the knowledge concerning global sea-level rise as well as local sea-level rise in Grenada in the 21st century could help to keep adaptation on track with the development. However, limited adaptation, i.e., the failure to proactively adapt, is indicated in IPCC (2023) as a major driver for large negative impact of climate change, independent of the level of global warming.

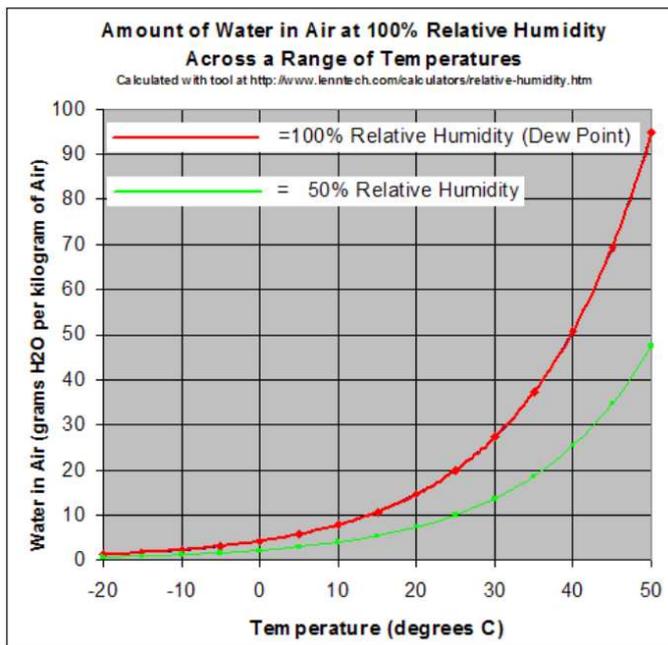


Figure 19. Amount of water that can be stored in the atmosphere as function of air temperature.

6.3 Scenarios of Extreme Precipitation Events

Among the links between climate changes and weather, one of the best understood and robust connections is the acceleration of the water cycle. A fundamental fact is that warmer air can hold more moisture. The increase water vapor that can be stored in the atmosphere follows the Clausius-Clapeyron equation, which establishes an exponential relationship between air temperature and the amount of water air can hold (Fig. 19). This relationship roughly states that for 1 K of temperature increase, the air can hold 7% more water vapor (e.g., Vecellio et al., 2022). If evaporation does not change, this implies that for a warmer atmosphere it takes much longer to reach 100% relative humidity and for rain to fall, but when rain falls, there is far more water available to create extreme precipitation (Fischer & Knutti, 2016). Likewise, the condensation of the larger amounts of water vapor releases more energy available for rapid intensification of tropical cyclones (Trenberth et al., 2018).

It is expected that in a warmer world on average the number of days with mild rain will be decreasing, while the days with heavy rain will be increasing (Fig. 27). This trend to more days with heavy rain will be most visible in the tropics. In tropical cyclones this effect is boosted (Trenberth et al., 2018). Atmospheric rivers are also increasingly being detected as the source of extreme precipitation events. For example, the extreme flood in Pakistan was the result of a combination of atmospheric rivers and increased snow melt (Nanditha et al., 2023). The very wet winter in California after a long drought also saw a number of atmospheric rivers sustaining the transport of warm and wet air into California. The trends are very clearly pointing in the direction of longer droughts and more heavy rain events.

Increasingly extreme precipitation events also take place outside of the tropics. An example is the extreme flood in Germany and adjacent countries in 2021 and caused several hundred fatalities (e.g., Schleusner et al., 2021). Another major flooding event was the July 20, 2021 flood in Zhengzhou, Henan Province, China, caused by an exceptionally heavy rainstorm, that impacted more than 14 million people and caused nearly 400 fatalities (Xie et al., 2023). In many of these cases, the record-breaking precipitation does not exceed the previous long-term record by a small amount but rather by 50% and more. The new unprecedented records provide an indication for the precipitation scenarios that should be considered in preparing for future floods. It seems reasonable to plan for floods that exceed previous records by 50%. The flood in Germany and flood in other regions illustrate that the built environment is not prepared for these hydrometeorological hazards, and warning systems are insufficient to capture the magnitude of the events correctly. The loss of lives is significant. Considering this, it will be very important to improve warning systems for extreme precipitation events (Hidalgo et al., 2023; Xie et al., 2023).

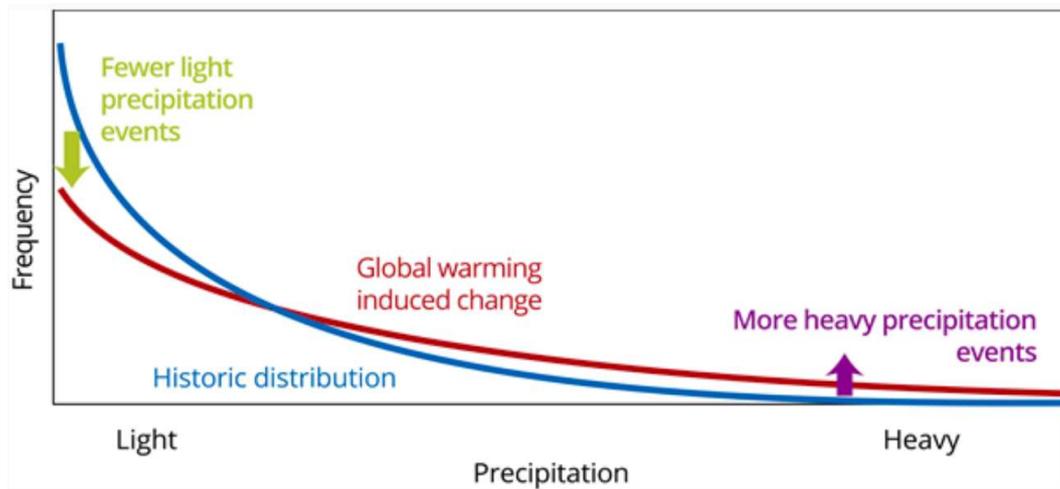


Figure 20. Expected changes in the distribution of precipitation in a warmer atmosphere. It can be expected that there will be a decrease in days with light precipitation and an increase in heavy rainfall events. The evaporation rate will increase slower than the total amount of water that can be stored in a warmer atmosphere. This leads to more heavy events and less water available outside of these events. From Fischer & Knutti (2016).

6.4 Hurricane and Storm-Surge Scenarios

It is widely acknowledged that the expansion of population in the coastal zone combined with increase of tourism industry that also is larger in the coastal zone than in other regions is leading to a transformation of large stretches of the coastal zone that in most cases is a degradation (e.g., Dey & Mazumder, 2023). This development is increasing susceptibility of the coastal areas to flooding caused by storm surges caused by cyclones. In many areas, LSL rise is increasing the probability of flooding significantly. For Grenada, tropical storms and hurricanes can produce large storm surges and LSL rise adds to the maximum flood level these surges can reach. With increasing rates of LSL rise, it can be expected that the protection provide by coastal features rapidly will decrease (Hermans et al., 2023), independent of whether these features are human-made or not. “Due to relative sea level rise, current 1-in-100 year extreme sea level events are projected to occur at least annually in more than half of all tide gauge locations by 2100 under all considered scenarios (high confidence)” IPCC (2023). While no trend in the total number of globally occurring tropical cyclones has been detected, there is a clear trend to stronger hurricanes in the North Atlantic while the number of weaker hurricanes is decreasing (Holland and Bruyère, 2014). The IPCC (2023) states: “Other projected regional changes include intensification of tropical cyclones and/or extratropical storms (medium confidence), and increases in aridity and fire weather (medium to high confidence).”

Besides a trend to stronger and larger hurricanes, there is also a trend to more rapid intensification of hurricanes in part of the North Atlantic (Balaguru et al., 2018). Rapid intensification can cut down warning times and the time available to prepare for an event. If this trend continues, the proactive preparation for hurricanes making landfall will become more important to keep the extent of the inflicted disasters as small as possible.

6.5 Droughts and Heat Waves

Heat waves are expected to become more frequent, longer lasting and more intense in almost all inhabited regions (Domeisen et al., 2023). While heat waves in Grenada will be attenuated due to the high heat capacity of the surrounding ocean, the increasing ocean temperature will result in more long-lasting events of temperatures above current averages.

A major concern related to heat waves is a combination of higher temperatures with high relative humidity. Conditions with wet-bulb temperatures above 35°C are known to be lethal to humans, and

new research indicates that even lower temperatures have severe impact on human health particularly for younger people (Vecellio et al., 2022). Events of wet-bulb temperatures above this limit have been reported to have already occurred in some locations (Raymond et al., 2020). While it is unlikely that such events will be frequent in Caribbean islands, heat-related impacts on human health and economy cannot be excluded. It will therefore be important to consider means to prepare the built environment already now for longer-lasting heat waves with high dry and wet-bulb temperatures.

Heat waves and droughts also impact wild life. It is important to note that marine ectotherms appear to be more sensitive heat stress than terrestrial ectotherms (Pinsky et al., 2019). It can be expected that the warming will impact the territorial waters of Grenada significantly.

7 Foresight and Possible Futures

7.1 Introduction to Foresight: Methods and Modeling

It is important to note that no crystal ball will allow us a glimpse into the future and that predictions should never be considered set in stone. In a system as complex and dynamic as Grenada, it quickly becomes impossible to accurately predict the future. Before we are able to examine possible interventions for the system's benefit, we must first practice responsible governance and consider a range of possible eventualities with which Grenada may have to contend. To this end, the use of foresight science is an invaluable method that can provide insights about a system's potential futures. Foresight is particularly helpful in this instance because it uses a systematic approach to generate future predictions for planning and management by drawing on analytical and predictive tools to understand both the system's past and present. Here, we will be using our three hazard scenarios that were developed in the previous section; sea level rise, heavy precipitation, and expansion to explore Grenada's possible futures. In addition, we will consider the impact that global climate trends will have on Grenada and back casting will be used to formulate desirable futures and the actions needed to help guide Grenada towards them from the present trajectory. Several action-oriented trajectories will be categorized based on the desirability of their possible outcomes, from collapse to transformation. Finally, we will consider what it will take to result in both a best- and worst-case future for Grenada.

7.2 Scenario Based Foresight

The key factor when modeling possible futures is the level of action taken by stakeholders during a system response to hazards.

