©Conservation International Photo by Remesa Lang

NORTH BRAZIL SHELF MANGROVE PROJECT

NATURE BASED SOLUTIONS

DISCLAIMER

SUGGESTED CITATION

Mak, M., May, C., Beers, L., and Crooks, S. 2019. Setting the foundations for zero net loss of the mangroves that underpin human wellbeing in the North Brazil Shelf LME: Nature Based Solutions. Report by Conservation International and Silvestrum Climate Associates.

TABLE OF CONTENTS

TABLES

FIGURES

ATTACHMENTS

ACRONYMS / ABBREVIATIONS

ACRONYM	SIGNIFICATION
%	percent
CLME + SAP	Caribbean & North Brazil Shelf Large Marine Ecosystems + Strategic Action Programme
cm	centimeter
DHI	Danish Hydraulic Institute
ESRI	Environmental Systems Research Institute
GDP	Gross Domestic Product
GGI	Green-gray infrastructure
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
km	kilometer
LME	Large Marine Ecosystem
m	meter
mm	millimeter
NASA	National Aeronautics and Space Administration
NBS-LME	North Brazil Shelf-Large Marine Ecosystem
NOAA	National Oceanic and Atmospheric Administration
RCP	Representative Concentration Pathways
SAGE	Systems Approach to Geomorphic Engineering
SFEI	San Francisco Estuary Institute
sec	second
spp	species
USACE	United States Army Corps of Engineers
USGCRP	United States Global Change Research Program
yr	year

1 Executive Summary

This report synthesizes the current understanding of the physical processes, hydrodynamic mechanisms, and anthropogenic activities that influence mangrove condition and associated flood risk across the North Brazil Shelf Large Marine Ecosystem (NBS-LME), specifically in Guyana and Suriname. A Coastal Vulnerability and Adaptation Framework is presented to provide technical support in resilience building of coastal communities and built infrastructure while persevering or restoring natural ecosystems.

The dynamic NBS-LME coastal plain is driven by migration of enormous mud banks that flow northwest as slow-moving waves along the shore from the Amazon river, Brazil to the Orinoco river, Venezuela. Mangroves grow seaward as mud banks pass and erode the mudflats. Landward from the shoreline, the coastal plain has existed in relative stability. Land conversion for agriculture and settlement is most intense in Guyana, progressively decreasing in intensity through Suriname, French Guiana, and Brazil. Lands drained for settlement and the associated economic, social, and mobility infrastructure is often situated below sea level, requiring drainage channels and levees for protection from riverine and coastal flooding. Extensive areas of farmland have been abandoned due to flooding and acidic soils. Ongoing discussions about coastal plain management recognize the importance of ecological conservation, the demand for land conversion to agriculture and settlement, and the growing frequency and scale of flooding from sea level rise.

Mangroves (saline tidal forested wetlands) and coastal swamps (freshwater forested wetlands) are interconnected components of the coastal plain landscape that are at, or just above, sea level. The presence of vegetation both helps to buffer wave energy that drives erosion and to bind soft sediment, although the capacity for mangroves to bind sediments is limited to the upper reaches of the tidal range (and is therefore sensitive to rapidly rising sea levels). Established vegetation also provides some attenuation of coastal storm surge which can drive widespread inland flooding, reducing high flood velocities and trapping damaging debris.

In the dynamic mudbank environment, mangroves are subject to periods of erosion and accretion with the passage of mud waves. Infrastructure built within the dynamic fringe of the mangroves is subject to periodic erosion threats as passing mud wave troughs lower the elevation of the mudflat shoreline. Existing "gray" engineered structures (e.g., levees and seawalls) further exacerbate erosion by enhancing wave energy and hindering sedimentation on adjacent mudflats. The deployment of nature-based solutions (e.g., green infrastructure, ecosystem-based adaptation, ecosystem focused governance policies) can strike a balance between coastal hazard protection for the built inland development and preservation of a natural shoreline that supports the ecologically rich character of the NBS-LME. An outcome of this study is a Coastal Vulnerability and Adaptation Framework, a tool to identify shoreline segments vulnerable to coastal hazards and the potential consequences to communities and the built environment from these hazards (an outcome of the Coastal Vulnerability and Adaptation Framework is a Coastal Vulnerability-Consequence Index that aggregates this information). The Coastal Vulnerability-Consequence Index allows for a deep dive into the vulnerability and consequence of each shoreline segment and highlights potential regional scale vulnerabilities that may require cross-jurisdiction adaptation strategy planning.

Nature-based solutions can vary across the spectrum from 100 percent green to hybrid green-gray solutions that are more engineered. Selecting the appropriate solution may be governed by the existing shoreline typology, for example shorelines with adjacent built infrastructure may require more engineered solutions than shorelines with settlements that are set back from the shoreline. In some instances, setting back infrastructure can help create space to restore or sustain mangroves. The NBS-LME region is sediment rich; therefore, mangroves can likely build vertically to sustain themselves in the face of high rates of sea level rise. However, mangroves will likely retreat landward with sea level rise. Where engineered coastal flood protection measures exist, landward mangrove migration will be squeezed between rising waters and hard infrastructure. With thoughtful planning, mangrove restoration and enhancement can be an important component of nature-based solutions for climate adaptation, flood risk reduction, and for ecosystem survival.

2 Introduction

2.1 Project Background

The project entitled “Setting the foundations for zero net loss of the mangroves that underpin human wellbeing in the North Brazil Shelf LME (NBS-LME)” (from here on the “NBS Mangrove Project”), is a one-year primer project to help establish a shared and multi-national process for an Integrated Coastal Management in the NBS-LME. The project recognizes the prevalence, socio-ecological importance and connectivity of mangroves in the retention and generation of key ecosystem services (fisheries, coastal protection and defense, water quality, blue carbon etc.) from which communities in the NBS-LME countries are beneficiaries. This project builds on, and supports, the antecedents and key elements of the regional agreement established within the CLME+ SAP for the NBS-LME region.

The objectives of the NBS Mangrove Project are:

1. To generate the necessary baseline knowledge and technical assessments as inputs towards a collaborative vision and a coordinated well-informed management of NBS-LME mangrove systems, with emphasis on the information needs of Guyana and Suriname.
2. To support development of transboundary coordination mechanism(s) between the countries of Guyana, Suriname, French Guiana, and Brazil (state of Amapá) towards the improved integrated coastal management of the extensive, ecologically connected yet vulnerable mangrove habitat of the NBS-LME region.

2.2 Report Objectives

Natural ecosystems provide a host of benefits to local communities and national economies, and if managed correctly, they can also provide coastal flood protection from damaging surge and wave hazards. This report builds the knowledge base to support successful implementation of nature-based solutions in the NBS-LME region within a regional framework. Key topics presented in this report include:

1. An overview of the sea level rise scenarios to be considered;
2. An account and quantification of the influence of geomorphology and mangrove species composition in reducing storm surge and stabilizing sediment; and
3. A review of known environmental and anthropogenic factors that influence mangrove condition and associated flood risk.
4. An overview of a Coastal Vulnerability and Adaptation Framework and Coastal Vulnerability-Consequence Index to identify local- and regional-scale vulnerabilities to coastal hazards;
5. Quantification of geologic and coastal processes leading to coastal vulnerability;
6. An overview of nature-based (green) and engineered (gray) solutions;
7. An evaluation of costs and discussion of cost-benefits for implementing nature-based solutions;

8. Existing tools and models to support detailed coastal evaluations in support of nature-based shoreline solutions for coastal protection; and
9. Identification of data gap and next steps to complete the Coastal Vulnerability and Adaptation Framework for the NBS-LME.

3 Sea Level Rise Scenarios

3.1 Key Messages

- Understanding how sea levels have risen historically, and how they are projected to rise over time, is critical when planning and implementing coastal defense structures that can be adapted and strengthened over time.
    - Based on global sea level modeling, historical sea level rise across the NBS-LME region from 1992 to 2017 range from 3.5 to 3.8 mm/yr. There have been several evaluations of historical sea level rise using tide observations near Georgetown, Guyana, with weak consensus across results.
- Adaptation projects (or new development) should consider sea level rise expected at the end of the project lifespan.
- Sea level rise projected for a mid-century (2050) and late-century (2100) time horizon is presented in Section 3.3 for two climate change scenarios.

3.2 Historical Sea Level Rise

Prior studies using tide station observations near Georgetown, Guyana reported a wide range of historical sea level rise rates over time, ranging from 10.2 mm/yr from 1951 to 1979 (Ruh Ali 2016), 5.1 mm/yr from 1960 to 1981 (Dalrymple and Pulwarty 2006), 4.7 mm/yr from 1960 to 2010 (Ruh Ali 2016), and 3.8 m/yr from 1992 to 2017[1]. Across the NBS-LME region, historical sea level rise (1992 – 2017) appears to be consistent, with no apparent trend across the coastline (see Table 1).

Table 1. Historical Relative Sea Level Rise (in mm/yr) for the NBS-LME region from 1992 to 2017

Country	Administrative Region	Historical Sea Level Rise (mm/yr)
Guyana	Barima_Waini	3.5
Guyana	Demerara-Mahaica (Georgetown)	3.8
Guyana	Mahica Berbice	3.9
Suriname	Nickerie	3.7
Suriname	Coronie/Saramacca	3.6
Suriname	Paramaribo	3.8
Suriname	Commewijne/Marowijne	3.8

Source: NASA 2019

---

[1] Estimates are available from a trend analysis of gridded data (approximately 18.5 km grid spacing) developed by NASA using satellite observations of sea surface anomalies from mean sea level. This information is available through NASA's Making Earth System Data Records for Use in Research Environments program. Accessed using NASA Sea Level Change Data Analysis Tool: https://sealevel.nasa.gov/data-analysis-tool/

Historic rates of sea level rise in the NBS-LME region exceed global averages of 3.3 mm/yr[2]. As sea levels rise, coastal defense structures are more likely to be overtopped, resulting in inland flooding. Although many mangrove stands have kept pace with historical sea level rise, increasing rates of sea level rise may impact the ability of the mangroves to stay in place.

3.3 Regional Future Sea Level Rise

Global sea level rise projections are based on global temperature increases due to greenhouse gas emissions. These cause the thermal expansion of seawater and melting of ice sheets, leading to rising sea levels. Regional sea level rise projections consider the global processes, while also including local factors such as oceanographic process and vertical land motion (e.g., subsidence and uplift).

Over the next few decades, climate and sea level rise projections have a high degree of certainty, but after midcentury, the changes are harder to forecast and depend strongly on the amount of greenhouse gases emitted globally and on the sensitivity of Earth's climate to those emissions (Wuebbles et al. 2017). In 2014, the Intergovernmental Panel on Climate Change (IPCC) adopted a set of four greenhouse gas concentration trajectories known as "Representative Concentration Pathways," or RCPs (IPCC 2014):

- RCP 8.5 assumes anthropogenic global greenhouse gas emissions continue to rise over the next century (i.e., there are no significant efforts to limit or reduce emissions)
- RCP 6.0 assumed anthropogenic global greenhouse gas emissions peak in 2080 and then decline
- RCP 4.5 assumes anthropogenic global greenhouse gas emissions peak in 2040 and then decline
- RCP 2.6 assumes stringent emissions reductions, with anthropogenic global emissions declining by about 70% between 2015 and 2050, to zero by 2080, and below zero thereafter (i.e., humans would absorb more greenhouse gasses from the atmosphere than they emit).

RCPs are defined by their total radiative forcing (Watts per square meter) by 2100, which represents a cumulative measure of human emissions of greenhouse gases. RCP 8.5 is the recommended upper bound scenario for estimating future sea level rise. RCP 8.5 is recommended because thus far, worldwide greenhouse gas emissions have continued to follow this trajectory, and because it supports a conservative risk management approach. However, global efforts to curb emissions and develop mechanisms to capture carbon from the atmosphere (such as wetland restoration and reforestation) are in progress. If these global efforts prove successful, at some point in the future a gradual bend away from RCP 8.5 and towards a lower scenario would occur. Therefore, RCP 4.5 could represent a potential realistic future pathway. Achieving RCP 2.6 would require significant actions at a global scale to reach net zero and ultimately negative emissions after mid-century, while achieving RCP 4.5 requires actions on the scale of those set by the Paris Agreements (Strauss and Kulp 2018).

---

[2] https://sealevel.nasa.gov/understanding-sea-level/key-indicators/global-mean-sea-level accessed May 2019

At a minimum, sea level rise trends should be considered for both mid-century and late-century time horizons. A mid-century time horizon supports typical planning horizons of 20- to 30-years. A late-century time horizon supports longer-term planning efforts including land use decisions and the timing of implementation for larger-scale climate adaptation needs. If the expected lifespan of a project is known, sea level rise expected by the end of a project lifespan should be used, even if this beyond the end of the century.

Table 2 presents regional sea level rise estimates appropriate for the NBS-LME region for mid-century (2050) and late-century (2100) under RCP 2.6 and RCP 8.5. These estimates are presented in a sea level rise and coastal hazard assessment for the Caribbean Basin by Strauss and Kulp (2018), using values derived from Kopp et al. (2017) at a tide station in Belem, Brazil. The second nearest tide station in Puerto Plata, Dominican Republic has similar estimates to the Belem station (Strauss and Kulp 2018). For simplicity only the sea level rise projections for RCP 2.6 and RCP 8.5 are presented in Table 2. In summary, sea level rise will continue and is projected to accelerate. How quickly and by how much will depend on global efforts to curb greenhouse gas emissions.