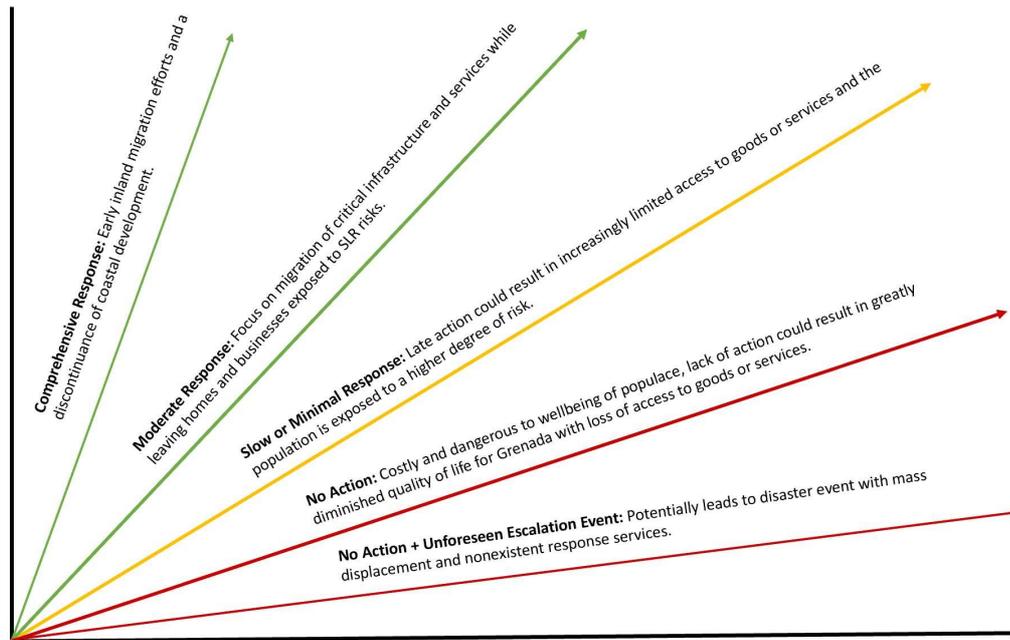
7.2.1 Possible Future: Sea Level Rise

In the case of sea level rise, there were three potential scenarios modelled in Section 6: (1) a linear increase, (2) an exponential rate of increase, (3) and a linear trend evolving into an unexpected and rapid rise (see Fig. 12 above). The possible futures resulting from LSL rise are indicated in Fig. 21.

A defining feature of Grenada is that much of its critical infrastructure is currently operating in low-lying, coastal areas. Regardless of which sea level rise scenario we model, most if not all of that infrastructure will be impacted by approximately three meters of sea level rise. This means that every possible future for Grenada involves significant impacts on the built environment as a direct result of sea level rise. Grenada's response to this hazard will determine the severity of those impacts.

For example, if a moderate amount of preparation over a period of a few years is done to migrate critical infrastructure such as St. George's hospital, government offices, police stations, and grocery stores to inland areas with higher elevation, then these necessary services will be better insulated and protected, resulting in the most basic needs of the populace being met even under the hazard's stress. However, by only focusing on critical infrastructure, the damage and displacement due to encroaching sea levels will still impact homes and businesses, which will inevitably harm the local economy.

A more comprehensive response, regardless of the sea level rise scenario's timetable, would be to



Possible Futures Under Sea Level Rise

Figure 21. Possible futures under local sea level rise.

transition both vital and non-vital infrastructure, to include businesses and residences, inland above the three meter mark and discontinue any further low-lying coastal development. This course of action would have multiple benefits, by not only protecting the majority of the island’s infrastructure long-term, but by also allowing space for the natural migration of important ecosystems such as mangroves and beaches.

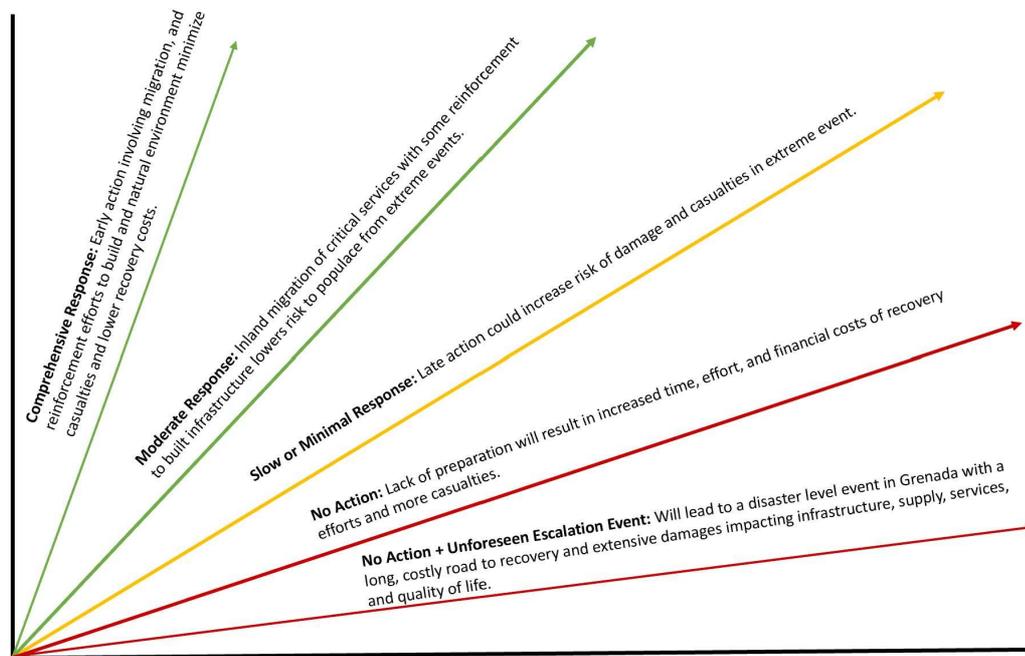
On the opposite end of the spectrum, a lack of preparatory response to sea level rise could be costly and potential dangerous for Grenada in the future. Here, rising sea levels will continuously encroach upon and degrade the coastal infrastructure, and large portions of the population will be displaced with nowhere readily available to move. This forced migration without prior planning will likely result in quickly built, unsafe housing, inevitably increasing the population’s risk of exposure to a host of new hazards resulting from the disorganized migration and rapid scrambling to relocate away from rising sea levels.

7.2.2 Possible Future: Hurricane, Storm Surge, and Extreme Precipitation Events

Where the response to sea level rise can be considered to spatially occur at a measured pace over the course of years or even decades, this is not the case with hurricanes, storm surges, or extreme precipitation events. These hazards are more difficult to accurately predict both in timeline and scope. What we do know is these hazards are associated with far greater risk to the populace, due partially to their unpredictability but also their direct impact on human safety, which makes early preparation even more crucial. Additionally, the impacts of sea level rise result in an increase to the spatial risks of flooding from storm surge and precipitation as the water tables moves higher and floodwaters are able to more easily threaten a larger area than previously seen (Fig. 22).

A moderate response to these events could include a similar inland migration of critical services as seen with the potential futures associated with sea level rise. However, this alone would not be enough to safeguard against these extreme events. For example, heavy precipitation can lead to increased erosion, resulting in larger landslides as well as high velocity, damaging winds from hurricanes. These hazards will require reinforcements to the built infrastructure in addition to potential migration.

A comprehensive approach involving multi-action based planning would likely be most effective in mitigating risk and minimizing threats to the safety of the populace. By combining inland migration



Possible Futures Under Hurricanes, Storm Surge, and Extreme Precipitation Events

Figure 22. Possible futures under hurricanes, storm surge, and extreme precipitation events.

of population centers to areas of higher elevation to reduce the impacts of flooding and deploying soil stabilization methods along natural inclines surrounding these new settlements to mitigate the threat of landslides, a lowered risk to people and property will result. It should be stressed however, that due to the unpredictable nature of hurricanes, storm surge, and extreme precipitation events, the earlier these preventative actions occur, the lower the risk to the populace will become.

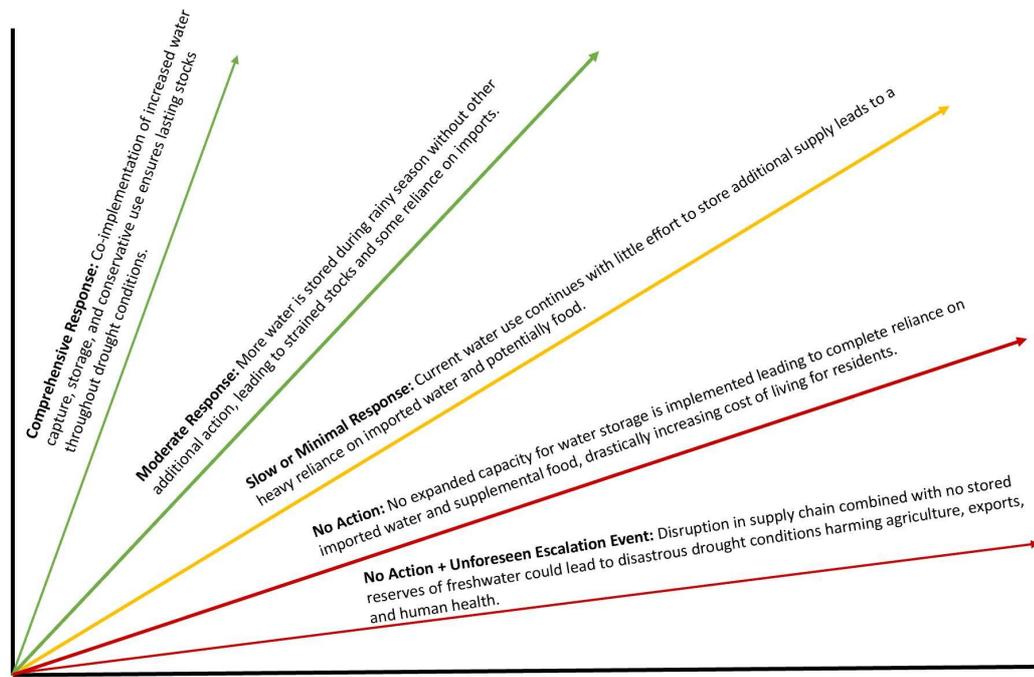
If action is implemented late or not at all, Grenada can expect to deal with an event of extreme damage and potentially high casualty in the coming decades. The later preventative action is taken, the higher the monetary cost will become in a post-disaster recovery scenario. FEMA estimates that approximately \$6 is saved for every \$1 spent on disaster mitigation (FEMA, 2018). So, it is never too early to invest in the safety of Grenadian citizens.

7.2.3 Possible Future: Droughts and Heatwaves

The last hazard scenario discussed in Section 6 examines the evidence for extended periods of droughts and rising temperatures in Grenada. These extended dry seasons will not only strain freshwater supply on island, they will also cause soil impaction resulting in a drastically decreased ability for the ground to absorb rainwater during extreme precipitation events. This phenomena will likely lead to intense flash flooding events during the rainy season and due to the clay-loam nature of Grenada's soil, increase the severity of landslides over time as well (Fig. 23).

A moderate response to an extended and more intense dry season could be comprised of storing more water during the rainy season to compensate for drought conditions. However, without other practices co-implemented this will likely result in a rapid decline of said water stocks and force a greater reliance on imported water. This would not only impact potable water for human consumption but also that which is used for agricultural purposes. This would have the doubly negative effect of diminishing on-island food production as well.

The more comprehensive option of response would be to not only increase water storage during the rainy season but also expand storage capacity and encourage conservative water use both domestically and agriculturally. This would relieve some pressure on the supply chain, thus lowering the cost of production via a decreased reliance on expensive imported water. Additionally, this would make the



Possible Futures Under Droughts and Heatwaves

Figure 23. Possible futures under drought and heatwaves.

food supply more secure because it is being produced locally and sustainably on island further reducing costs.

To ignore the extended dry season and choose to take no precautionary action greatly increases the risk of Grenada suffering catastrophic drought conditions. As previously stated, this would inevitably strain potable water stocks for domestic use as well as the freshwater used in agriculture. The droughts could negatively impact grow conditions for domestically produced food and increase cost of living based on the necessity to import supplemental food and water to compensate dwindling stocks. It could also reduce the yield of important cash crop exports like nutmeg and cocoa, thereby threatening the health and security of the economy.

7.3 Back-Casting

Back-casting is a scenario based modelling method that starts by envisioning a desirable future for a system. Then it is determined how this future can be attained by working backward from said desirable future and towards the present to determine the necessary steps or actions that will be necessary to guide a system's trajectory towards the desired outcome. In order to imagine a desirable future for Grenada we must consider our goal statement: "A built environment in Grenada that enables the people to cope with the impacts of sea level rise and heavy precipitation by securing the safety and well-being of all and by distributing the risks equally while safeguarding the socio-economic and environmental system." Therefore, our desired futures should be formulated to consider sustainable land use, a protected natural environment, infrastructure built with resilience in mind, decreased economic inequality, and equitable assumption of risk among all sectors of the populace.

For our sea level rise scenario, the most desirable future for Grenada would be one in which the steady rate of sea level encroachment causes minimal or preferably, no interruptions to daily life on island. For hurricanes, storm surge, and extreme precipitation event scenarios, the most desirable future would be one in which there is minimal risk of harm or damage from flooding, landslides, or high-velocity winds due to increased safety measures and reinforcements implemented with regards to both the built and natural environments. Finally, with regards to droughts and heatwave scenarios, the most desirable

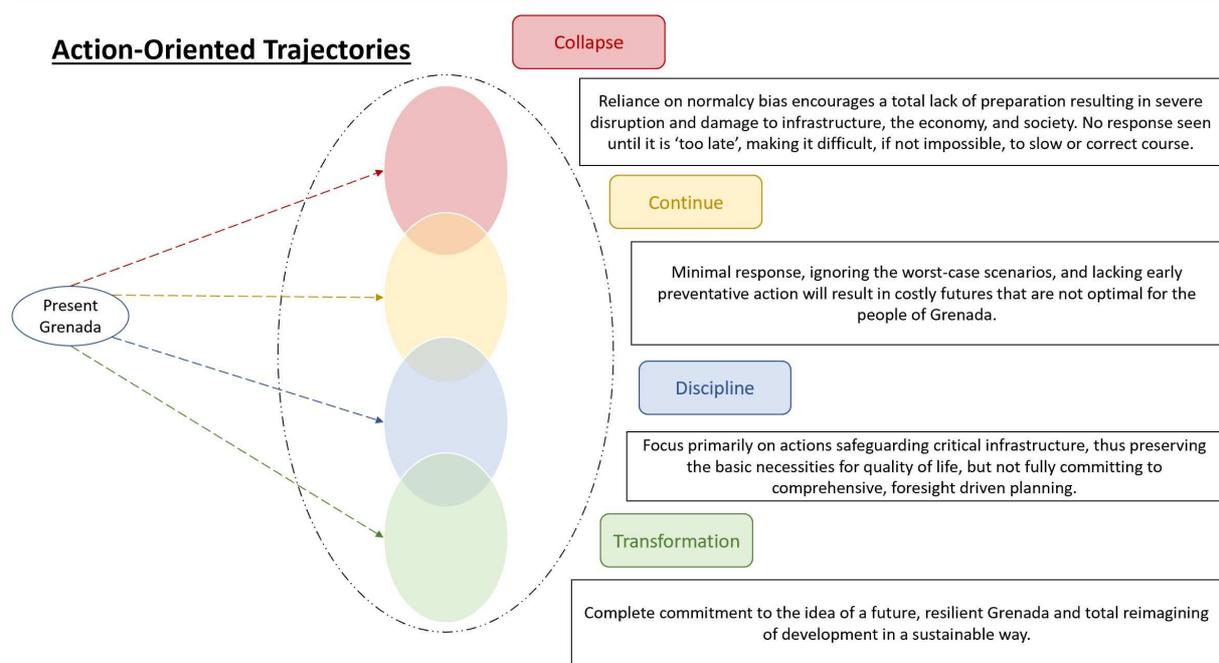


Figure 24. Possible futures emerging from action oriented trajectories.

future is one that will include water use is fully supported on the island throughout longer dry seasons by more complete storage and capture methods, and where there is little need for costly importation of water or supplemental food rations. Each of these futures will require trajectories that involve comprehensive responses by cooperating stakeholders to adequately steer the system response to address the evolving interplay between inherent fragilities and pressures from hazards over time.

7.4 Action-Oriented Trajectories

It is important to remember that any possible future will be dependent on the level of action, or lack thereof, taken by stakeholders. So, we look to action-oriented trajectories to give us an idea of what different levels of engagement or action will produce favorable vs unfavorable futures. These futures can be sorted into four different archetypes; collapse, continue, discipline, and transformation, each categorized based on the level of action and engagement present within the trajectory itself (Fig. 24).

Collapse is our worst outcome archetypal future being driven primarily by a lack of action and exacerbated by the rapid development of hazards. Oftentimes this response absence is spurred on by an over reliance on normalcy bias among stakeholders, typically resulting in minimization of the risk of a hazard's severity and timeline. This bias often encourages a lack of preparation for the system response. In the case of Grenada, the collapse archetype would likely present as a mix of severe disruption or damage to infrastructure, the economy, and society as a whole. Low-lying coastal areas will become permanently flooded and unusable, abandoned infrastructure would contribute to a decline in public health and safety as they break down into environmental pollutants, and the loss of most beaches to erosion and lack of migration capacity would drastically impact the tourism industry, thereby jeopardizing Grenada's near homogenous economy. The main factor driving a collapse archetype for Grenada would be that no response to foresight models is implemented until it is 'too late', making it difficult, if not impossible, to slow or correct the system's trajectory to avoid a disaster.

Continue represents an archetypal future that would be expected if a system maintained its current trajectory with no change. It should be noted that for Grenada, the Planning and Development Authority's current interest in building a sustainable and resilient future for the island should be praised and encouraged. However, action is what ultimately determines a system's trajectory, not solely intentions. Currently, we see minimal response regarding hazards such as sea level rise and a common lack of risk

awareness from the general public. Should this knowledge deficit among the populace continue, it is likely that any institution seeking sustainable change will face external pressures to focus on unsustainable economic growth and ignore the worst-case scenarios, which will result in Grenada lacking any early implementation of preventative action. This late term response or lack of action will result in costly futures for Grenada both in terms of physical damages stemming from unaddressed fragilities of the built and natural environment, and also that of increasingly unequal distribution of risk for citizens who do not have the capital to migrate or rebuild with no outside support and late-term notice. These pressures and costs will result in a range of futures that ultimately, are not optimal or desirable for the people of Grenada.

Discipline describes an archetypal future where a system's response incorporates and maintains actions intended to mitigate the effect of hazards. This can include strict adherence to a limited range of response-based mitigation or the deployment of long-term planning that addresses some, but not all, of the hazards impacting the system. For Grenada, this means a focus primarily on actions that would safeguard critical infrastructure, such as hospitals, grocery stores, and services like power and water, thus preserving the basic necessities for the citizens of Grenada long-term. However, this trajectory, while implementing a selection of preventative action, does not fully commit to comprehensive, foresight driven planning. This future will preserve a measure of quality of life and security currently enjoyed by citizens, but it will sacrifice in other areas. Specifically, by not engaging in early residential and economic planning to meet the impending land use needs resulting from future inland migration, the socio-economic status of many Grenadians will likely see a sharp decline as a result.

Transformation is representative of the goal archetypal future that embodies the most desirable, best-case outcomes for a system. In order to achieve a transformative future, the trajectory must involve a total reestablishment of current processes based on value shift away from continuing trends towards revitalizing action. For Grenada, there must be a complete commitment to the idea of a future that is resilient, redistributes risk equitably among all socio-economic classes, and involves a total reworking of how land and resources are used, and restrictions that allow development to progress only in a sustainable way. There will need to be a broadening of Grenada's economy to rely on more than tourism, thereby increasing its resiliency. Also, an early response of mass inland migration of all goods, services, and people will become necessary in the near future with infrastructure built to account for the modelled hazard scenarios. Finally, an environment of cooperation among all levels of society must be successfully fostered and maintained so that the necessary stakeholders may take the action required to transform Grenada's system into a resilient one.

7.5 Foresight: Best and Worst Futures

The best case future for Grenada will rely heavily on cooperation and input from all aspects of the community, including local individuals, community-level engagement, NGOs and Government sponsorship and planning efforts, and adherence to necessary system change by foreign interests. In order to formulate the optimal desired future for Grenada, implementing actions based on foresight is integral to achieving this future.

On the other end of the spectrum, a worst-case future for Grenada is possible and largely contingent on communication and cooperation breakdowns among the relevant stakeholders, an active or even passive resistance to change, and an unwillingness to reprioritize current trajectories, including operations approved for the expansion of wealth that ultimately jeopardize the future resilience of the system.

7.6 Summary Statement

Present day has become a tipping point for Grenada and other similar, small island nations contending with the same modern challenges. Global change, evolving hazards, and fragilities unique to island states threaten the Grenadian way of life like never before. But before action can be taken to avoid an unfavorable future, we must be able to properly assess the risks.

8 Risk Assessments

8.1 Introduction to the Risk Assessment

Risk is a concept that has been hotly debated and revised over time as scientists have struggled to find one unifying definition and set of conditions that allow for risk to be assessed in all walks of science. There are typically a few conditions of risk that remain constant which includes the probability of a future to occur, the main hazard associated with that future, exposure of valued assets, and the fragilities contained within a system (Aven, 2016). “In general, risk means the possibility of loss or injury. Risk is an event that, if it occurs, has unwanted consequences.” (Pinto & Garvey, 2012). Here we define: *Risk is the potential for consequences where something of value is at stake and where the outcome is uncertain.*

To measure risk, we utilize the equation

$$R = p(h) \cdot f(a, h) \cdot v(a), \quad (1)$$

where p is the probability of hazard h to happen, f is the fragility of the exposed asset a relevant for the hazard, and v is the value of the asset.

Risk plays many roles in the decision-making process, from directly impacting the conclusions of studies to indirectly pushing legislators and other unaffiliated decision-makers to take different courses of action based on perceived risk scenarios, where one may choose to take steps that avoid a certain future, whereas other courses of action would create resilience against possible risk scenarios (Aven, 2016).