Table 2. Projected Relative Sea Level Rise (in meters) for the NBS-LME region

	Mid-Century (2050)	Late-Century (2100)
Scenario	Median	Median
RCP 2.6	0.23	0.53
RCP 8.5	0.30	1.50

Source: Strauss and Kulp (2018)

4 Storm Surge Attenuation

4.1 Key Messages

- Storm surges are small across the NBS-LME region, with coastal water levels elevated by 0.4 m or less in Suriname (World Bank Group 2017).
- While storm surges are relatively small, there are significant residential development and economic activities that occur in low-lying areas within the coastal hazard zone.
- A wider mangrove forest is required to reduce storm surge-driven water levels than needed to reduce wave hazards.
- The physical and spatial characteristics of mangroves (e.g., aerial root diameter and population density) play a role in the efficiency in reducing storm surge.
- The landward width of mangroves can provide significant reduction in storm surge levels; approximately 3 km of mangroves are needed to reduce storm surge levels by up to 50 percent.

Coastal flooding is a concern in the low-lying coastal areas, especially where inland areas are below sea level. These low-lying areas near the shoreline, with rural settlements and agricultural lands, are already threatened by tidal flooding during spring tides. While direct impacts from hurricanes are not currently a concern, low-pressure systems can elevate local ocean water levels and create storm surge conditions that result in inland flooding. In the NBS-LME region, most storm surges are small, with coastal water levels elevated by 0.4 m or less in Suriname (World Bank Group 2017). However, more extreme events can occur, and a 2.5-m storm surge event is associated with a 1% annual chance of occurrence (Burke and Ding 2016). High winds occurring concurrently with storm surge can exacerbate inland flooding and coastal erosion due to increases in wave energy (World Bank Group 2017). Georgetown (on average 2 m below sea level) and the East Coast Demerara are particularly vulnerable. In early 2005, extreme rainfall coupled with storm surge overtopped the seawall and the conservancy dam, resulting in devastating widespread flooding (Hickey and Weis 2012). It is estimated that the 2005 floods caused US$465 million (GYD$98 billion; SRD$3.5 billion) in damage, equating 59% of Guyana's Gross Domestic Product[3].

Although mangroves are effective at reducing wave energy and wave heights (see discussion in Section 0), mangroves are less effective at reducing storm surge levels. Storm surge can elevate coastal water levels for a lengthy period (measurable in hours to days), whereas wind-driven or ocean-swell waves have shorter durations (measurable in seconds to minutes). Therefore, a substantially wider mangrove forest would be required to reduce storm surge-driven water levels than needed to reduce wave hazards. Empirical studies and numerical modeling efforts have estimated 4 to 48 cm of storm surge reduction per kilometer of mangrove width (Krauss et al. 2009, Zhang et al. 2012). Zhang et al. (2012) found that the greatest rate of attenuation in storm surge occurred at the seaward edge of mangroves,

---

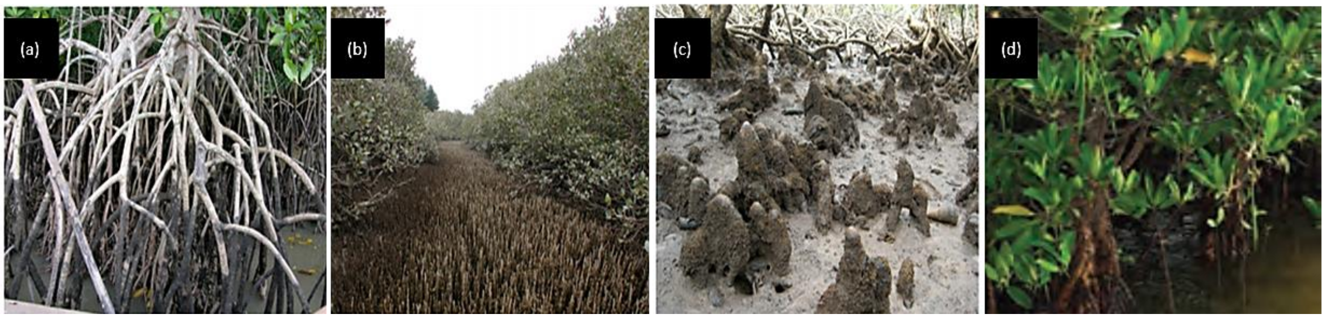
[3] http://www.latinamerica.undp.org/content/rblac/en/home/presscenter/articles/2015/12/04/widespread-floods-affect-livelihoods-in-guyana.html, accessed May 2019

with decreasing efficiency further inland. Several factors contribute to the rate of storm surge attenuation through mangrove forests, including:

- Mangrove vegetation characteristics (e.g., forest width, tree density, and structural complexity (roots, stems, branches, and foliage) of the dominant species or species mix)
- Physical characteristics (e.g., presence of channels and pools)
- Topography and bathymetry (e.g., slope and surface roughness)
- Storm characteristics (e.g., height and forward speed storm surge)

Using tidal flow as a proxy for storm surge, mangroves have been found to influence both flood and ebb stages of tidal flow, with vegetation and bottom mud playing a factor in rise and fall velocities. This effect can also be observed during a falling tide. With mangrove trees submerged, the surface roughness slows the retreating waters, while water levels in the creeks fall at a faster rate.

Mangrove species composition and density play an important role in storm surge attenuation. The mangrove species *Rhizophora* spp. and *Bruguiera* spp. (with aerial roots – e.g., prop roots, knee roots, or pneumatophores[4]) have been observed to have greater influence on the flood and ebb stages than for example young *Kandelia* mangroves (Mazda and Magi 1997, McIvor et al. 2012) which do not have aerial roots. Figure 1 shows the various mangrove root types.



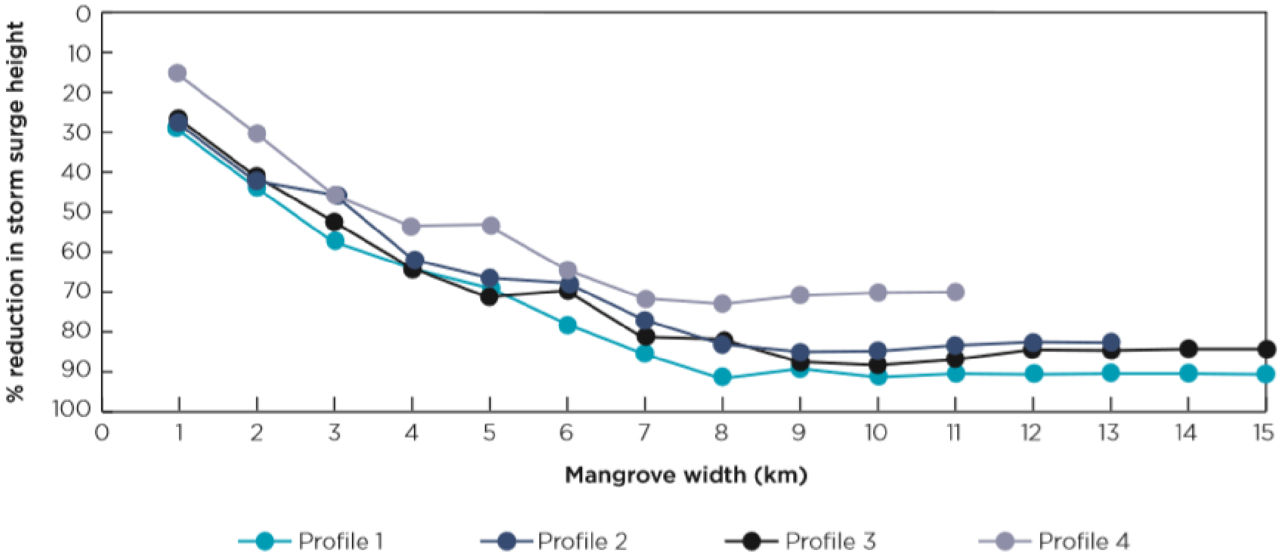
Source: World Bank 2016

Figure 1. (a) Prop roots (*Rhizophora* spp.) (b) Pneumatophores (*Avicennia* spp.) (c) Knee roots (*Bruguiera* spp.) (d) Non-aerial roots (*Kandelia* spp.)

The density of mangrove vegetation and the diameter of the aerial roots and stems contribute to mangrove efficacy in reducing storm surge levels (Alongi 2008, Krauss et al. 2009). However, there is little data available to confirm this assumption. Zhang et al. (2012) showed that the landward width of mangroves can provide significant reduction in storm surge levels; approximately 3 km of mangroves are needed to reduce storm surge levels by up to 50%, as shown in Figure 2. Krauss et al. (2009) found peak water level reductions from 4.2 to 9.4 cm per 1 km of mangrove forests (in response to hurricanes reaching the southeastern coast of the United States).

---

[4] a specialized root of mangrove that branches upwards, rising above ground, and undergoes gaseous exchange with the atmosphere



Source: World Bank 2016

Figure 2. Reduction of storm surge height by mangroves (Gulf Coast - United States)

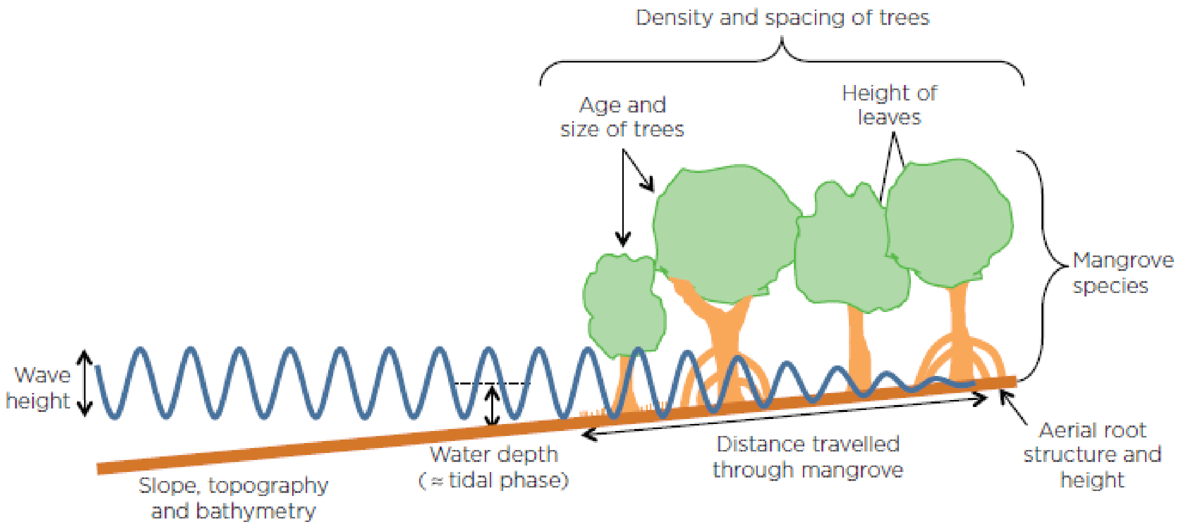
5 Wave Attenuation

5.1 Key Messages

- Wave hazards are the principal contributor to erosion along the NBS coastline.
- Mangrove forests can effectively reduce wave energy and stabilize shorelines, with several factors contributing to the rate of wave height attenuation (e.g., species type and density, age, topographic, and storm characteristics).
- Mangroves have been found to reduce wave heights by 13-66 percent per 100 m.
- It can be advantageous to have several mangrove species present to maximize wave attenuation across rising water levels; due to the roughness provided by different species across different elevations.

Mangrove species with dense aerial roots are particularly effective at wave attenuation. The species *Rhizophora* spp., for example, forms a dense above-ground system of prop roots that can rapidly reduce wave heights as the wave propagates through the mangrove stand.

At higher tidal water levels, mangrove trunks above the root system offer less obstructions to attenuate wave energy. Therefore, mangroves with prop root systems can achieve higher wave attenuation at shallower water depths, and as water depths increase their wave attenuation efficiency decreases. Interestingly, the pneumatophores of *Sonneratia* spp. and *Avicennia* spp. can attenuate waves more effectively than *Rhizophora* spp. at shallow depths because they have smaller prop roots that provide a greater overall surface area for restricting flows.



Source: McIvor et al. 2012

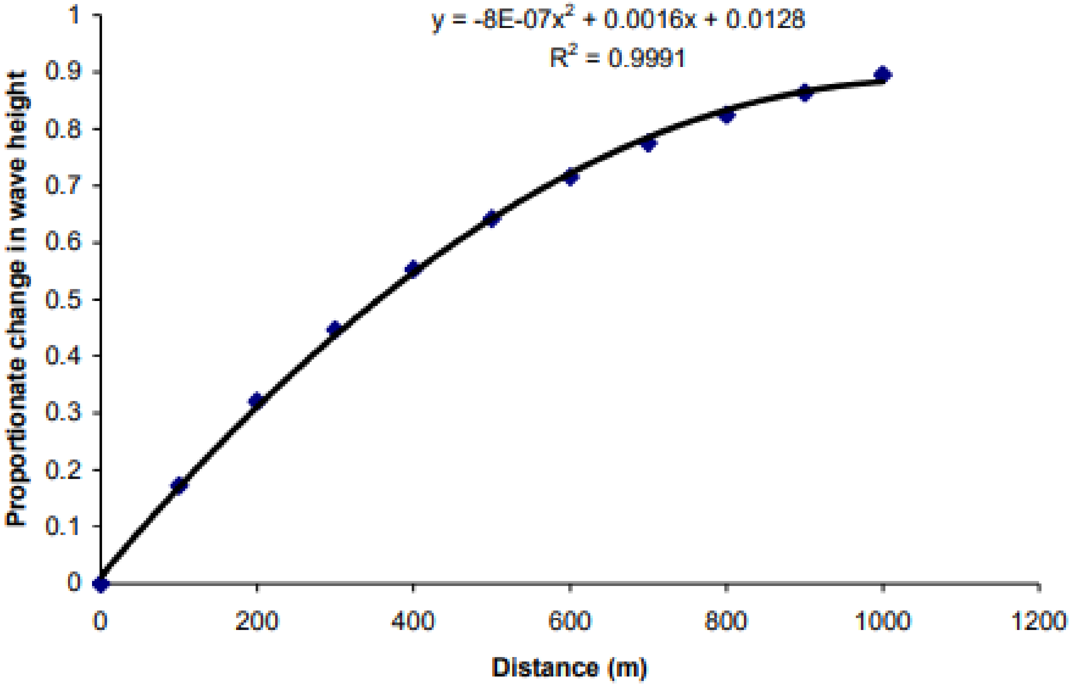
Figure 3. Key factors contributing to wave attenuation

Generally, as water levels rise, wave attenuation effectiveness decreases until water levels reach the elevation of the thick branches and leaves and a higher degree of effectiveness is regained. Species such as *Kandelia* spp. without aerial roots provide limited wave attenuation potential (compared to other mangrove species) at lower water levels but can provide wave attenuation at higher water levels when the branches and leaves are submerged.

Mazda and Magi (1997) confirmed that mangrove tree age also correlates with wave height reduction. Younger species, with less volume and density, provide the least amount of bottom friction for attenuating wave heights. In comparison, older species provide greater attenuation because they have more developed branches and leaves that can provide additional friction.

Thus, mangrove measurements can help quantify the wave attenuation potential of existing mangrove forests. Measurements should include trunk height, width and density, and foliage height and width. Since several factors play a role in the amount of wave attenuation achieved by mangroves, it is advantageous to have a forest composition of different species types to achieve maximum attenuation across a range of water depths (Tanaka et al. 2007).

Figure 4 presents the reduction of wave height by *Kandelia* spp. per mangrove forest width (Barbier et al. 2008). Almost 0.4 km of *Kandelia* spp. mangrove forest is needed to reduce wave heights by 50 percent, and 1 km is required to reduce wave heights by 90 percent (Barbier et al. 2008). Other studies have citied wave height reduction of 13-66 percent per 100 m of mangrove (McIvor et al. 2012, Spalding et al. 2014).



Source: Barbier 2008

Figure 4. Reduction of wave height by mangroves at mid-tide (*Kandelia* spp.)

6 Sediment Stabilization

6.1 Key Messages

- While root types (e.g., aerial roots, prop roots) vary across mangrove species, in general the mangrove root systems are effective in trapping sediments.
- Pneumatophores (aerial roots) are generally more effective in maintaining buildup of sediment elevations than prop roots

Mangrove roots are effective at trapping sediments and minimizing coastal erosion by creating stable banks (Thom 1967, McIvor et al. 2012, Flemming 2012). However, the sediment below mangrove roots may not be stabilized. Root undercutting can lead to significant loss of mangroves and subsequent shoreline retreat. Mangroves generally exist at the top half of the tidal range and the roots are typically shallow (although root depth varies by species).

Some species (*Avicennia germinans* and *Laguncularia racemosa*) have denser root mats (e.g., compared to *Rhizophora mangle*) and are better able to stabilize the shoreline. Higher rates of sediment accretion have been observed under species with prop roots (*Rhizophora* spp.) compared to species with pneumatophores (*Sonneratia alba*) (Krauss et al. 2003). However, prop roots are not as successful at maintaining sediment elevation over time compared to pneumatophores.

Pneumatophores, aerial roots that branch upwards from the ground, may have less influence on overall sediment deposition processes, but play a role in the binding and retention of sediments (Krauss et al. 2003). Filamentous algae in combination with mangrove roots has been suggested to aid in the trapping and retention of detrital particles and mineral sediment (Mckee 2011). Gleason and Ewel (2006) found that root growth was greatest in pneumatophore root zones compared to prop root or knee root zones.

7 Anthropogenic and Environmental Factors

This section discusses the anthropogenic and environmental factors that cause mangrove degradation or limit growth, impacting the efficacy of mangroves in providing coastal protection. Environmental factors, such as high tides and strong storms, which are already contributing to flood risk in the NBS-LME region, will be further exacerbated by climate change. Rising sea levels and increased wave energy from potentially more intense tropical and North Atlantic storms will result in accelerated shoreline erosion and may affect the overall sediment dynamics of the unique NBS system. In addition, there is the potential for increasing damage to mangroves themselves through defoliation or complete destruction (Gilman et al. 2008). Both anthropogenic influences and changing environmental conditions are anticipated to disturb the mudbank dynamics between the migrating mudbanks and interbanks (i.e., the level space between mudbanks) leading to exacerbated flood risks.

7.1 Key Messages

- Engineered sea defense structures (e.g., seawalls) promote wave reflection and erosion of adjacent shoreline areas. This includes shoreline adjacent mangrove populations.
- The wave environment in the NBS-LME region is heavily influenced by mudbank and interbank dynamics; migrating mudbanks dissipate wave energy (i.e., wave heights dissipate as they interact with the mudflats and wide intertidal areas) and allows mudflat accretion to occur. Shorelines at interbank areas between mudbanks are exposed to higher wave energy and rapid erosion.
- Rapid colonization of mangroves can occur when mudbanks are present and provide wave dissipation
- Land use management (e.g., water conservation activities) outside of the coastal zone play a role in the health of mangrove populations by limiting freshwater pluses and increasing salinity in tidal creeks.
- ‘Coastal squeeze’ due to shoreline adjacent urbanization prevents landward mangrove expansion and/or migration to keep pace with sea level rise.

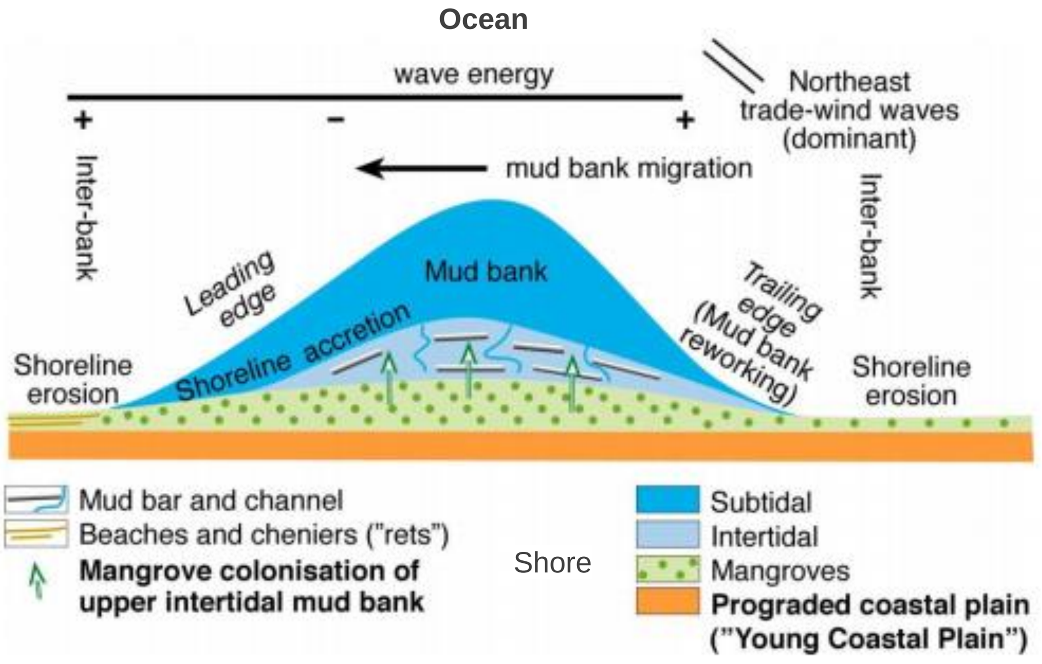
7.2 Geomorphological Factors

The continental shelf extends for approximately 300 km off the NBS shoreline. The nearshore shelf extends approximately 30 km, with water depths ranging from 0 to 20 m (Allison and Lee 2004). The shallow shelf allows for larger storm surge heights to reach the shoreline than can occur in nearshore areas with steeper slopes.

In the NBS-LME region, wave energy is heavily influenced by the presence of large mudbanks. Mudbank migration along the NBS coastline is a dynamic process that incorporates continuous cycling of large quantities of sediment between the shoreline and nearshore zone. Mudbanks can extend to depths of 20 m (up to 30 km offshore) and migrate westward alongshore at average rates from 0.5-1.5 km/year (Anthony et al. 2008).

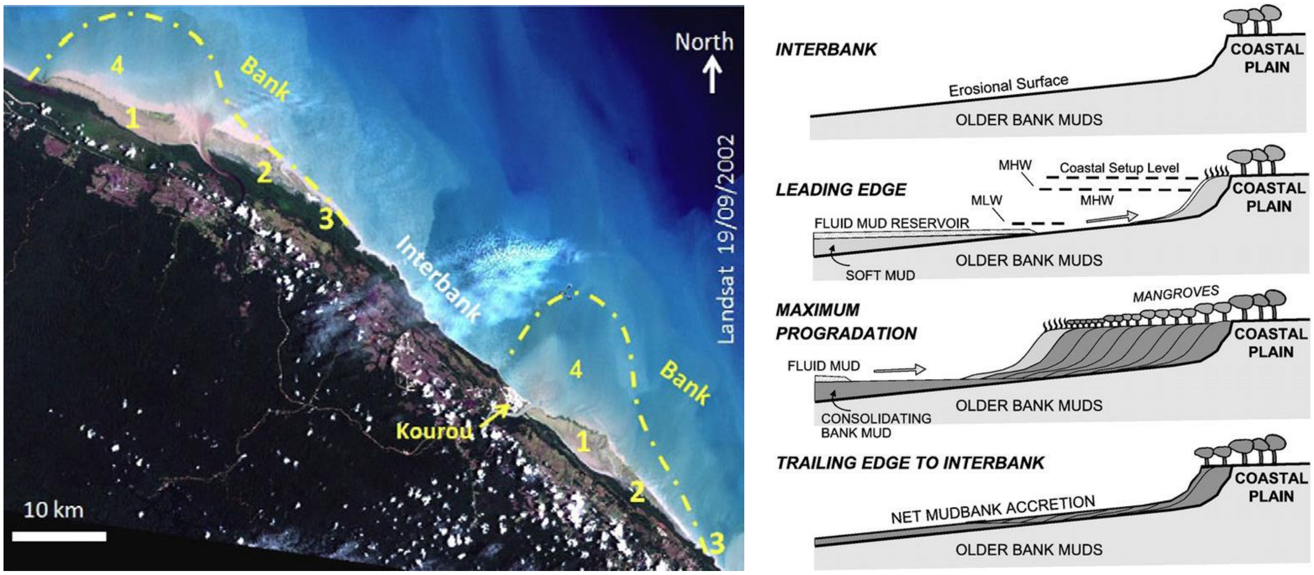
When a mudbank is moving alongshore, it protects the shoreline by dissipating wave energy (i.e., wave heights dissipate as they interact with the mudflats and wide intertidal areas) and allows mudflat accretion to occur. The degree of wave attenuation is governed by the local shoreline geomorphology and coastal hydrodynamics (e.g., mudbank cycle, wave direction, and water depth). If wave energy is dissipated before the shoreline is reached, rapid colonization of mangroves can occur to further stabilize the shoreline. In interbank areas between accreting mudbanks, the shoreline is subject to wave attack and rapid erosion until the next mudbank arrives. Mangroves at these locations, especially newly established mangroves, are at a heightened risk of erosion (Allison and Lee 2004). Figure 5 illustrates the typical movement of mudbanks westward along the NBS coastline. Figure 6 presents differences in shoreline profile at mudbank and interbank locations.

The presence of chenier ridges can also help dissipate wave energy (Anthony et al. 2019). Chenier ridges are crests comprised of sand and shell that can extend 2 to 4 m above mean sea level and generally form in areas with high wave energy (e.g., such as interbank areas) capable of transporting sediments with larger particle sizes (e.g., sand, shell deposits, or gravel). Figure 7 illustrates a chenier ridge regime in Suriname, with active chenier ridges highlighted by the number 5 (chenier ridges in the trailing edge of an interbank) and the number 6 (chenier ridge in the trailing edge of an interbank that is actively eroding). The number 7 in Figure 7 highlights an older inland chenier ridge formed during prior interbank periods, now setback from the shoreline after mudbank waves have passed.



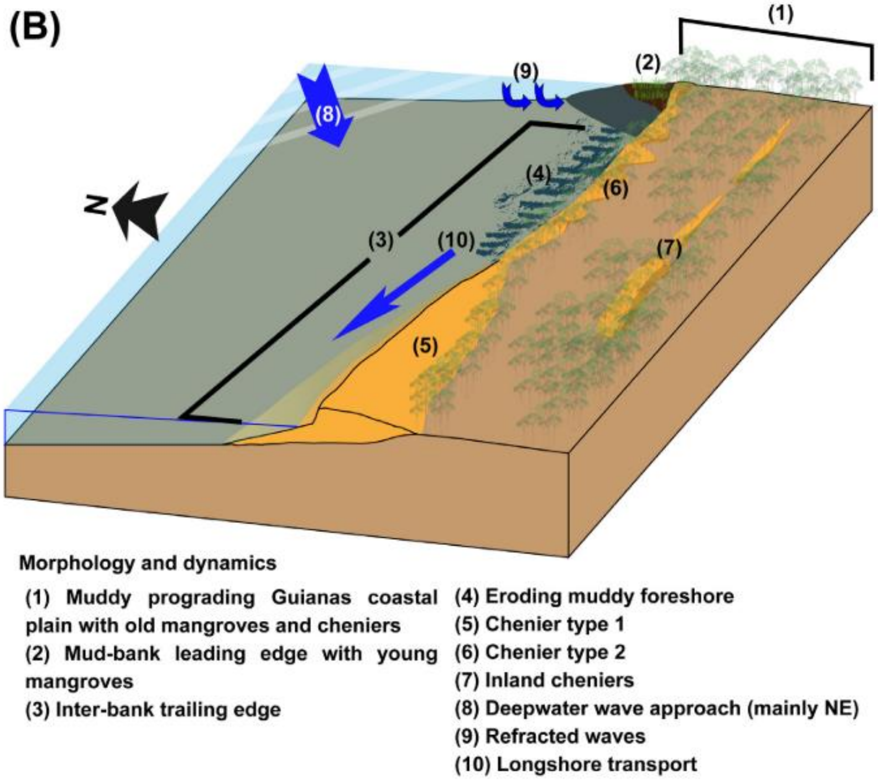
Source: Anthony 2016

Figure 5. Typical mudbank dynamics



Source: Anthony et al. 2013, Anthony et al., 2010

Figure 6. Mudbank to interbank example (left); mudbank to interbank shoreline profiles (right)



Source: Anthony et al. 2019

Figure 7. Chenier ridge regime in Suriname

7.3 Hardened Sea Defense Structures

Impacts of anthropogenic activities are evident along the Guyana coastline where approximately 250 km of the shoreline has been hardened with engineered sea defense structures (Anthony and Gratiot 2012). These structures eliminated historical mangrove populations and are preventing mangrove establishment on the incoming mudbanks by isolating mangrove propagules from disseminating seaward (Anthony and Gratiot 2012). Engineered sea defense structures such as seawalls do not provide wave dissipation. Instead, these structures can create erosion issues that result in undermining of the structure and eventual structural collapse (see Figure 8). Waves reflect off the hardened structure, promoting nearshore turbulence and erosion of the structure's foundation and the seabed in front of the structure. Increased nearshore turbulence can also inhibit sediment aggregation, increasing the risk of mudbank liquefaction and ultimately perturbing the dynamics of the mudbank and interbank system. This can lead to more persistent erosion of the interbank shoreline.