For the purposes of this study, we utilize a method that has been called 'Risk-based decision-making' which prioritizes taking actions that are monitored and compared with changes in the environment to determine what future steps need to be taken as the result of actualization of risk (Rausand, 2013). This utilizes a mix of preventing the worst of future scenarios whilst preparing areas less affected by more severe outcomes to be mitigated to inform the interventions that will need to be taken to ensure Grenada maintains a sustainable future in the long term.

8.2 Visualizing Risk

In addition to utilizing the risk equation stated in Section 8.1, we use visual aids to help demonstrate the relationship of risk relative to different proposed futures. In Fig. 25 are the two charts we will be using to supplement the risk assessment of each hazard scenario. On the left is a graph visualizing correlational trend, often resulting in an exponential trend as will be seen in Section 8.3. The matrix to the right in provides a more definitive relationship between the probability of a future occurrence and the impact on Grenada if the future would be to occur. Additionally, the risk assessment is based on a future occurrence without any current modifications to the built environment when considering the impacts locally.

8.3 Assessing Risk

8.3.1 Assessing Risk: Mean Sea Level Rise

Despite being an island with high altitudes due to its relatively recent formation from oceanic volcanic activity, sea level rise poses a great risk to the population of Grenada where most developments are located within 3 m of the current sea level (Fig. 26). From the threat to critical infrastructure facilities like the major electricity-producing centers, hospitals, and public safety to the population hubs located along the coastline, to tourism-dependent centers like airports and hotels no adaptation measures become more damaging with every future. But the damages that will occur are not limited strictly to the built environment, but expand into the natural environment as the culturally important, natural ecosystems of beaches, mangroves, and even coral reefs suffer from increasing sea levels facing undo burden under the extreme future samplings where they will suffer in migration.

Yet, the damages exceed that of the assets critical for Grenadian success. Aside from possible damages the existing fragilities might explode into other issues if not addressed in the coming years. Aside

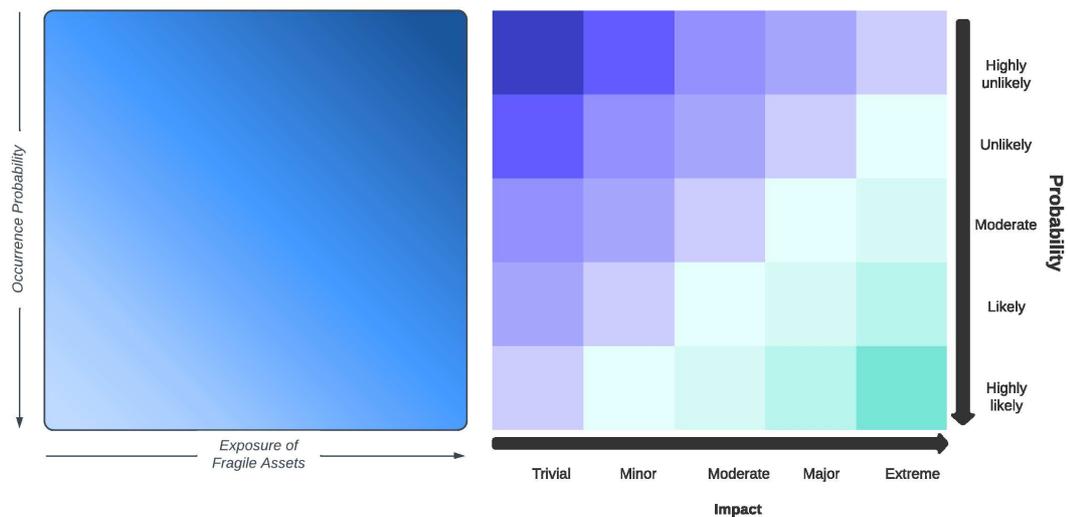


Figure 25. Risk mapping template.

from damages to the hospital that reduce health coverage would be the safety issues that accompany the flooding of homes and runoff of raw sewage into population centers thereby increasing demand for hospital care in a time of decreased capacity. Or the downward spiral of the economy and jobs through the degradation of the tourism industry which runs Grenada further worsening poverty within the nation.

Although past reports by the Grenadian government have centered around changes in sea level of 0.5 m with a maximum of 1.4 m (Government of Grenada, 2017), the conclusions concerning LSL related hazards in Section 6 indicate that partial melting of the GIS or WAIS would exceed those maximum estimates. Based upon the likely melt of the GIS and WAIS from increased glacial instability and projected sea level rise from thermal expansion of the ocean, it then establishes a strong likelihood of a 1 to 2 m GSL rise by the end of the century. Furthermore, upon the worst-case scenarios of the near-complete collapse of both ice sheets and sea level rise from heating at the high end of the spectrum, it would likely conclude with a 10 m sea level increase relative to the present day. Based upon the impacts indicated above and the probability of those circumstances occurring, the conclusion presented in Fig. 26 show the greatest risk being associated with 10 m sea level rise. However, there is more to the threat of sea level rise than the total increase over the next century.

8.3.2 Assessing Risk: Rate of Sea Level Rise

The temporal changes in the rate of sea level rise are central to the distribution of risk over time. Although past historic trends suggest an non-linear increase in sea level with accelerating rates, the likelihood of glacial collapse discussed in Section 6 would more than likely introduce large step-like rises superimposed on an accelerated rise.

Many of the same exposed assets and fragilities are shared with the rise discussed in Section 8.3.1, except that the lack of foresight transforms into a component of collapse if there remains a lack of preparation from a potentially disastrous conclusion of stepped increases in sea level as explained in Section 7. Although the stepped increase remains a risky situation, the riskiest future is a combination of a slowly accelerated and stepped increase based upon probability and associated damages in societal rebuttal for adaptation against the future, as demonstrated in Fig. 27. However, there remain more scenarios of similar causation to be investigated.

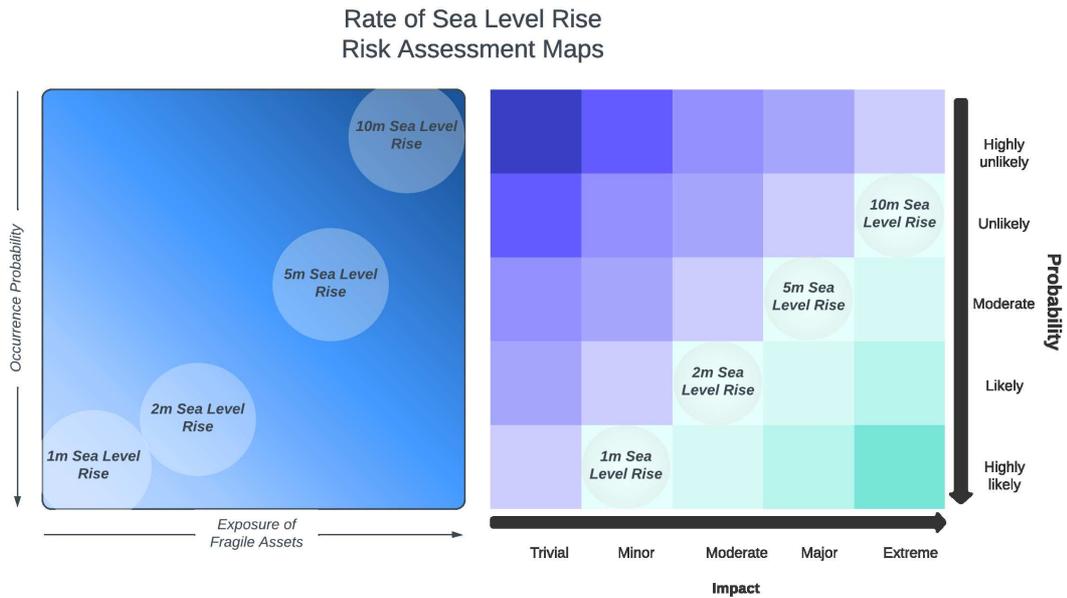


Figure 26. Mean Sea Level Rise Risk Mapping.

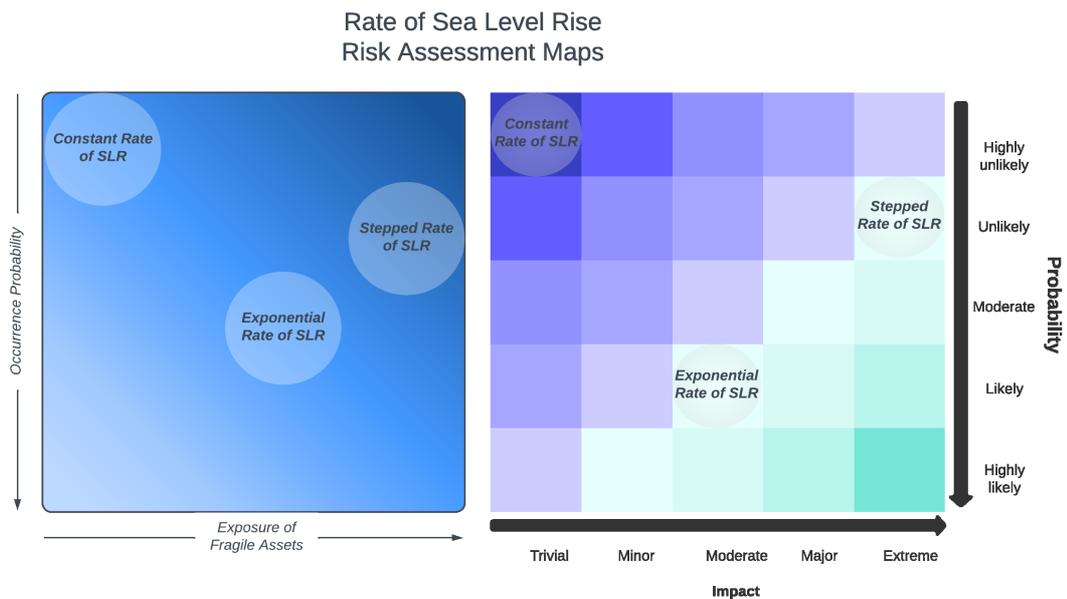


Figure 27. Rate of Sea Level Rise Risk Mapping.