Source: Winterwerp et al. 2013 (left); USACE 2019[5] (right)

Figure 8. Failure of hardened sea defense structure in Guyana

7.4 Land Use Management

Although mangroves are salt tolerant, they are best suited for brackish water (i.e., a mixture of salty and fresh water) and require freshwater pulses periodically for optimal health and survival. Anthropogenic activities, including damming or impounding upstream drainage areas for water storage, can limit fresh water supplies in tidal creeks, impacting mangrove health. Reductions in freshwater flows can also result in saline soil conditions along the shoreline and in low-lying coastal areas, with cascading

---

[5] Accessed: https://www.reuters.com/investigates/special-report/waters-edge-the-crisis-of-rising-sea-levels/

consequences and impacts to mangrove health. Saline conditions can inhibit the mangrove growth rate and diversity, resulting in the diminished production of organic matter and its sediment binding ability. Degradation of mangrove growth, density, or coverage reduces the ability of mangroves to dissipate wave energy and provide flood risk reduction for inland coastal areas.

Subsidence also impacts the ability of mangrove ecosystems to adjust to sea level rise as it can reduce or eliminate any elevation gained through the mangrove's natural sediment trapping abilities. Subsidence occurs most commonly due to groundwater extraction, oil extraction, drainage channeling, and deforestation.

'Coastal squeeze' occurs when there is insufficient landward space to allow mangroves to migrate inland as sea levels rise. Mangrove forest migration is often constrained by inland land uses, such as developed urban areas, rural areas, agricultural lands, or aquaculture ponds. If the mangroves cannot migrate inland, the width of the mangrove forest could become smaller and smaller as sea level rise until the mangroves ultimately disappears. Preserving nearshore areas for mangrove migration can increase the overall resilience of the mangrove forest and maintain its ability to provide flood risk reduction benefits for inland development.

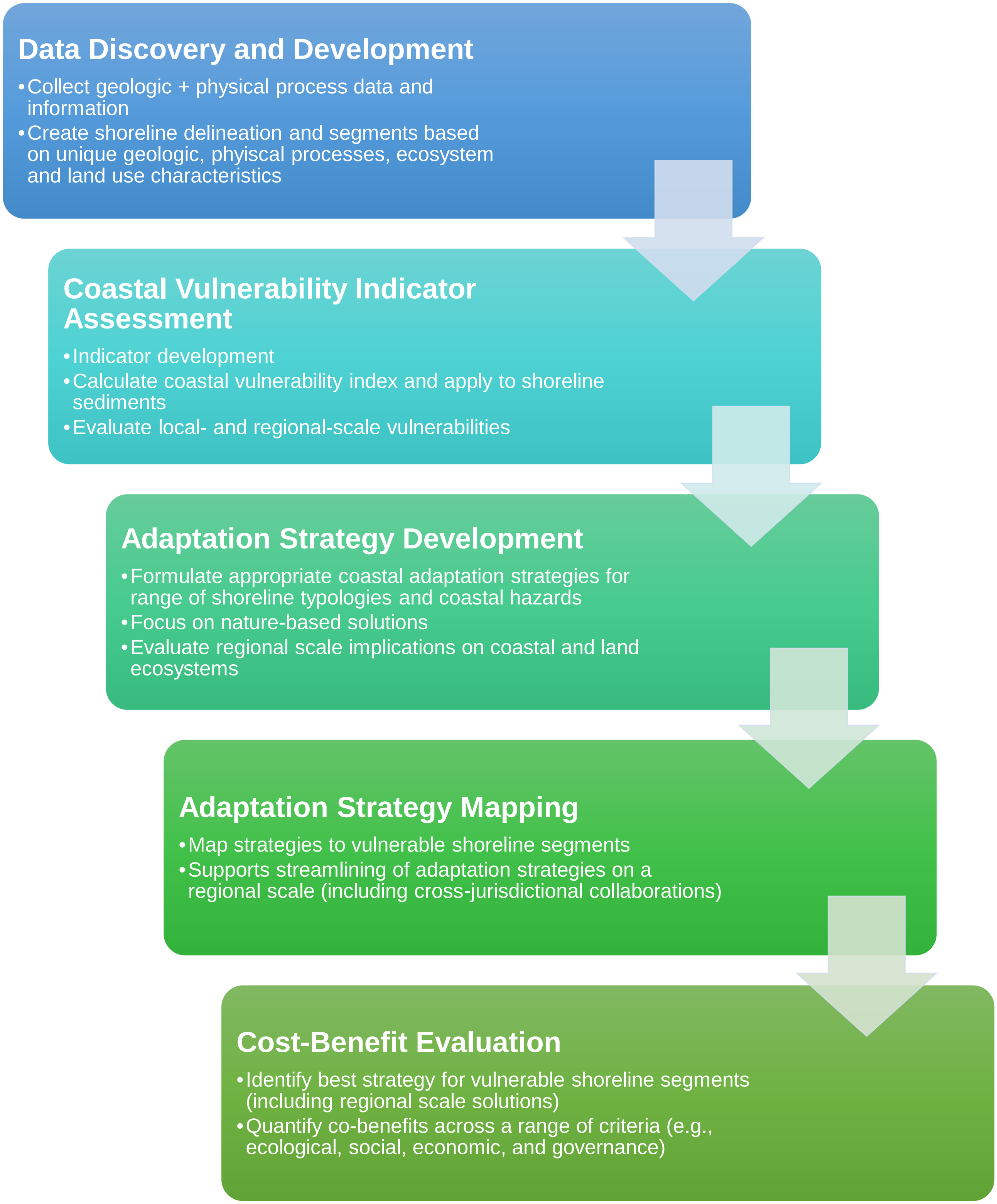
8 Tools for Assessing Flood Risk and Informing Adaptation

8.1 Key Messages

- A Coastal Vulnerability Assessment Framework (Framework) for the NBS-LME region can help support sustainable local and regional adaptation planning that transitions from reactive to proactive (e.g., adaptation in response to high erosion events versus adaptation planning prior to impacts occurring).
- The Framework, and the creation of a vulnerability index, can aid in identifying the shoreline segments most vulnerable to existing and future coastal hazards.
- A coastal vulnerability index coupled with a shoreline delineation can highlight regional vulnerabilities. This can enable collaborative adaptation strategy development across multiple jurisdictions and stakeholders.

8.2 Coastal Vulnerability and Adaptation Framework

Index-based frameworks are commonly used to assess coastal hazard vulnerability (Gornitz, V.; Beaty, T., Daniels 1997, McLaughlin et al. 2010, Balica et al. 2012, Ruh Ali 2016, Pantusa et al. 2018). They are beneficial in supporting coastal management and planning decisions across multiple geographical scales (from local to regional), and they can easily be modified to include new and more refined data as it becomes available (including monitoring data from completed adaptation projects), so that shoreline vulnerabilities can be revisited and adaptation progress can be tracked. Figure 9 presents an overview of the steps within a typical Framework.



Data Discovery and Development

- Collect geologic + physical process data and information
- Create shoreline delineation and segments based on unique geologic, phyiscal processes, ecosystem and land use characteristics

Coastal Vulnerability Indicator Assessment

- Indicator development
- Calculate coastal vulnerability index and apply to shoreline sediments
- Evaluate local- and regional-scale vulnerabilities

Adaptation Strategy Development

- Formulate appropriate coastal adaptation strategies for range of shoreline typologies and coastal hazards
- Focus on nature-based solutions
- Evaluate regional scale implications on coastal and land ecosystems

Adaptation Strategy Mapping

- Map strategies to vulnerable shoreline segments
- Supports streamlining of adaptation strategies on a regional scale (including cross-jurisdictional collaborations)

Cost-Benefit Evaluation

- Identify best strategy for vulnerable shoreline segments (including regional scale solutions)
- Quantify co-benefits across a range of criteria (e.g., ecological, social, economic, and governance)

Figure 9. Key stages in the coastal vulnerability and adaptation framework

The following sections provide additional details for the Data Development and Discovery and the Coastal Vulnerability Assessment steps shown in Figure 9.

8.3 Data Discovery and Development

Building a robust Framework requires identifying indicators that represent the relevant geologic and physical processes that drive coastal evolution and vulnerability for the region of interest (Pendleton et al. 2004, 2010). Geologic indicators may include site geomorphology, coastal land use, sedimentation rates, shoreline change rates, coastal slope, and coastal elevation. Physical process indicators include wave climate/energy (e.g., significant wave heights, wave period), tidal range, and historic and future sea level rise.

The data discovery phase involves identifying the relevant indicators of coastal vulnerability and collecting available spatially varying information to quantify each indicator’s contribution to a shoreline segment’s coastal vulnerability. For this study, data discovery was primarily done through desktop review of readily available information and data sources, including scientific literature and reports (both peer and non-peer reviewed). Data was collected on existing site conditions and coastal hazards at multiple locations along the NBS shoreline. Spatially varying datasets (e.g., wave heights at multiple locations) are necessary for differentiating vulnerabilities along the shoreline areas. When possible, datasets formatted for input into Geographic Information System (GIS) software were preferred. Online datasets provided information related to wave characteristics, administrative regions, topography, and bathymetry. Supplemental information was provided by Conservation International and their local partners (e.g., National Agricultural Research & Extension Institute).

Table 3 presents the data sources used to define the relevant indicators, grouped by theme (e.g., site morphology, wave climate, land use). Remaining data gaps are presented in Section 11.

Table 3. Data sources for Coastal Vulnerability Framework

Topic	Theme	Indicator	Description	Data Source
Geologic	Site Morphology	Coastal Elevation	Low-lying shorelines (relative to tide elevations) are most vulnerable to flooding and sea level rise	NASA Shuttle Radar Topography Mission (SRTM) Version 3.0 Global 1 arc second (~30 meters) topographic digital elevation model. Origin date: February 2000. Accessed: https://earthexplorer.usgs.gov
		Coastal Slope	Represents vulnerability to flooding and potential	Not Available
		Shoreline Change Rate	Supports understanding of shoreline erosion or accretion	Not Available
		Shoreline Geomorphology	Different shoreline types have varying degrees of susceptibility to erosion or ability to accrete with sea level rise.	Defined using aerial imagery layer and supporting information from Ruh Ali (2016) and Environmental Services Limited (2018).
		Wave Exposure	Represents available floodplain and potential features that can provide storm dissipation	Defined using aerial imagery layer and supporting information from Ruh Ali (2016) and Environmental Services Limited (2018).
		Beach Width	Abundance or limitation of sediment supply to promote progradation or maintain stability of shoreline	Not Available
Physical	Sediment Dynamics	Sediment Supply	The average wave height of the highest third of wave heights within a wave spectra and period. High significant wave heights contribute to coastal erosion.	Not Available

Topic	Theme	Indicator	Description	Data Source
Physical	Wave Climate / Wave Energy[1]	Significant Wave Height	Directionality of incoming waves shapes the shoreline thorough erosion, and can move sediment in the same direction	DHI MIKE21 Spectral Wave Model accessed at DHI Metocean Data Portal (https://www.metocean-on-demand.com/#/main). Additional wave climate information from (World Bank Group 2017, Cete. C., Haage, S.; Hardwarsing, V., Kalloe, S.; Ma-ajong 2018)
		Wave Direction	Longer wave periods (e.g., swell waves) are typically associated with more powerful wave energy than shorter wave periods (wind waves)	DHI MIKE21 Spectral Wave Model accessed at DHI Metocean Data Portal (https://www.metocean-on-demand.com/#/main). Additional wave climate information from (World Bank Group 2017, Cete. C., Haage, S.; Hardwarsing, V., Kalloe, S.; Ma-ajong 2018)
		Wave Period	Indicates potential scale of shoreline width influenced by daily inundation (and or/waves). Shorelines with large tide ranges have tidal currents that contribute to erosion and sediment transport. Tidal range also dictates suitable habitat type for nature-based solutions.	DHI MIKE21 Spectral Wave Model accessed at DHI Metocean Data Portal (https://www.metocean-on-demand.com/#/main). Additional wave climate information from (World Bank Group 2017, Cete. C., Haage, S.; Hardwarsing, V., Kalloe, S.; Ma-ajong 2018)
	Tidal Range	Tidal Range	Magnitude of storm surge supports evaluation of high-water level events. The 25-year storm surge magnitude was selected since it typically exceeds the design standard for existing nature-based projects in the NBS-LME region.	(Prevedel 1997, United States Army Corps of Engineers 1998, Ruh Ali 2016, Anthony et al. 2019)

Topic	Theme	Indicator	Description	Data Source
Physical	Storm Surge	25-Year Storm Surge	Mangroves can build vertically with sea level rise, given the right sediment supply, but only up to a certain rate of sea level rise.	Ranges adapted from Burke and Ding (2016). Local estimates not available.
	Sea Level Change	Historical Sea Level Rise	Higher amounts of sea level rise can outpace vegetation growth. High rates of sea level rise will also lessen the protection of existing sea defense infrastructure, requiring adaptation sooner.	Guyana Regions 2, 3, and 4 (Ruh Ali 2016)
		Future Sea Level Rise	Reflects type of development behind the shoreline. Engineered shorelines with development confine the space where adaptation solutions can be implemented.	Strauss and Kulp 2018
Land Use	Land Use	Coastal Typology	Some shoreline areas already have existing armoring (e.g., seawall, revetments, bulkheads), which, if in good condition, reduce vulnerability to storms.	Not Available
		Land Use/Land Cover Connectivity	Identifies potential ease of implementing adaptation strategies behind a shoreline segment based on size of suitable land use/land cover available and the shared boundary length when sub-areas are connected.	Not Available.
		Population	Population living behind shoreline region	Not Available
	Land Use	Per Capita GDP	Measure of potential financial impact from coastal hazard exposure. Total per capita	Not Available

Topic	Theme	Indicator	Description	Data Source
Land Use			GPD within hydrologically connected area behind shoreline segment.	
		Critical Facilities	Critical facilities (e.g., hospitals, schools, fire departments, police stations) impacted from coastal hazard exposure.	Not Available
		Infrastructure Cost	Cost of critical infrastructure and critical facilities (e.g., roads, hospitals, treatment plants). Provides understanding of potential consequence to climate impacts.	Not Available
		Presence of Engineered Shoreline	The vegetation buffer available behind the shoreline edge provides attenuation in storm surge and wave heights; greater vegetation width provides greater storm attenuation.	Not Available
		Vegetation Width	Available natural buffer to provide storm attenuation and erosion protection.	Not Available

Notes: [1] Wave climate/energy in this study is characterized by statistics of wave height and wave period. High wave heights with long periods are associated with high wave energy with likely potential damage coastal structures.

A geospatial shoreline delineation is an important part of the Data Development and Discovery phase. It supports both the classification of the shoreline into the various shoreline typologies, as well as visualizations of the Framework results. A contiguous shoreline delineation was digitized for the Guyana and Suriname coastlines using ESRI's ArcMap software, primarily using ERSI's World Imagery aerial imagery reference and topographic/bathymetry data to trace the transition between open water and landward topography where there is a distinct change in shoreline slope. The shoreline delineation was completed at a geographical scale of 1:20,000 meters.

The shoreline was sub-divided into individual segments of approximately 10 kilometers in length[6]. The Guyana shoreline was divided into 32 individual segments, presented in Figure 10. The Suriname shoreline was divided into 45 individual segments, presented in Figure 11. Each shoreline segment is assigned a unique name (e.g., S_R3_4), comprised of a country identifier (e.g., S for Suriname), region number (e.g., R3 for Region 3), and segment number (e.g., 4). The names of all individual shoreline segments are available in Attachment A and B respectively.

The shoreline segments were delineated without using political boundaries to designate breaks between segments. Coastal hazards occur with disregard to political boundaries, and ultimately adaptation strategies may need to be cross-jurisdictional. The current segmentation of the shoreline supports identification of potential cross-jurisdictional vulnerabilities.

---

[6] Region 2 – 4 in Guyana was divided into segments of approximately 5 kilometers, following the existing shoreline delineation by Ayat (2016).

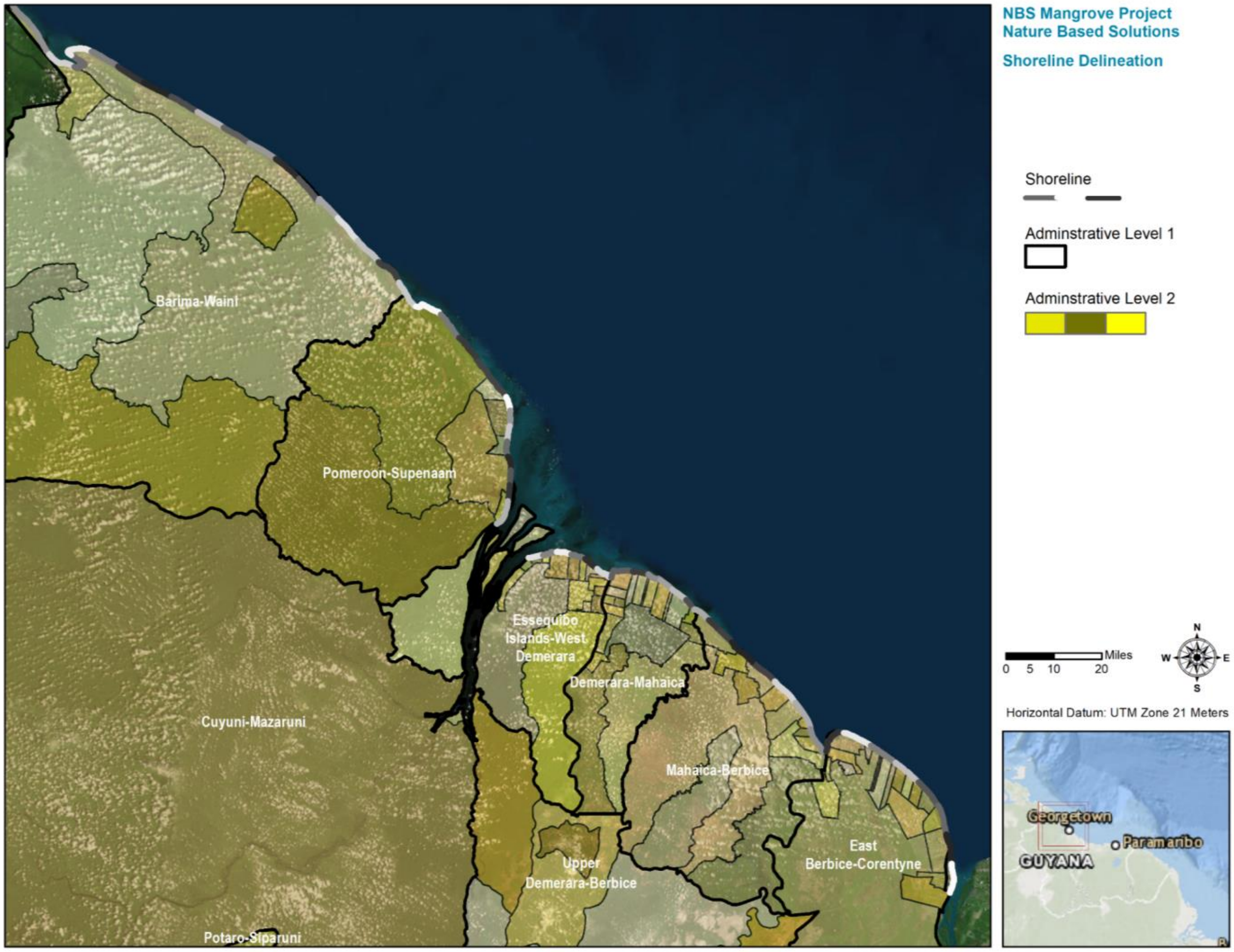


Figure 10. Shoreline delineation for Guyana

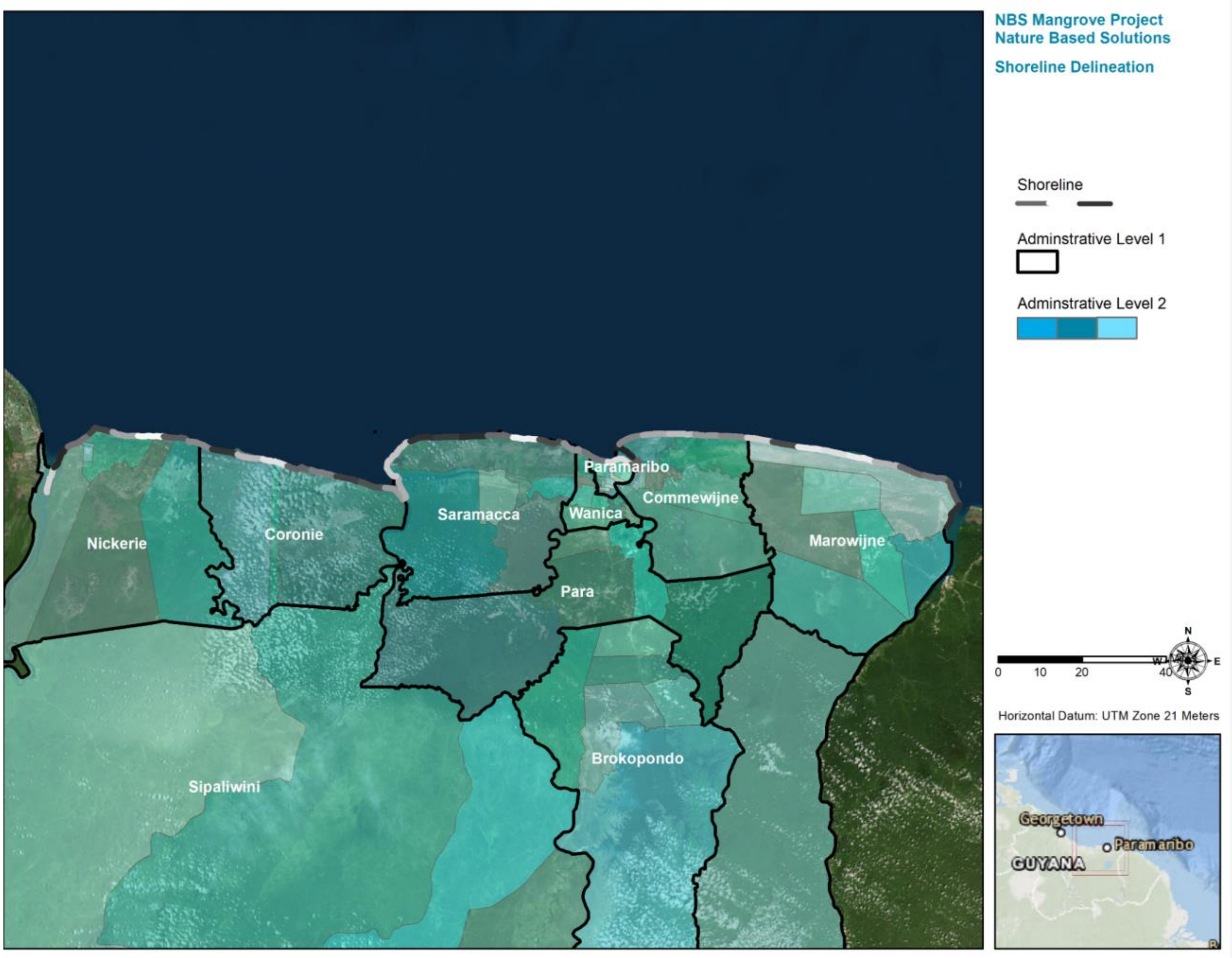


Figure 11. Shoreline delineation for Suriname

8.4 Evaluating Vulnerability to Climate Change

8.4.1 Vulnerability

Climate vulnerability measures the degree to which a community is susceptible to, and unable to cope with, the adverse effects of climate change, including climate variability and extremes (IPCC 2007). It is expressed as a function of the sensitivity, exposure, and adaptive capacity of the ecosystems and human communities therein. The three principal components of vulnerability are:

- *Exposure* - nature and degree to which a system and/or a hazard may physically interact with an asset. An indicator of exposure in the NBS-LME region includes the wave heights reaching the shoreline during storm events (e.g., higher wave heights are an indicator of higher exposure).
- *Sensitivity* - the degree to which a system is affected, either adversely or beneficially, by a hazard. This can include a human/social dimension. An indicator of sensitivity in the NBS-LME

region is the shoreline geomorphology (e.g., coastlines with beaches are sensitive to wave attack).

- *Adaptative Capacity* **–** the inherent ability of a system to adjust to an impact without the need for significant intervention or modification, and/or the existing flexibility or redundancy within a system that allows for continued functionality when a system is under stress. An indicator of adaptive capacity in the NBS-LME region is the sediment supply (e.g., shoreline areas with low sediment supply have less adaptive capacity to recover from wave induced erosion).

Evaluating a system under the three principle components of vulnerability helps identify the most vulnerable aspects of a system so that adaptation strategies can be planned to mitigate or reduce the impacts associated with climate change. Strategies generally either reduce exposure and/or sensitivity to climate hazards or they support adaptive capacity building against future hazards. The evaluation of coastal vulnerability across the NBS-LME region relies on a catalog of individual coastal vulnerability indicators under each of the three components of vulnerability, presented in Section 8.4.3.

8.4.2 Risk

Climate hazards impacting the NBS shoreline can result in a range of consequences, from direct impacts to infrastructure and facilities, to indirect effects on mobility and society. In practice, a qualitative risk assessment is often defined as Risk = Consequence × Likelihood. Consequence is defined as the magnitude or level of impact (e.g., costs associated with flood damage or total population affected), and likelihood is the probability of the specific consequence occurring. The higher the probability of a “worse” effect occurring, the greater the level of risk. In a climate change risk assessment, consequences can be defined and quantified for a given climate impact or hazard by selecting risk metrics that define, measure, and quantify anticipated consequences. However, defining the likelihood of a specific climate change impact occurring is more challenging. The risk equation (i.e., Risk = Consequence × Likelihood) is often applied relative to specific events, or shocks, that could occur, such as an earthquake or the structural failure of a bridge or building. Climate change and sea level rise are not “shocks,” but rather slow, chronic stressors that progress over time.