8.3.3 Assessing Risk: Extreme Precipitation Events

Trends in precipitation have been observed globally by the significant increase of heavy precipitation events occurring. The assets in Grenada potentially impacted by extreme precipitation include major agricultural exports such as cocoa and nutmeg as well as general agriculture for local produce. Heavy precipitations may have the undesired effect of drowning out local crops or even resulting in landslides that jeopardize nearby agricultural plantations. More so, many developments within the mountains, especially roadways, are at risk for increased probabilities of landslides, which have resulted in the deadliest car accidents in Grenada’s history as a result. Coastal developments like homes, hotels, and even the St. George’s hospital still remain in trouble as exasperated flooding can cause damage, expedited

Extreme Precipitation Events (EPEs) Risk Assessment Maps

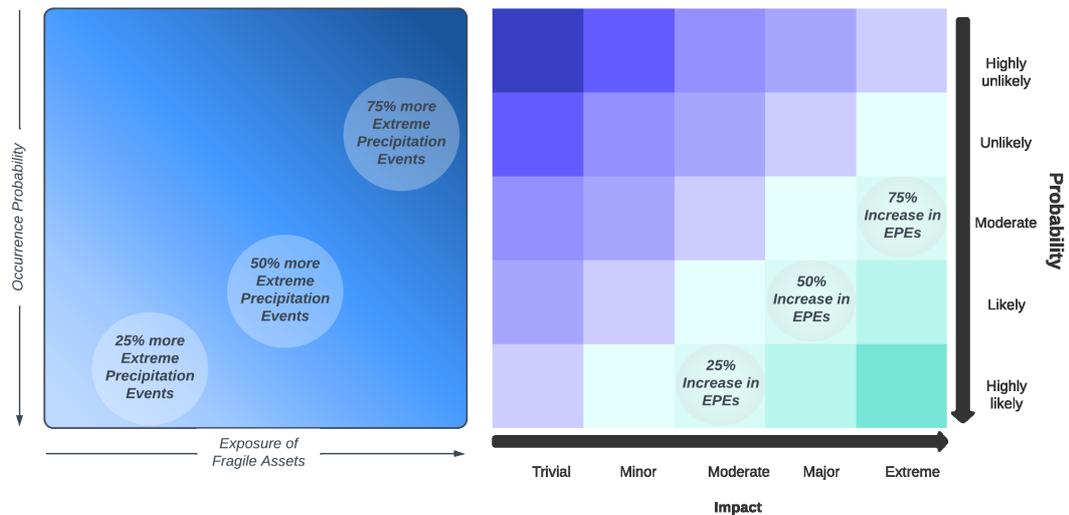


Figure 28. Extreme Precipitation Event Risk Mapping.

if during high tide.

With the increases in carbon dioxide and other greenhouse gases in the atmosphere, the rate of global warming is resulting in a higher capacity of moisture being held by the atmosphere. While this plays into tropical storms, it also contributes to the evolution of storms to become more damaging moving forward into the future. As this continues, the amount of precipitation expected to see on average among storms will increase. Yet, with it being concentrated among fewer and fewer storms, this then poses risks for the capacity of Grenada to handle more rain at once.

The risk of these futures is demonstrated in Fig. 28, where a 50% increase remains very possible within the present day from the previously mentioned historic trends being observed globally. The fear of a 75% increase in precipitation per storm then becomes even more concerning by 2100 in the relatively high probability combined with the massive damage posed by such event occurrences. This leads to the next risk assessment similar to extreme rainfall events.

8.3.4 Assessing Risk: Hurricane and Storm Surges

Historically, Grenada has avoided most major hurricanes that have devastated Caribbean island states and gulf nations due to the geography of being south of hurricane ally. However, this reality does not invalidate the possibility of devastating hurricanes hitting the island as with Hurricane Ivan and Emily in 2004 and 2005 respectively. However, its impacts are not limited to direct hits as the storm surges caused by passing hurricanes to the North and East can have proverbial impacts through storm surges that threaten coastal communities.

Similar to heavy rainfall events, the largest vulnerabilities are exposed to low-lying developments and infrastructure against storm surges. From national roadways to coastal hotels, no preparation would result in damages incurred and harm to economic capacity. Similarly, the storm surges produced jeopardize supply chains both through imports and transportation amongst the islands of local products, including increased food insecurity as a result. Furthermore, the lack of foresight for locals and developments only increases the future risks experienced by coastal developments without planning for the afflicted areas.

Although there is no substantive evidence to indicate whether hurricanes may increase or decrease in frequency if there is any change at all, current data does suggest an increase in the intensity of storms hitting the Caribbean as well as the rate of intensification. Combined pose a risk of greater storm surges and worse hurricanes in the event of another hitting Grenada like 20 years ago. Although a 20% increase

Development of Natural Ecosystems Risk Assessment Maps

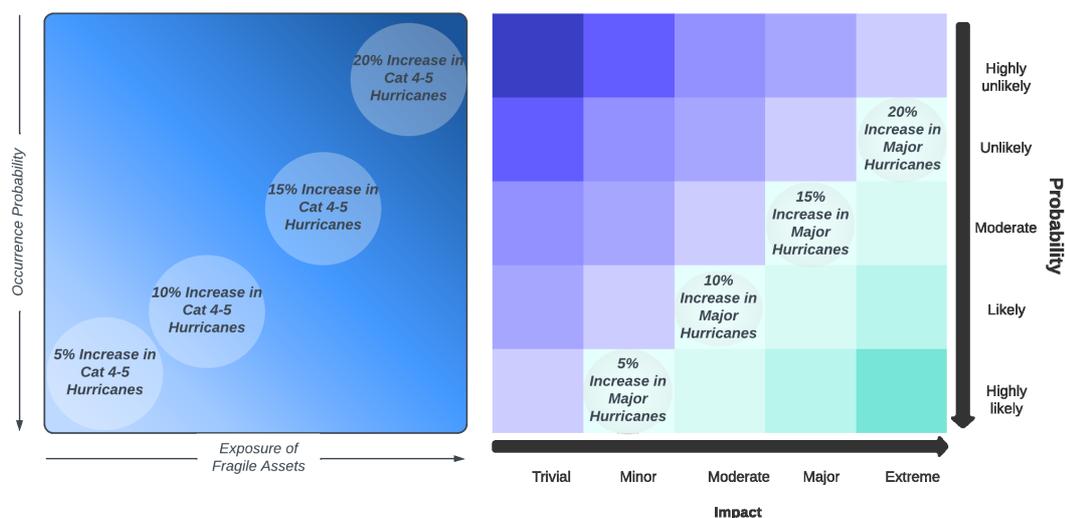


Figure 29. Hurricane and Storm Surge Risk Mapping.

in frequency for category 4 and 5 hurricanes may be on the higher end of the estimate of what hurricane intensification will look like, the risk posed especially from just one hitting landfall is perhaps the greatest threat facing Grenada from the lack of preparation to handle a worse storm than has been experienced before.

8.3.5 Assessing Risk: Droughts and Heat Waves

Although unrelated to the topics of the case study at first glance, droughts and heat waves pose a unique threat through the amplification of extreme rainfall events that may occur during the heightened dry periods in future. Despite rainfall estimated to decrease in the southeastern Caribbean over time and thereby increased dry periods coupled with increasing temperatures bolstered by warming oceans, the drying of soil in Grenada makes an already difficult situation to absorb incoming rainfall even more difficult instead resulting in increased damage and risk from heavy rainfall events as discussed in Section 8.3.3.

However, the threats of drought still encompass other areas aside from amplification. Many of the cash crops of Grenada rely upon the tropical weather and associated moisture for growth. Without this availability, crucial crop yields like that of bananas will decrease over time damaging the ability for Grenada to diversify its economy. This can similarly be seen in the aspect of tourism if weather conditions become unfriendly in parts of the year shutting down certain industries, decreasing tax revenues, and leaving citizens unemployed during critical conditions that provide both personal and economic damages during those times. The further damages imposed by the reduction in agricultural capacity and water shortages further exasperate wealth inequalities and food insecurity within the nation posing major threats for Grenada.

Fig. 30 encompasses the points brought up to visualize the increases in average temperature Grenada will experience with probabilities derived from the ability of the global community to meet the goals of the Paris Accords which at this time seem flexible. While there remains a possibility to meet the 1.5-2°C goal limit by 2100, there is also a stronger likelihood of an overshoot unless countries act to reduce emissions even further than the current goals set forth. As such, while the first two scenarios remain highly likely, the latter two are of keen interest for risk because of the possibility of relying upon what members of the global community decide to do. In conjunction with the damages associated with increasing temperatures both independently and referencing other hazard scenarios puts a 4°C as the riskiest future for Grenada to consider in preparing for increased drought and heatwaves.

Drought-Temperature Risk Assessment Maps

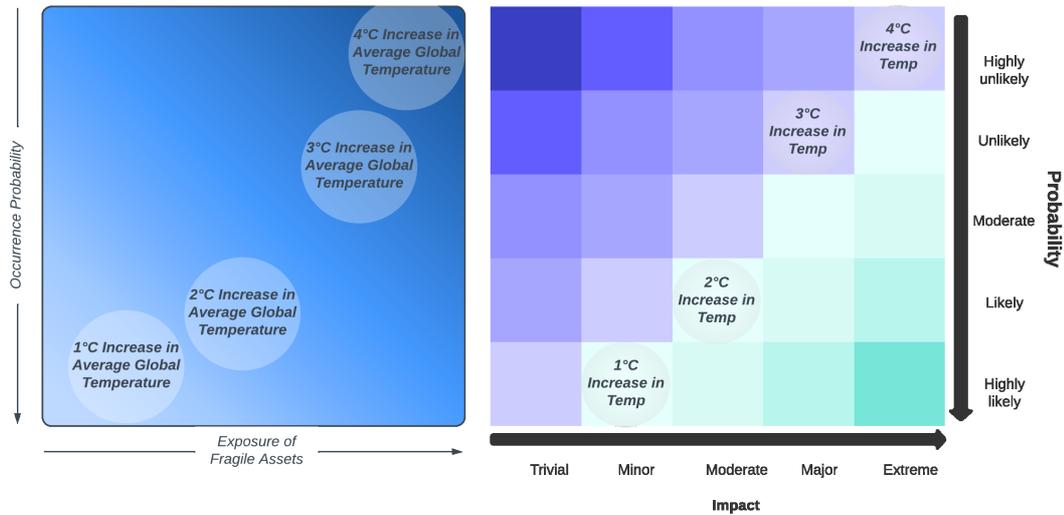


Figure 30. Drought from Temperature Increases Risk Mapping.

8.4 Conclusion of the Risk Assessment

Analyzing each of the risk assessments cannot simply be done individually but must be viewed holistically to see the impacts not just isolated but on other future scenarios. Examples can include rising sea levels would result in worse impacts being felt by storm surges, or the presence of prolonged, severe drought resulting in worse landslides when heavy rainfall events will occur. As we investigate interventions to mitigate and adapt to the riskiest futures assessed earlier in this section, we must also look holistically at interventions that work to address all futures and associated fragilities to reach the most optimal future for Grenada.

9 Assessing Interventions

9.1 Interventions for the Built Environment

9.1.1 Identifying Critical Infrastructure at Risk and Preparing for Moves

Key to preparing Grenada for the impacts of climate change is identifying critical infrastructure and locations. Such areas would include places such as Spice Mall, hospitals, government builds, roads, etc. that provide necessary services to the Grenadian people. In order to identify critical infrastructure, stress tests must be conducted, in either simulations or tabletop games, to identify how certain buildings would react in the event of floods or power outages. This will then allow for preparations to be conducted to move these buildings into protected areas. Identifying key infrastructure is important in the long term as it helps Grenada to reach several desirable futures as discussed in Section 7.