The Risk framework considers the potential timing and scale of the consequence. Timing provides a measure of urgency of the potential risk (i.e., how soon could the consequence occur?), while the scale of the consequence provides a measure of how large that risk is geographically within a community (e.g., how many people, or how many businesses, could be affected?). The combination of urgency and scale can provide context for project prioritization and adaptation decisions.

- *Consequence* **-** The result or effect of the climate change impacts on society, equity, the economy, and the built and natural environment. Consequences can be quantitative or qualitative. To define, measure, and quantify risk (i.e., consequence), both physical impacts to landward infrastructure as well as the potential societal impacts to the greater community are evaluated. Physical impacts can include functional or operational impacts to the community or region due to physical damage or a reduction in service. Societal impacts, such as social disruption, can be measured as the number of residents and businesses potentially impacted, and the number of critical facilities (e.g., hospitals, schools, emergency service facilities) within the impacted area.
- *Likelihood* **-** The qualitative risk equation is often applied relative to specific events, or shocks, that could occur, such as a 1-percent annual chance (i.e., 100-year) coastal flood event. In this

instance, the likelihood of the event occurring is 1-percent in any given year. However, with climate related impacts such as SLR, the hazard is a slow, chronic progression of increasing water levels that will worsen over time coupled with intermittent shocks (e.g., precipitation-driven flood events, coastal flood events). Additionally, the chronic hazards (e.g., SLR) will increase the frequency and severity of potential shocks (e.g., coastal flood event), and may also worsen other hazards (e.g., rising groundwater levels). The future frequency and probability of occurrence of the climate hazards is challenging to quantify in a non-stationary climate, and the challenges are compounded when secondary climate hazards are also considered. For this reason, this assessment considers consequence as the primary approach to evaluate Risk.

8.4.3 Coastal Vulnerability and Consequence Assessment

Table 4 presents a summary of the relevant coastal indicators for the NBS-LME region. The indicators are grouped under the three principle components of vulnerability (exposure, sensitivity, and adaptive capacity) and the one principle component of risk (consequence). Each principle component of vulnerability and risk is comprised of several indicators. Each indicator can be assigned a numerical score (and equivalent rating) that sums to represent the overall vulnerability or consequence of an individual shoreline segment to coastal hazards.

Table 5 presents the value ranges for 21 individual indicators, based on the ratings of *very low* (score =0), *low* (score = 1), *moderate* (score = 2), *high* (score = 3), and *very high* (score = 4). The ranges are reflective of prior studies (Pendleton et al. 2004, 2010, Ruh Ali 2016, Conger 2018, Pantusa et al. 2018, Serio et al. 2018) and adapted for local conditions using best professional judgment. By assigning a score (and rating) to each indicator, the relative contribution of each indicator to the vulnerability and risk components, and the overall coastal vulnerability or consequence, of each shoreline segment can be evaluated (see Table 6). This information also supports the roll up of these indicators into on overall vulnerability score (and equivalent rating) and similarly an overall risk score (and equivalent rating) by aggregating the scores using the key in Table 7.

Ultimately, a composite Coastal Vulnerability-Consequence Index (CV-CI) can be assigned to each shoreline segment using the matrix shown in Table 8. The purpose of the CV-CI is to provides a high-level overview of where there is a high need for adaptation solutions to reduce or mitigate coastal hazards. If there are several adjacent shoreline segments with a similar CV-CI score (and similar vulnerabilities and consequence indicator scores), then it is possible that a broader scale adaptation intervention may be required.

The Framework can also be used to explore potential adaptation solutions for a specific segment or combination of segments that may be targeted to address exposure, sensitivity, or adaptive capacity. This will allow adaptation solutions to be evaluated to ensure that the solutions are addressing the correct underlying vulnerabilities.

To summarize, within this Framework, four levels of quantitative assessments can be compared across the entire NBS shoreline, helping to identify the most vulnerable segments of shoreline and the associated impacts:

1. Indicator scores/ratings (e.g., wave exposure or shoreline elevation) – see Table 5.
    - Ratings for individual indicators are assigned across a range of quantitative values (using literature references and professional judgement) at a resolution that can differentiate between shoreline segments. Ratings range from very low (scope = 0) to very high (score = 4). If an exposure indicator is rated as very high, this indicator likely plays an important role in the overall vulnerability score. The availability of individual indicator ratings at this level of detail provides the ability to evaluate how individual indicators contribute to exposure, sensitivity, adaptative capacity, and/or consequence to coastal hazards.
2. Exposure, sensitivity, adaptative capacity, and consequence scores/ratings (sum of individual indicators) – see Table 6.
    - Exposure, sensitivity, adaptative capacity, and consequence ratings are the sum of the individual indicator scores for each respective component. For example, a shoreline segment's exposure rating is based on the aggregate of the individual indicators under exposure (e.g., significant wave height, tidal range, future sea level rise, etc.). The summed score then defines an overall rating for exposure. Each shoreline segment will have a unique combination of individual indicator ratings that sum to the respective overall ratings for exposure, sensitivity, adaptive capacity, and consequence.
3. Vulnerability (sum of exposure, sensitivity, and adaptative capacity) and risk (consequence) scores/ratings – see Table 7.
    - The vulnerability and risk scores and ratings are the aggregate of exposure, sensitivity, adaptative capacity, and consequence scores and ratings. This provides a simplified snapshot of the shoreline segments that are the most vulnerable or have the highest consequence if exposed to coastal hazards.

Coastal Vulnerability-Consequence Index (integration of vulnerability and consequence ratings) – see Table 6. Exposure, sensitivity, adaptative capacity, and consequence scoring

Indicator Rating	Very Low	Low	Moderate	High	Very High
Vulnerability					
Exposure	0-2	2-6	7-11	12-15	16-20
Sensitivity	0-5	6-11	12-19	20-26	27-32
Adaptative Capacity	0-3	4-7	8-10	11-13	14-16
Risk					
Consequence	0-3	4-7	8-10	11-13	14-16

Table 7. Overall vulnerability (sum of exposure, sensitivity, and adaptative capacity) and risk (consequence) scoring

Overall Vulnerability Score	Overall Risk (Consequence) Score	Vulnerability / Consequence Rating
0 – 12	0 - 1	Very Low
15 - 27	2 - 5	Low
28 – 42	6 - 10	Moderate
43 – 56	11 - 14	High
57 - 68	14 - 16	Very High

4. Table 8.
    - The CV-CI combines the vulnerability and risk ratings into a single index to provide a high-level overview of the shoreline segments that have the highest adaptation need.

Typically, weightings are not used to adjust the degree of influence or importance of the individual indicators. Assigning weightings generally requires input from stakeholders and project partners to assess various weighting schemes and their effect on the overall results. Weightings should not be applied until the Framework results have been fully evaluated and the importance of each indicator on the overall results considered.

Figure 12 summarizes the process for assigning scores/ratings to identify the CV-CI for each shoreline segment.

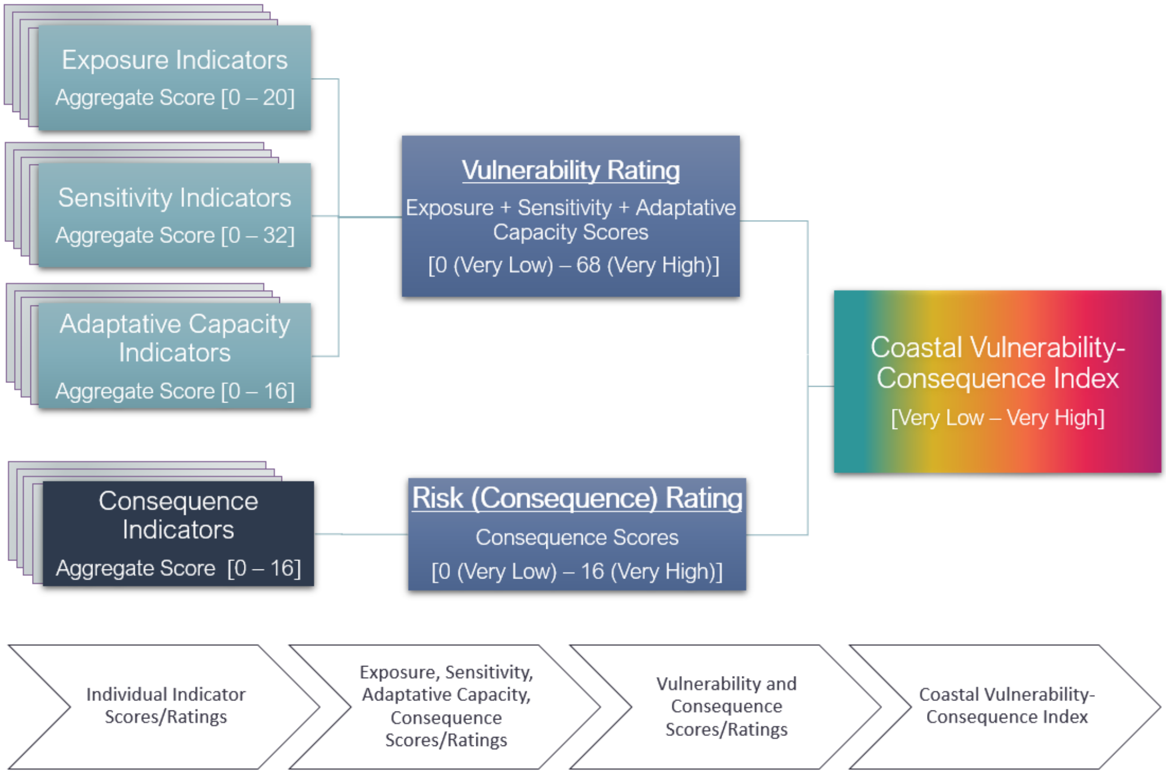


Figure 12. Defining Coastal Vulnerability-Consequence Index

Attachment A presents the supporting information for the Framework for Guyana, populated with all available data collected to date. Attachment B presents similar information for Suriname. Data gaps are denoted in both Attachments.

Table 4. Factors for coastal vulnerability and consequence assessment (factor listed in decreasing order of importance)

VULNERABILITY

	Theme	Indicator	Description
Exposure	Wave Climate/Energy	Significant Wave Height (m)	The average wave height of the highest third of wave heights within a wave spectra and period. High significant wave heights contribute to coastal erosion.
	Storm Surge/Overtopping	25-year Storm Surge Depth (m) above Coastal Elevation	Magnitude of storm surge supports evaluation of high-water level events. The 25-year storm surge magnitude was selected since it typically exceeds the design standard for existing nature-based projects in the NBS-LME region.
	Tidal Range	Tidal Range (m)	Indicates potential scale of shoreline width influenced by daily inundation (and or/waves). Shorelines with large tide ranges have tidal currents that contribute to erosion and sediment transport. Tidal range also dictates suitable habitat type for nature-based solutions.
	Sea Level Change	Future Sea Level Rise (mm/year)	Higher amounts of sea level rise can outpace vegetation growth. High rates of sea level rise will also lessen the protection of existing sea defense infrastructure, requiring adaptation sooner.
	Sea Level Change	Historical Sea Level Rise (mm/year)	Mangroves can build vertically with sea level rise, given the right sediment supply, but only up to a certain rate of sea level rise.

	Theme	Indicator	Description
Sensitivity	Site Morphology	Wave Exposure	Represents available floodplain and potential features that can provide storm dissipation
	Site Morphology	Shoreline Geomorphology	Different shoreline types have varying degrees of susceptibility to erosion or ability to accrete with sea level rise.
	Site Morphology	Coastal Elevation (m) – above mean sea level	Low-lying shorelines (relative to tide elevations) are most vulnerable to flooding and sea level rise
	Site Morphology	Vegetation Width (m)	Available natural buffer to provide storm attenuation and erosion protection.
	Site Morphology	Shoreline Change Rate (m/year)	Supports understanding of shoreline erosion or accretion
	Land Use	Presence of Engineered Shoreline	The vegetation buffer available behind the shoreline edge provides attenuation in storm surge and wave heights; greater vegetation width provides greater storm attenuation.
	Site Morphology	Coastal Slope (%)	Represents vulnerability to flooding and potential rate of shoreline retreat.
	Site Morphology	Beach Width (m)	Abundance or limitation of sediment supply to promote progradation or maintain stability of shoreline

	Theme	Indicator	Description
Adaptative Capacity	Land Use	Coastal Typology	Shoreline Adjacent or Setback (Mixed Urban, Aquaculture/Agriculture, Sparse Residential, No Development)
	Sediment Dynamics	Sediment Supply	Abundance or limitation of sediment supply to promote progradation or maintain stability of shoreline
	Land Use	Land Use/Land Cover Connectivity (Ratio of boundary shared)	Identifies potential ease of implementing adaptation strategies behind a shoreline segment based on size of suitable land use/land cover available and the shared boundary length when sub-areas are connected. Quantified as the ratio of shared boundary length to total area available with suitable land use/land cover. A high shared boundary to area ratio occurs when a smaller total area is available with potential complex connections between sub-areas.

RISK

	Theme	Indicator	Description
Consequence	Land Use	Population (Percentile of country total)	Measure of potential population impacted from coastal hazard exposure. Measured within hydrologically connected areas behind shoreline segment.
	Land Use	Per capita Gross Domestic Product (GDP) (Percentile of country total)	Measure of potential financial impact from to coastal hazard exposure. Measured within hydrologically connected areas behind shoreline segment.
	Land Use	Critical Facilities (Percentile of country total)	Critical facilities (e.g., hospitals, schools, fire departments, police stations) within coastal hazard exposure zone. Measured within hydrologically connected areas behind shoreline segment.
	Land Use	Infrastructure - Repair/Replacement Cost (Percentile of country total)	Cost of critical infrastructure and critical facilities (e.g., roads, hospitals, treatment plants) within hydrologic areas behind shoreline segment.