Pros of such an intervention would include the early identification of high risk areas and proper movement or preparation of infrastructure in preparation for climate-change related natural hazards.

Cons of this intervention would mainly include logistics, time, and costs associated with moving or preparing infrastructure. For example, if the St. George's general hospital was identified as key infrastructure that needs to be relocated, how could such a relocation be managed?

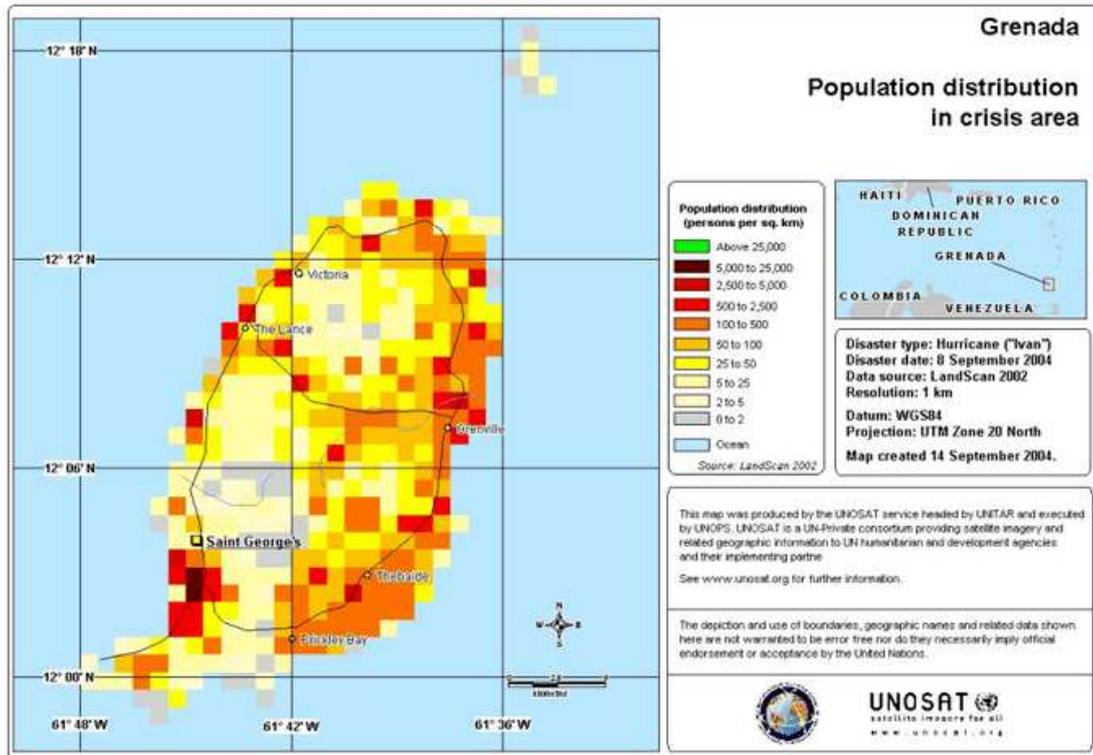


Figure 31. Map showing population density in Grenada after Hurricane Ivan in 2004.

9.1.2 Preparing People For Migration to Higher Grounds

Another major issue facing the coastal communities in Grenada is the necessity of relocating some of these communities in preparation for a low-probability but high-impact major rise in LSL. A major challenge is in preparing coastal communities for potential displacements. First, areas must be identified where people could move. These areas would include spaces of low population density or, ideally, abandoned farms and lots which have already been partially cleared to ease the movement. As seen in Fig. 31, which shows population density after hurricane Ivan made landfall, there are many open areas in the southern part of Grenada which could receive population displaced by rising sea levels or other natural hazards. Government aid could also be implemented in this strategy in order to make the process equitable. However, this intervention must also take into account the displacement of endemic species and the impact on the inland ecosystems.

One major pro of this intervention would be the movement of population centers out of high risk areas. Another benefit would include the ability for mangroves and beaches to migrate as the built environment moves out of population centers.

However, the movement of Grenadians into these uninhabited areas would result in conflicts with the natural environment. Considerations and further research would be needed to analyze the potential environmental impact. Logistics of migrating communities directly impacted by rising seas or threatened by future impacts would also be a challenge as certain areas would need more financial resources.

9.1.3 The creation of seawalls in very limited locations in Grenada

Seawalls, in their most basic form, serve to keep rising tides, waves, and storm surge out of populated areas. For Grenada, these sea walls could also serve other purposes, such as the creation of walkways or paths to serve some form of public service. In Grenada, there are two main locations where sea walls would serve the best purpose, in Grenville and around the ports of St. Georges. While seawalls are a feasible option, in terms of both costs and construction, these walls will not provide protection in the long

term. As discussed in Section 6, sea level rise could reach values of 2 m to 15 m by 2100. Unfortunately, there is a tendency to neglecting the worst case scenarios and plan for the low-impact part of the hazard spectrum (Kemp et al., 2022). This practice inherently ignores the high risk part of the spectrum.

The main benefit of the construction of a sea wall, besides the temporary protection from storm surge and sea level rise, would be the protection it offers to the built environment. However, the construction of sea walls does present some downsides, two of which affect the natural environment along the coast. Concrete often contains microplastics which, if eroded, could leech into the surrounding coastal waters, and it could result in the destruction of any coastal seagrass beds or reefs. Another downside is the maintenance that would be required to keep the sea wall in working order. On the Atlantic side of Grenada, where wave action is more intense, a sea wall would be more exposed to erosive forces and would require constant reconstruction, putting a strain on the material needs of Grenada.

9.1.4 Mapping and Preparations of Future Flood Zones

To reach an ideal future, as discussed in Section 7 under the possible futures regarding extreme precipitation events, Grenada must prepare for an increase in the intensity of flash floods resulting from unprecedented heavy rain events. Utilizing an existing high-accuracy digital elevation model and hydrological runoff models, future flood zones for extreme precipitation events exceeding the past maximum rainfall event by, e.g., 50% can be mapped. These simulations provide information on where future flash floods will pose the biggest threat. The resulting maps of future flood zones can be used to identify key infrastructure and dense population in these flood zones. The maps also provide a basis for a revised land use plan.

However, before such a simulation can be conducted, there are some measures that need to be taken. Jetten (2016) outlines several areas of data improvement, including rainfall and storm data, which are currently lacking or fragmented and generally provide no information of future severity of hurricanes, and soil quality, which is not well studied. In order to compensate for these areas, Grenada must conduct further land quality assessments and accurately map vegetation cover and the built environment (Jetten, 2016). Combined, these measurements will allow for accurate conduction of simulations that would allow for areas to be designated as high risk. For those areas at highest risk, preparations could be made to relocate critical infrastructure and exposed population. And with continued monitoring and annual reports, this information could provide Grenada with information needed to prepare for the foreseen future.

Pros of this intervention would include better mapping of soil quality and ground cover, which would come from the development of mapping and spatial analysis programs. Improvements in rainfall data and estimations would also better prepare Grenada for future extreme precipitation events and allow for better preparations. And accurate mapping would allow for the identification of future flood zones which could then be migrated or reinforced to better prepare.

Cons of this intervention, while limited, would include factors associated with the logistics revolving around the conduction of *Light Detection and Ranging (LiDAR)* surveys which includes gathering the necessary tools and mapping materials. And the overall costs of moving parts of the built environment would need to be further assessed as, depending on the severity of the flood zones, this could involve the migration of a significant amount of the population.

9.1.5 Increasing Resilience of Critical Electrical Service Infrastructure

As discussed in Section 7 and in Government of Grenada (2021), sustainable infrastructure and energy are key focus areas to prepare for the future of climate change. A shift to a decentralized energy grid would not only reduce the need for larger energy facilities, but also allow for the opportunity to shift to renewable energy sources (Ha & Kumar, 2021). However, for the implementation of such an energy grid to be successful, government cooperation with local urban and rural communities must be maintained. An decentralized energy grid that is run by corporations or government agencies can often be affected by corruption and lead to the improper distribution of resources, leaving some communities disproportion-

ately vulnerable to failures in the energy sector (Ha & Kumar, 2021). In order to overcome this, Grenada must be able to establish a decentralized energy grid that takes in the account of all stakeholders involved, including the people. By shifting to a decentralized electric grid, Grenadians could better prepare for the expected increase in hurricane strength as previous hurricanes exposed weakness inherent with a large, centralized energy plant. And while initial costs could be an issue, government assistance, or assistance from outside agencies, could be used to ensure a fair distribution of such energy generators.

Pros of this intervention would include an increase in the resilience of electrical grids, better preparing Grenada for extreme weather expected in the next 100 years, a shift towards renewable energy sources, such as solar panels or wind turbines, to additionally meet climate goals proposed in Government of Grenada (2021).

Cons of this intervention include the costs associated with a switch from a centralized energy grid to a decentralized grid, which would involve costs of solar arrays and wind turbines and the installation of such systems, and the possibility of corruption that could lead to disproportionate spread in building such systems. Logistics of installing such systems would also require assistance as rural areas or more remote locations would need more assistance in ensuring the quality of such energy systems.

9.2 Interventions for the Ecosystem

9.2.1 Further development of mangrove restoration

Currently, Grenada operates several successful mangrove restoration projects through several government agencies and NGOs. However, in several areas water flow within the mangrove system has been heavily affected. Further restoration efforts should target the restoration of water flows in these areas (Van Loon et al., 2016). By restoring such a system, many coastal water ecosystems would see stabilization in physiological ocean conditions. Another benefit would include natural preventative measures against storm surge. Mangroves act as a natural barrier against wave action as well which would protect many coastal buildings and environments (Lovelock et al., 2022). However, one major drawback of such restoration efforts is it directly conflicts with continued development, and already existing development, present around the island.

9.2.2 Natural Landslide prevention system

Extreme precipitation events, combined with a dryer top soil layer as a result of droughts, will inevitably lead to an increase of the probability of landslide hazard to occur (Fig. 32). In order to promote sustainable development on Grenada, natural solutions can be taken in order to stabilize the ground and mitigate this threat. This would include planting native trees, shrubs, and crops in order to stabilize the soil around areas at high risk for landslides, as seen in the image above. In these areas, according to land degradation analysis conducted by the *Food and Agriculture Organization (FAO)* (FAO, 2015), hurricanes in 2004 and 2005 uprooted many of the native trees, exposing these areas to landslides from further intense rainstorms. Soil conservation efforts and sustainable development of these steep areas initiated partially by the FAO and Ministry of Agriculture have already begun planting trees back in these areas. By continuing on this program and improving drainage of these areas, through natural methods, can further decrease the risk of landslides. For example, in more agricultural areas, farmers can plant additional crops in these risk areas to both gain additional harvest and protect their lands from further erosion.

Pros of this intervention involve an increase in sustainable measures to protect valuable infrastructure and agricultural lands, an increase in ground stabilization, and, in some cases, additional methods of economic growth.

Cons of this intervention mainly would involve the logistics behind such a strategy. For instance, in some areas, land availability is limited, leaving little room to plant such trees to stabilize the ground. The equitable distribution of plants would also need to be addressed as some areas may require more aid or attention than others.

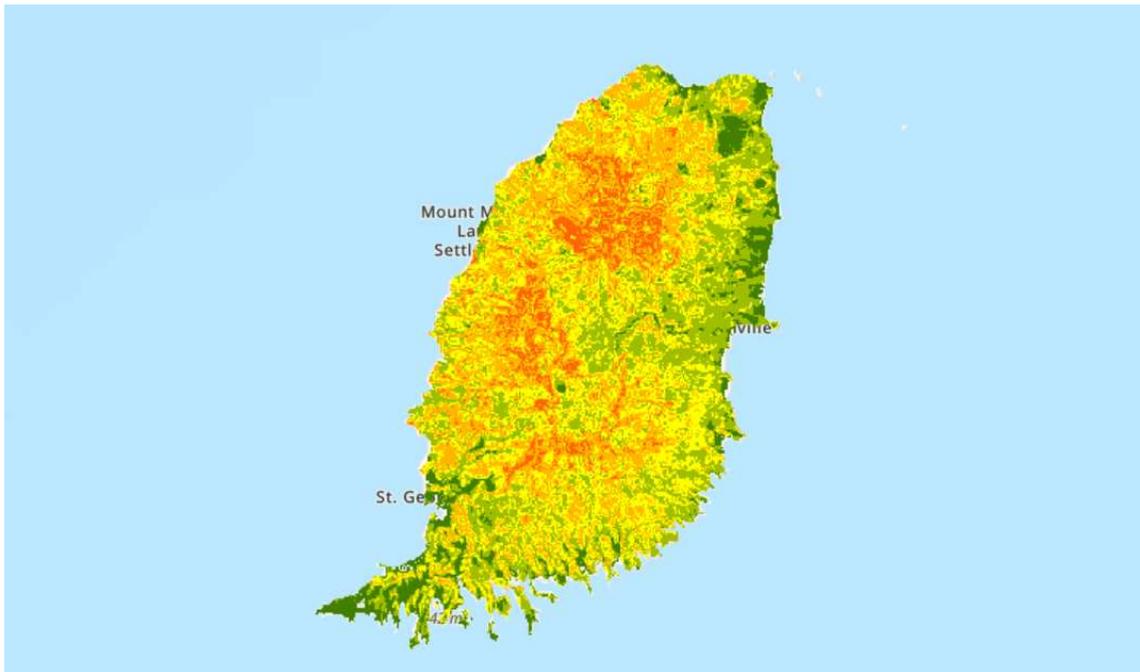


Figure 32. High risk areas (red) for landslide probability. Source: ???

9.3 Interventions for the Local Economy

9.3.1 Strengthening Global Supply Chain

With climate change overall, Grenada faces several challenges that could affect their established global supply chain. This could come in the form of physical disruptions to infrastructure, changes in weather patterns affecting shipping routes, and even a shift towards more sustainable products, all of which have the potential to cause significant impacts. However, there are measures that could be taken to strengthen or reinforce some aspects of the current supply chain. This could include the identification of all aspects of the supply chain to better understand areas that may be exposed to more risk, or a diversification of their suppliers from a couple major distributors to many small distributors to better distribute the risk. Reinforcements could include the development of contingency plans to have a faster reaction to any faults that may occur. And these reinforcements could further be broken down into responses for a variety of scenarios such as sea level rise, extreme precipitation events, droughts, etc.

Pros of such an intervention would include a strengthening of the supply chain to better prepare for climate change. This would also include some economic stability as we face an ever more uncertain future. And by further improving on the resilience of the supply chain, Grenada could create a sustainably functioning economy that can have a faster bounce back after disasters.

While the cons of this intervention are minor compared to the benefits imposed by such an intervention, they still must be addressed. Such cons would include increased logistics and complexity of trade and resource importation, higher costs associated with reinforcing certain aspects of the supply chain, and possible trade offs with sustainability goals set by Government of Grenada (2021).

9.3.2 Sustainable Tourism

Currently, Grenada's economy relies heavily on tourism and the tourist based industry. However, climate change does pose some threats to the tourism industry, such as damage to infrastructure, disruption in trips and excursions, and damage to popular attractions both natural and man-made. But there are some paths Grenada could take to ensure a continuation of tourism, while also promoting sustainable tourism and environmentally friendly approaches to the tourism industry. Two main changes that could be made are a shift towards ecotourism or cultural tourism. Both seek to connect tourists to the natural envi-

ronment of Grenada while also promoting further education on the history and culture of the Grenadian people which has the possibility of boosting interest from tourists in the island. Tourists could also be educated on sustainable practices associated with traveling such as waste management, water conservation, and how their travels may affect the natural environment surrounding Grenada.

Benefits of sustainable tourism include cultural preservation through education programs and community events. Environmental protection is another benefit of sustainable tourism as tourists are educated on the endemic wildlife of the island and how they can better preserve natural ecosystems. There is also the possibility the tourism industry is protected as a result of the development of sustainable tourism as tourists are more educated about the effects of climate change on the environment and tourism itself.

However, downsides of sustainable tourism include factors such as increased costs of excursions or attractions. Some sustainable tourism practices also limit the variety of choices presented to tourists as they visit, by reducing overall choices in both foods and attractions available. There are also several logistical challenges associated with the implementation of such programs as they often require extreme cooperation between stakeholders and local communities.

9.3.3 Desalination to extract freshwater from saltwater

The overall process of desalination is still in its infancy, often running high costs and energy demands and being seen as environmentally damaging. However, as we move into a future where water security is becoming an issue, it is still important to consider all options. Currently desalination plants require an immense amount of energy to run which is often supplemented by the burning of fossil fuels. However, there are some methods of renewable energy which can be used to power these plants. In Grenada, a possible decentralization of the energy grid must be considered to prepare for more intense storms, a desalination plant would put too much stress on the local power grid Pistocchi et al. (2020). Environmental impacts must also be weighed as a desalination plant, if run on fossil fuels, would not only negatively impact the current emissions goal set by Grenada, but also affect local ecosystems (Pistocchi et al., 2020). While this option may appear suitable for Grenada due to the abundance of surrounding sea water, costs to run such a facility would be extremely high.

While desalination is not the right path towards a sustainable future in Grenada, at least in its current state, there are still some benefits associated with such a process. This would include the abundance of saltwater around Grenada and the sustainable source of freshwater if such a process would be feasible.

Unfortunately, desalination itself is a costly process. And with current methods of desalination primarily relying on fossil fuels, a desalination plant in Grenada would not be sustainable in terms of both emissions output and environmental impact.

9.3.4 Extraction of atmospheric water via condensation

Another approach to improve water security is the extraction of water from the atmosphere. Over the last two decades a number of technologies have been developed for *Atmospheric Water Generation (AWG)* under different climate conditions (Lord et al., 2021). For the temperature and humidity range prevalent in the Caribbean, direct condensation of water is the most appropriate approach (Rao et al., 2022). Units for AWG are available from small units producing 10 l/day to large units for 5,000 l/day and more. Larger units can be combined to very large water factories. Typical energy requirements are on the order of 0.25 kWh/l. The best use of this technology is for decentralized water extraction at the location where the water is used as drinking water or other application requiring highest water quality.

The main pro of AWG is the large amount of water available in the atmosphere, and the very high rate of replenishing. Atmospheric water in form of water vapor has an average residence time of 8 days, and tapping into this reservoir means that the water is replenished in very short time. Moreover, the ongoing climate change is expected to increase water vapor in the atmosphere (IPCC, 2023). AWG can easily be combined with local solar systems providing the energy needed for the production of drinking water (Lord et al., 2021).

The main challenge associated with AWG is in a separation of water used as drinking water and water

used for other purposes. This may require separate piping systems for drinking water and water for other uses in buildings. There is also a danger in using electricity produced with fossil fuels for AWG. AWG should be restricted to providing drinking water preferably in a decentralized approach reducing the need for infrastructure for the distribution of drinking water.

9.3.5 Swales for farms to capture water and prepare for drought

Swales are a form of water capture system that involve natural methods for storing, or in some cases redirecting, water. Since many farms are located on hillsides or at the bottom of valleys, runoff from rains would easily collect in these ditches, allowing for farmers to collect water to cope with more intense droughts and heatwaves, lowering the amount of freshwater needed to sustain daily life and agricultural needs. The actual implications of swales can come in multiple forms: grassed or wet. Grassed swales are covered by grasses or shrubs and trees, but are mainly used to redirect water rather than collect water. Wet swales are designed to collect water similar to a pond in that they create a reservoir of water. However, these are often not recommended to be used in heavily populated areas as they can act as a breeding ground for mosquitoes. In Grenada, soil permeability is also a major issue as water can seep out of these swales, possibly contaminating groundwater or coastal water. Plastic or material lining would then be needed to ensure water does not seep into the surrounding soil. However, smaller swales in areas not heavily affected by mosquitos could be used to alleviate some water usage in response to more severe droughts and heatwaves.

Pros of this intervention include the natural capture of rainwater for agricultural use to alleviate consumption of store water. This would also include sustainable methods for collecting rainwater as most swales work best when combined with the planting of trees or crops nearby. Swales in some cases also halt soil erosion by stabilizing topsoil by promoting root growth.

However, cons of this intervention are of great concern, especially for human health. One major issue is that it provides a breeding ground for mosquitoes, which spread disease and can harm local populations. Groundwater and coastal water contamination is another issue as, if the swale is not prevented from spreading into the surrounding soil, water can leach into the surrounding environment. High evaporation rates may be another concern as a wet swale would be exposed to the elements and water storage would end up getting wasted.

Careful consideration of the implications of swales in agricultural practice would be needed in order to weigh the pros and cons of their construction. Whereas they may work in some, less populated areas, heavily populated areas would need to assess the health risks.

9.3.6 Improvement of Stored water

In Grenada, many properties in some way include the storage of water for daily use. While currently, these systems are able to meet the needs of daily life, an increase in drought intensity (Kemp et al., 2022) could put immense strain on stored water. In some areas, water reservoirs could be reduced rapidly due to increasing water usage. In order to combat this, Grenadian water storage must be improved to better prepare for such events. This would include the increase in size of water storage tanks or perhaps the increase in number of water tanks. While future drought severity is still uncertain, the improvement of water storage systems would allow Grenada to cope with a seasonal shift between dry and wet seasons. Improved storage of water can further be split into two sections, designed for agricultural practices and personal use, both of which come with pros and cons.

For agricultural use, an increase in stored water would allow farmers to meet both personal needs and agricultural needs in the case of a drought. However, smaller farms may not have the necessary space for large water storage systems. This would then need to be combated by an increase in vertical size of tanks, to reduce horizontal space taken up, or more land would need to be cleared to make space for the water storage systems.