Table 5. Quantification of factors contributing to coastal vulnerability in the NBS-LME region

VULNERABILITY

	Theme	Indicator	Description	Rating Scale	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)
Exposure	Wave Climate/Energy	Significant Wave Height (m)	The average wave height of the highest third of wave heights within a wave spectra and period. High significant wave heights contribute to coastal erosion.	Higher wave heights result in higher chronic erosion and/or episodic erosive events or damage to shoreline structures.	0.0 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	>2.0
	Storm Surge/Overtopping	25-year Storm Surge Depth (m) above Coastal Elevation	Magnitude of storm surge supports evaluation of high-water level events. The 25-year storm surge magnitude was selected since it typically exceeds the design standard for existing nature-based projects in the NBS-LME region.	Higher overtopping depths result in potentially higher landward extent of flooding.	0	0 - 0.25	0.25 – 1.0	1.0 - 2.0	>2.0
	Tidal Range	Tidal Range (m)	Indicates potential scale of shoreline width influenced by daily inundation (and or/waves). Tidal range also dictates suitable habitat type for nature-based solutions.	Shorelines with large tide ranges have tidal currents that contribute to erosion and sediment transport.	>3.25	2.5 - 3.25	1.75 - 2.5	1.0 - 1.75	<1.0
	Sea Level Change	Future Sea Level Rise (mm/year)	Higher amounts of sea level rise can outpace vegetation growth. High rates of sea level rise will also lessen the protection of existing sea defense infrastructure, requiring adaptation sooner.	Higher local rates of sea level rise due to local land subsidence, changes in freshwater inputs, or regional ocean currents will result in earlier and/or more frequent future flooding.	<2.0	2.0 - 2.5	2.5 - 3.0	3.0 - 3.5	>3.5
	Sea Level Change	Historical Sea Level Rise (mm/year)	Mangroves can build vertically with sea level rise, given the right sediment supply, but only up to a certain rate of sea level rise.	Higher local rates of sea level rise due to local land subsidence, changes in freshwater inputs, or regional ocean currents indicate areas that may be exposed to flooding earlier and/or more frequently in the future.	<2.0	2.0 - 2.5	2.5 - 3.0	3.0 - 3.5	>3.5

	Theme	Indicator	Description	Rating Scale	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)
Sensitivity	Site Morphology	Wave Exposure	Represents available floodplain and potential features that can provide storm dissipation	Exposed shorelines are most susceptible to wave damage.	Very protected	Protected	Semi Protected	Semi Exposed	Exposed
	Site Morphology	Shoreline Geomorphology	Different shoreline types have varying degrees of susceptibility to erosion or ability to accrete with sea level rise.	Soft vegetated shorelines are typically more sensitive (e.g., most susceptible to damage) to coastal hazards, while rocky/cliff coasts have minimal response.	Rocky/Cliff coasts	Medium cliffs, indented coasts	Sand, Pebbles, Boulders	Cobble & Sandy Beaches	Mudflats, Mangroves
	Site Morphology	Coastal Elevation (m) – above mean sea level	Measure of average elevation of shoreline.	Low-lying shorelines (relative to tide elevations) are generally the most sensitive to flooding and sea level rise because they are pathways for water to reach inland areas.	>12.0	9.0 - 12.0	6.0 - 9.0	3.0 - 6.0	<3.0
	Site Morphology	Vegetation Width (m)	The vegetation buffer available behind the shoreline edge provides attenuation in storm surge and wave heights; also provides erosion protection.	A greater vegetation buffer at the shoreline reduces shoreline sensitivity to coastal hazards by providing storm attenuation and erosion protection during storm events.	>1000	500 - 1000	100 - 500	50 - 100	>50
	Site Morphology	Shoreline Change Rate (m/year)	Supports understanding of shoreline erosion or accretion	Negative rates of shoreline change (retreating shoreline) indicate a high rate of erosion and these areas are more susceptible to impacts during large storm events.	>2.0	1.0 - 2.0	(-) 1.0 - 1.0	(-) 2.0 - (-) 1.0	< (-) 2.0
	Land Use/Land Cover	Presence of Engineered Shoreline	The presence of a hardened shoreline can provide protection from coastal hazards, however the current condition (e.g., new or poor condition) is a large factor in its effectiveness.	The presence of a hardened shoreline reduces shoreline sensitivity to coastal hazards, however only if it's in fair to good condition.	Yes (in good condition)	-	Yes (in fair condition)	-	Yes (in poor condition); No Protection
	Site Morphology	Coastal Slope (%)	Represents vulnerability to flooding and potential	A high coastal slope reduces the impact of sea level rise, while a shallow slope allows for potentially widespread landward flooding during storm events.	>1.5	1.0 - 1.5	0.5 - 1.0	0.5 - 0.3	<0.3
	Site Morphology	Beach Width (m)	Measure of beach width	Larger beach buffer reduces sensitivity to coastal hazards.	>100	50 - 100	25 - 50	43763	<10

	Theme	Indicator	Description	Rating Scale	Very High (0)	High (1)	Moderate (2)	Low (3)	Very Low (4)
Adaptative Capacity	Land Use/Land Cover	Coastal Typology	Shoreline Adjacent or Setback (Mixed Urban, Aquaculture/Agriculture, Sparse Residential, No Development)	Land uses with higher density of infrastructure (buildings, roads, structures) that are adjacent to the shoreline have low adaptive capacity (high vulnerability) to adjust while exposed to coastal hazards or recover from impacts. Commercial/residential development and mobility routes have little redundancy (high adaptive capacity).	Shore Adjacent - Mixed Urban	Setback - Mixed Urban; Shore Adjacent - Aquaculture/ Agriculture	Shore Adjacent - Sparse Residential; Setback - Aquaculture/Agriculture	-	No Development

Adaptative Capacity	Land Use/Land Cover	Presence of Engineered Shoreline	The presence of a hardened shoreline can provide protection from coastal hazards, however the current condition (e.g., new or poor condition) is a large factor ability to adapt to larger storm event	Hardened shorelines have little adaptive capacity (high vulnerability) to adjust to increasing coastal hazards. Hardened shorelines in poor condition have the least adaptive capacity (highest vulnerability). Natural shorelines generally have greater adaptive capacity to respond to coastal hazards.	Yes (in poor condition)	-	Yes (in fair condition); No Protection (natural)	-	Yes (in good condition)
	Sediment Dynamics	Sediment Supply	Abundance or limitation of sediment supply to promote progradation or maintain stability of shoreline	A retreating coast in a coastal regime with lower sediment supply has less adaptative capacity (high vulnerability) to adapt after impacts from coastal hazards.	Retreating Coast	-	Stable Coast	-	Prograding Coast
	Land Use/Land Cover	Land Use/Land Cover Connectivity (Ratio of shared boundary to area)	Identifies potential ease of implementing adaptation strategies behind a shoreline segment based on size of suitable land use/land cover available and the shared boundary length when sub-areas are connected. Quantified as the ratio of shared boundary length to total area available with suitable land use/land cover. A high shared boundary to area ratio occurs when a smaller total area is available with potential complex connections between sub-areas.	A lower ratio of shared boundary to area can indicate that a larger aggregate of suitable land is available with less obstacles (e.g., separation by high ground) between sub-areas, meaning higher adaptation potential (lower vulnerability). Small aggregates of suitable land use/land cover have greater obstacles for adaptation, meaning low adaptation potential (higher vulnerability). A lower shared perimeter to total area ratio is the most desirable and representative of a less complexity in the geographical features of available sub-areas.	<0.2	0.2 – 0.4	0.4 – 0.6	0.6 – 0.8	>0.8

RISK

	Theme	Indicator	Description	Rating Scale	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)
Consequence	Land Use/Land Cover	Population (Percentile in country total)	Measure of potential population impacted from coastal hazard exposure. Total population within hydrologically connected area behind shoreline segment, as percentile within total population in overall 25-year storm exposure zone.	A higher percentile of population within an exposure zone has higher consequence.	<1%	1 - 5%	5 - 10 %	10 - 15%	15 - 20 %
	Land Use/Land Cover	Per capita Gross Domestic Product (GDP) (Percentile in country total)	Measure of potential financial impact from coastal hazard exposure. Total per capita GPD within hydrologically connected area behind shoreline segment, as percentile within total population in overall 25-year storm exposure zone.	An exposed area with higher per capita GDP compared to other exposed areas results in higher consequence to communities.	<1%	1 - 5%	5 - 10 %	10 - 15%	15 - 20 %
	Land Use/Land Cover	Critical Facilities (Percentile in country total)	Critical facilities (e.g., hospitals, schools, fire departments, police stations) impacted from coastal hazard exposure. Measured within hydrologically connected areas behind shoreline segment.	Higher number of critical facilities exposed to coastal hazards results in higher consequence to communities.	<1%	1 - 5%	5 - 10 %	10 - 15%	15 - 20 %

Consequence	Land Use/Land Cover	Infrastructure - Repair/Replacement Cost (Percentile in country total)	Cost of repair/replacement of critical infrastructures (e.g., roads, hospitals, treatment plants) due to impact from coastal hazard exposure. Cost of repair/replacement within hydrologically connected area behind shoreline segment, as percentile within total cost of repair/replacement of infrastructure in overall 25-year storm exposure zone.	Higher cost of repair/replacement of infrastructure exposed to coastal hazards results in higher consequence to communities.	<1%	1 - 5%	5 - 10 %	10 - 15%	15 - 20 %

Table 6. Exposure, sensitivity, adaptative capacity, and consequence scoring

Indicator Rating	Very Low	Low	Moderate	High	Very High
Vulnerability					
Exposure	0-2	2-6	7-11	12-15	16-20
Sensitivity	0-5	6-11	12-19	20-26	27-32
Adaptative Capacity	0-3	4-7	8-10	11-13	14-16
Risk					
Consequence	0-3	4-7	8-10	11-13	14-16

Table 7. Overall vulnerability (sum of exposure, sensitivity, and adaptative capacity) and risk (consequence) scoring

Overall Vulnerability Score	Overall Risk (Consequence) Score	Vulnerability / Consequence Rating
0 – 12	0 - 1	Very Low
15 - 27	2 - 5	Low
28 – 42	6 - 10	Moderate
43 – 56	11 - 14	High
57 - 68	14 - 16	Very High

Table 8. Coastal Vulnerability-Consequence Index Matrix

		Consequence Rating				
		Very Low	Low	Moderate	High	Very High
Vulnerability Rating	Very Low	Very Low	Low	Moderate	High	High
	Low	Low	Low	Moderate	High	High
	Moderate	Low	Moderate	Moderate	High	High
	High	Low	Moderate	High	High	Very High
	Very High	Low	Moderate	High	Very High	Very High

A CV-CI index of very low indicates that a shoreline segment is resilient to coastal hazards. Either there is very low vulnerability due to low exposure, sensitivity, or adaptative capacity to coastal hazards, or there is little consequence if exposed and therefore no action is needed at this time. High vulnerability could be associated with high wave energy, low shoreline elevation, and little to no mangrove buffer. Low consequence indicates sparse population with minimal infrastructure or infrastructure value. As the CV-VI increases to very high, the need for adaptation intervention increases. The CV-CI for each shoreline segment reflects the combined assessment of the 21 different indicators, and the individual indicators can be explored to better understand the CV-CI ratings and to inform potential adaptation solutions that can either reduce the vulnerabilities or reduce the potential consequences.

8.5 Framework Application in Guyana

Due to existing data gaps, the coastal vulnerability and consequence assessment could not be applied across the entire shoreline delineation in Guyana. However, a shoreline segment is used to highlight the utility of the Framework. Figure 13 shows the location of the example shoreline segment (G_R4_3) spanning approximately 5 km along the Guyana coastline. This area includes portions of the Lusignan, North Mon Repos, and Buxton villages in Demerara-Mahaica (Region 4) and is characterized by dense urban development (primarily residential and commercial) in the coastal floodplain. Subsistence farm plots are located further inland. Development is located behind a drainage canal that is set back from the shoreline and behind engineered coastal protection structures (e.g., riprap and earthen dam). Some shoreline stretches (along North Mon Repos) are also fronted by a small buffer of mangroves.

Data gaps for this segment were filled using ArcGIS tools and professional judgement based on available data and aerial imagery. This data should be considered preliminary and subject to further refinement as additional data becomes available[7].

Table 9 highlights the ranges for this shoreline segment associated with each of the 21 indicators, and Table 10 presents the rating and scoring summary. Table 12 shows how the vulnerability and consequence indicator scores equate to ratings that can be used to define the CV-CI using the matrix in Table 13. Using Table 12 and Table 13, shoreline segment G_R4_3 received a vulnerability score of 56 (rating of *High*), a consequence score of 16 (rating of *Very High*), translating to a CV-CI of *Very High*.

This segment is highly vulnerable to coastal hazards primarily due to its low-lying elevation, shallow slope, exposed location to wave energy, minimal natural buffer available for storm dissipation, and expected rising sea levels. Portions of this shoreline have been engineered which reduces its vulnerability in the short term, but the condition of the structure is unknown, and the natural infrastructure (mangrove buffer) at the shoreline is vulnerable to coastal hazards. If the landward areas behind the shoreline are exposed to coastal hazards, there is very high consequence to the community, economy, mobility, and environment. A shoreline segment that has a CV-CI of *Very High* should be prioritized for adaptation intervention. Within the regional framework, the adjacent shoreline segments and other shoreline segments should be considered. An evaluation of the individual indicator scores/ratings for other shoreline segments in proximity is needed to identify the scope and scale of an appropriate adaptation intervention.