For personal use, many local houses and commercial buildings rely on the capture of rainwater and stored water for daily consumption. With improved storage tanks, these communities would be better

able to cope with an intense drought, reducing total freshwater needs. However, once again we run into the issue of spacing. Many population centers have high population density and larger storage tanks simply do not fit in some areas. Costs are another thing to consider as some communities may not be able to afford an upgrade in water storage. Government or external assistance would then be needed to help those communities.

9.3.7 Improved rainwater capture systems

On many buildings in Grenada, the usage of rainwater capture is already being practiced. The size of these systems and their practicality in the event of longer dry seasons needs to be carefully assessed. It is expected that more and longer dry seasons will occur in this century (Domeisen et al., 2023). In order to better accommodate for these changes, rainwater harvesting must be improved. Such improvements would include multiple capture systems and larger water storage tanks, and perhaps the specialization of water usage for certain aspects of life. For instance, captured rainwater could be used to replace water being used for showers, sink, or toilets, if properly filtered. While this may initially be beneficial for alleviating water usage, longer dry seasons may reduce the efficiency of such a system due to the lack of rainwater available. Water quality of these systems would also have to be addressed as rainwater is often not recommended for human consumption (CDC, 2021). This would also create other issues regarding the proper filtering of rainwater and associated costs which may become unsustainable for poorer communities.

One major benefit of rainwater collection is that it is already being conducted across Grenada so any further implementation would require less logistics. Furthermore, any improvements can be conducted on a wide budget range, from do it yourself projects to industrial systems.

However, collecting rainwater does come with several downsides. First, we must address how a long, intense dry season would affect the rainwater collection and if amounts collected during the wet season would be sustainable for day to day use. Water quality would also be an issue as rainwater often collects particles of pollutants and any smoke that is present in the atmosphere. Rainwater harvesting also requires some form of durable infrastructure which may be overwhelmed by hurricanes and extreme precipitation, which could damage these systems and leave families vulnerable to water shortages.

9.4 Interventions for the Social Fabric of Grenada

9.4.1 Development of dynamic education programs in schools

As a foundational measure, education about climate change in schools around Grenada would generate support for sustainable development at all levels. And it is often the case that when a movement has a strong foundation in younger generations, it sees more success as the public is better informed about certain issues. For this intervention, we would propose varying levels of education to be implemented based on grade level. Starting with less intensive concepts being introduced at lower grade levels and more intense programs at higher levels. St George's University, which is currently trying to develop an environmental science program, could for instance have spatial analysis classes which would help students learn mapping software such as arcGIS pro or ERDAS imagine, while also producing maps that could be used in conservation efforts, such as maps of coastal mangroves or erosion. How these programs are developed could take multiple forms, either through school cooperation with NGOs or government agencies, or classes could be added to the curriculum at each grade level and could be sponsored by government agencies. Overall, such education programs would foster care throughout the younger generations and create a population genuinely interested in conservation efforts.

Benefits of such programs would include interagency cooperation, allowing for further creation of conservation programs. Mapping classes at higher levels of schooling, mainly college, could be incorporated in order to provide map data for government agencies and for public use. And costs of such an intervention would be relatively low. Timing of such an intervention, which initially may experience some issues, would eventually become enveloped in the school programs and last for generations.

Unfortunately, current college programs are focused on other areas. For instance, St. George's University is primarily focused on medical programs and a shift towards environmental science may initially experience some issues or pushback in terms of funding and popularity. And education programs must first come from government agencies which would have to cooperate in order to develop such an immersive program.

9.4.2 Creation of Public Education Programs

Further education of the public about climate change could be beneficial in the long run for both making informed decisions about climate policies, and to generally inform the public about their current situation. Such programs would build on some social media platforms and organizations who already target public education as social media and community programs are already popular with the public. This would mainly be used to target those groups who are out of school in order to ensure an informed population, and would relatively be inexpensive to implement. These programs would continue to provide updated information on sea level rise, changes in dry and wet seasons, and also showcase some methods of sustainable lifestyle choices that individuals can make to contribute to the sustainability goals outlined by Grenada. However, as with all education programs regarding climate change, eco-grief, which occurs when we experience a sense of loss upon learning about climate change, must be adequately addressed. Careful consideration for the type of education must be taken in account as to not displease people while also keeping the programs informative and long lasting. Such methods of education are already being conducted between the Ministry of Agriculture, who actively post projects and information on Facebook, and Grenada Fund for Conservation who bring in volunteers for mangrove restoration projects and learning opportunities.

Benefits of such a program would be the education of those groups of people who are out of school in order to continue the uptake of knowledge about certain topics. Public education, especially on social media, would also generate mass support and increase the popularity of these platforms, possibly resulting in the spread of these messages overseas. Such a program would also be relatively inexpensive and would be able to be continued for an extended period of time as independent content creators and groups would form the basis of the program.

Cons of this intervention would solely include the effect eco-grief may pose. If education is not carefully conducted, the idea that we are at a lost cause would result in a drop in popularity of almost all climate policies.

10 Discussion and Conclusions

Through the development of this case study, a major issue that was experienced by the researchers was utilizing a new version of the MCST which included two new sections: Exposed Assets and Risk Assessment. Those leading the sections were challenge with defining what both sections would contain.

The crafting of an all-encompassing conceptual model always remains a difficult feat to accomplish. Through the encapsulation of the interlocking and encompassing systems, the representation of feedback loops, or the simulation of hazards, fragilities, and exposed assets. Over the course of this case study each model was reworked or replaced from start to end as we sought to create the best conceptual model we could. Each model has undergone numerous revisions to achieve the end goal presented earlier on.

Over the course of the four months this case study was developed, there was only one week in Grenada. The opportunities to meet with stakeholders in person was limited. The use of roleplaying, although effective, is no substitute for personal interactions. While we concluded the role playing with a useful goal statement describing a desirable future consistent with the views of the stakeholders considered in the role playing and the in-person meetings, there remains a slight uncertainty that could only be reduced through more expansive and comprehensive in-person meetings.

Similarly, throughout the case study writing sections were developed out of order in order to meet the deadline whilst working to ensure an accurate understanding and explanation of the systems. Through the simultaneous development of the hazard scenarios, foresight, and risk assessments to the interventions

based upon what we heard from stakeholders adjusted to match the futures we aim to achieve with a conscious understanding of the risk of each future.

Though this case study forms the basis for a 50-year plan to address sea level rise and extreme precipitation events from climate change moving forward, it is not the only research that needs to be done in preparation. Future research areas, and possible new interventions and recommendations, should seek to incorporate the intersectionality with other issues especially highlighting species extinction and pollution challenges that connect with the issues addressed in this case study. Moving forward, a goal statement similar to the one derived here should be used as a basis to ensure interventions that not just address the physical issues, but elevate society as a whole:

A built environment in Grenada that enables the people to cope with the impacts of sea level rise and heavy precipitation by securing the safety and well-being of all and by distributing the risks equally while safeguarding the socio-economic and environmental system.

Crafted by the conversations with stakeholders and simulations of those that could not be organized, the interventions are based upon the objectives of the goal statement. Although non-definitive, it established the tone early on for the end reaches of this case study and finalizes the recommendations sought for the establishment of Grenada's future plans to address sea level rise and extreme precipitation events. Interventions were made to best address the goal statement and Grenada on pathways towards a desirable future outlined in Section 7.

11 Recommendations

After addressing the problem in the other sections and with the continuation of hazards being experienced, recommendations are presented after the other sections. The recommendations presented in this section has a goal to be implemented for the best result/ future for Grenada by the goal statement; A built environment in Grenada that enables the people to cope with the impacts of sea level rise and heavy precipitation by securing the safety and well-being of all and by distributing the risks equally while safeguarding the socio-economic and environmental system. T

Thus, these recommendations are made to reach a desired future for Grenada.

Recognizing that:

- Not one single stakeholder is responsible for making these decisions
- Grenada is running out of space for Grenadians
- Sea level rise is already causing flooding, increasing the severity of storm surges, causing erosion/ landslides, inundation etc.
- As the climate continues to change, we will experience a further increase in sea level rise, extreme precipitation events, and an increase in the severity of droughts and heatwaves.
- We do not exactly know the future of climate change and are unsure of what to expect

Acknowledging that:

- The Planning Development Authority is the main stakeholder dealing with this wicked problem
- The Planning Development Authority wants to do something but has limited resources/influence
- The Ministry of Agriculture is invested in the conservation missions being put forward with the Grenada fund for conservation
- The people are concerned about climate change

it is recommended that the:

Planning and Development Authority:

- Identifying Critical Infrastructure
 - Highlights high risk areas and buildings that can be targeted for moving
- Preparing built environment and people to move
 - Movement of population centers out of high risk areas
- Construction of Seawalls
 - Constructed in specific areas, around St. George's and Grenville, to keep out sea water
- Mapping and Preparation of Future Flood Zones
 - Increased mapping and data collection to identify future flood zones
 - Provides early warning system for high risk areas to begin moving out of flood zones

Ministry of Agriculture:

- Develop natural systems of landslide prevention
 - Planting of additional crops along river beds
 - Placement of native trees/shrubs along rivers in population centers
- Improvements to the storage of water
 - Larger containers to cope with longer dry seasons
- Development of rainwater capture systems
 - Reduced reliance on freshwater reserves
 - Efficient method of water capture

Grenada Fund for Conservation:

- Public education programs
 - Helps to inform public of issues regarding climate change
 - Generates public support

Education:

- Further education of climate change in schools
 - Variable education at each grade level
 - Mapping software taught at higher grade levels to better identify flood risk areas of Grenada

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Acronyms

AIS	Antarctic Ice Sheet
AWG	Atmospheric Water Generation
CBF	Caribbean Biodiversity Fund
CCI	Caribbean Challenge Initiative
GRENCODA-CCCCC	Caribbean Community Climate Change Center
EEI	Earth Energy Balance
ELSS	Earth's life-support system
FAO	Food and Agriculture Organization
GCS	Global Climate System
GFC	Grenada Fund for Conservation
GIS	Greenland Ice Sheet
GRENCODA	Grenada Community Development Agency
Grenlec	Grenada Electricity Services Ltd.
GPA	Grenadian Ports Authority
GSL	Global Sea Level
GTA	Grenada Tourism Authority
IAGDO	The Inter-Agency Group of Development Organisations
IMO	International Maritime Organization
IOPC	International Oil Pollution Compensation
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
LSL	Local Sea Level
MARI	Mitigation and Adaptation Research Institute
MCST	MARI Case Study Template
NAWASA	National Water and Sewage Authority
NGO	Nongovernmental Organization
PDF	Probability Density Function
PDA	Planning and Development Authority
PDF	Probability Density Function
TNC	Ther Ntaure Conservancy
UN	United Nations
WAIS	West Antarctic Ice Sheet

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