The high coastal vulnerability of this area has been validated through existing documentation of site conditions. A 2016 Annual Report by NAREI documented the high wave energy environment at the Lusignan shoreline. Prior efforts in 2014 to minimize shoreline erosion in this area by using seedling plantings failed, and a bamboo brushwood dam was constructed in 2016 to support raising the shoreline elevation and to establish mangroves and spartina grass.

---

[7] To fill the data gaps for all other segments additional time and effort (and applicable scope) would be necessary.

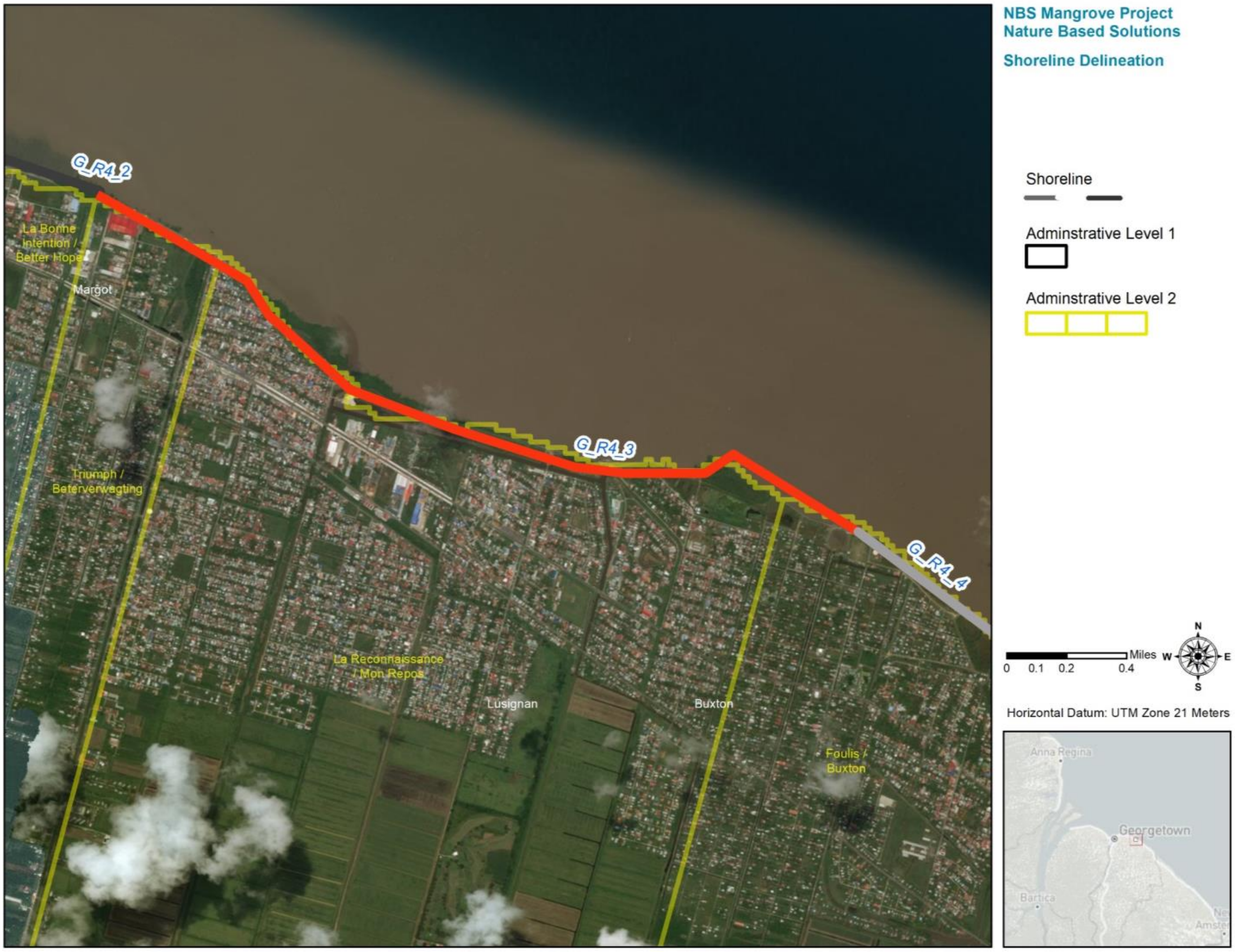


Figure 13. Location of Shoreline Segment (G_R4_3) near Lusignan and Buxton, Guyana

Table 9. Coastal Vulnerability Framework – applied to Guyana Shoreline Segment G_R4_3

VULNERABILITY

	Indicator	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)
Exposure	Significant Wave Height (m)	0.0 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	>2.0
	25-year Storm Surge Depth (m) above Coastal Elevation	0	0 - 0.25	0.25 – 1.0	1.0 - 2.0	>2.0
Ex	Tidal Range (m)	>3.25	2.5 - 3.25	1.75 - 2.5	1.0 - 1.75	<1.0

VULNERABILITY

	Future Sea Level Rise (mm/year)	<2.0	2.0 - 2.5	2.5 - 3.0	3.0 - 3.5	>3.5
	Historical Sea Level Rise (mm/year)	<2.0	2.0 - 2.5	2.5 - 3.0	3.0 - 3.5	>3.5

Sensitivity	Indicator	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)
	Wave Exposure	Very protected	Protected	Semi Protected	Semi Exposed	Exposed
	Shoreline Geomorphology	Rocky/Cliff coasts	Medium cliffs, indented coasts	Sand, Pebbles, Boulders	Cobble & Sandy Beaches	Mudflats, Mangroves
	Coastal Elevation (m) – above mean sea level	>12.0	9.0 - 12.0	6.0 - 9.0	3.0 - 6.0	<3.0
	Vegetation Width (m)	>1000	500 - 1000	100 - 500	50 - 100	>50
	Shoreline Change Rate (m/year)	>2.0	1.0 - 2.0	(-) 1.0 - 1.0	(-) 2.0 - (-) 1.0	< (-) 2.0
	Presence of Engineered Shoreline	Yes (in good condition)	-	Yes (in fair condition)	-	Yes (in poor condition); No Protection
	Coastal Slope (%)	>1.5	1.0 - 1.5	0.5 - 1.0	0.5 - 0.3	<0.3
	Beach Width (m)	>100	50 - 100	25 - 50	43763	<10

	Indicator	Very Low (4)	Low (3)	Moderate (2)	High (1)	Very High (0)
Adaptative Capacity	Coastal Typology	Shore Adjacent - Mixed Urban	Setback - Mixed Urban; Shore Adjacent - Aquaculture/Agriculture	Shore Adjacent - Sparse Residential; Setback - Aquaculture/Agriculture	-	No Development
	Presence of Engineered Shoreline	Yes (in poor condition)	-	Yes (in fair condition); No Protection (natural)	-	Yes (in good condition)
	Sediment Supply	Retreating Coast	-	Stable Coast	-	Prograding Coast
	Land Use/Land Cover Connectivity (Ratio of shared boundary to area)	<0.2	0.2 – 0.4	0.4 – 0.6	0.6 – 0.8	>0.8

RISK

	Indicator	Very Low (0)	Low (1)	Moderate (2)	High (3)	Very High (4)
Consequence	Population (Percentile in country total)	<1%	1 - 5%	5 - 10 %	10 - 15%	15 - 20 %
	Per capita Gross Domestic Product (GDP) (Percentile in country total)	<1%	1 - 5%	5 - 10 %	10 - 15%	15 - 20 %
	Critical Facilities (Percentile in country total)	<1%	1 - 5%	5 - 10 %	10 - 15%	15 - 20 %
	Infrastructure - Repair/Replacement Cost (Percentile in country total)	<1%	1 - 5%	5 - 10 %	10 - 15%	15 - 20 %

Notes:

1. Shaded ratings are based on preliminary data or best judgement and require further validation.
2. If multiple ratings for an indicator are highlighted, the highest score is taken. Multiple ratings occur when more than one characteristic defines a shoreline segment.

Table 10. Summary of coastal vulnerability scoring for Guyana Shoreline G_R4_3

VULNERABILITY

	Theme	Indicator	Exposure Rating	Exposure Score
Exposure	Wave Climate/Energy	Significant Wave Height	Very High	4
	Storm Surge/Overtopping	25-year Storm Surge Depth above Coastal Elevation	Moderate	2
	Tidal Range	Tidal Range	Moderate	2
	Sea Level Change	Future Sea Level Rise	Very High	4
	Sea Level Change	Historical Sea Level Rise	Very High	4
			Overall Exposure Score	16 (Very High)

	Theme	Indicator	Sensitivity Rating	Sensitivity Score
Sensitivity	Site Morphology	Wave Exposure	Very High	4
	Site Morphology	Shoreline Geomorphology	Very High	4
	Site Morphology	Coastal Elevation	Very High	4
	Site Morphology	Vegetation Width	Moderate	2
	Site Morphology	Shoreline Change Rate	Very High	4
	Land Use/Land Cover	Presence of Engineered Shoreline	Very High	4
	Site Morphology	Coastal Slope	Very High	4
	Site Morphology	Beach Width	Very High	4
			Overall Sensitivity Score	30 (Very High)

	Theme	Indicator	Adaptive Capacity Rating	Adaptive Capacity Score
Adaptative Capacity	Land Use/Land Cover	Coastal Typology	Very Low	4
	Land Use/Land Cover	Presence of Engineered Shoreline	Very Low	4
	Sediment Dynamics	Sediment Supply	Very High	0
	Land Use/Land Cover	Land Use/Land Cover Connectivity (Ratio of shared boundary to area)	Moderate	2
			Overall Adaptative Capacity Score	10 (Moderate)

RISK

	Theme	Indicator	Risk Rating	Risk Rating
Consequence	Land Use/Land Cover	Population (Percentile in country total)	Very High	4
	Land Use/Land Cover	Per capita Gross Domestic Product (GDP) (Percentile in country total)	Very High	4
	Land Use/Land Cover	Critical Facilities (Percentile in country total)	Very High	4
	Land Use/Land Cover	Infrastructure - Repair/Replacement Cost (Percentile in country total)	Very High	4
			Overall Consequence Score	16

Table 11. Vulnerability and consequence equivalent scores and ratings for Guyana Shoreline G_R4_3

Indicator Rating

	Segment G_R4_3	Very Low	Low	Moderate	High	Very High
Exposure	16	0-2	2-6	7-11	12-15	16-20
Sensitivity	30	0-5	6-11	12-19	20-26	27-32
Adaptative Capacity	10	0-3	4-7	8-10	11-13	14-16
Vulnerability Score	56					
Consequence	16	0-3	4-7	8-10	11-13	14-16
Risk Score	16					

Table 12. Vulnerability (sum of exposure, sensitivity and adaptive capacity) and Risk (consequence) scores and ratings

Vulnerability Indicators Score	Risk (Consequence) Indicators Score	Vulnerability /Consequence Rating	Description
0 – 12	0-1	Very Low	-
15 - 27	1-5	Low	-
28 – 42	6-10	Moderate	-
➔43 – 56	11-14	High	Segment G_R4_3 has High vulnerability due to Very High exposure and sensitivity, with Moderate adaptive capacity to adjust/adapt to coastal hazards. This is due to its low-lying elevation, shallow slope, exposed location to wave energy, minimal natural buffer available for storm dissipation, and expected rising sea levels. Portions of this shoreline have been engineered which reduces its vulnerability in the short term, but the condition of the structure is unknown.
57 - 68	➔14-16	Very High	Segment G_R4_3 has High consequence if exposed to coastal hazards due to dense population behind the shoreline with built infrastructure.

Table 13. Coastal Vulnerability-Consequence Index Matrix

		Consequence Rating				
		Very Low	Low	Moderate	High	Very High
Vulnerability Rating	Very Low	Very Low	Low	Moderate	High	High
	Low	Low	Low	Moderate	High	High
	Moderate	Low	Moderate	Moderate	High	High
	High	Low	Moderate	High	High	Very High
	Very High	Low	Moderate	High	Very High	Very High

9 Overview of Green-Gray Coastal Defense Solutions

9.1 Key Messages

- Integrating green and gray strategies to provide coastal hazard protection supports enhanced sustainability of both the ecological and built environment.
- Several broad shoreline typologies have been classified to support identification of appropriate green and gray strategies. These typologies capture a variety of shoreline types with similar physical processes, geologic characteristics, and land use. Identifying shoreline typologies helps group green and gray solutions together where they are most applicable.
- Adapting the existing natural environment with green or green-gray hybrid solutions to reduce coastal hazards and stabilize shorelines is expected to provide the lowest cost and most flexible option for providing flood protection for inland communities.

9.2 Existing Coastal Defense Projects

High wave energy is a key contributor to shoreline erosion and, over time, can prevent long-term establishment of vegetation (e.g., mangrove forests). High wave energy environments can transform a convex (stable) shoreline profile into a concave (eroding) shoreline profile, resulting in increasing wave heights and accelerated erosion. In some cases, the soft sediment below mangrove roots is cut away resulting in rapid and significant loss of the shoreline and mangrove forested areas. In Guyana and Suriname, coastal defense projects have focused on high wave energy areas with a goal of minimizing shoreline erosion, promoting shoreline accretion, and supporting the establishment of mangroves (National Agricultural Reserach and Extension Institute 2015, 2016, 2017). Figure 14 and Figure 15 show the locations of known projects in Guyana and Suriname. They were identified through Annual Reports published by the National Agricultural and Research Extension Institute (NAREI) from 2015 through 2018. Only projects in Guyana are documented in the NAREI Annual Reports. Other information sources included existing published literature documenting existing project locations (e.g., Interaction of Mangroves, Coastal Hydrodynamics, and Morphodynamics Along the Coastal Fringes of the Guianas. (Toorman et al. 2018a)).

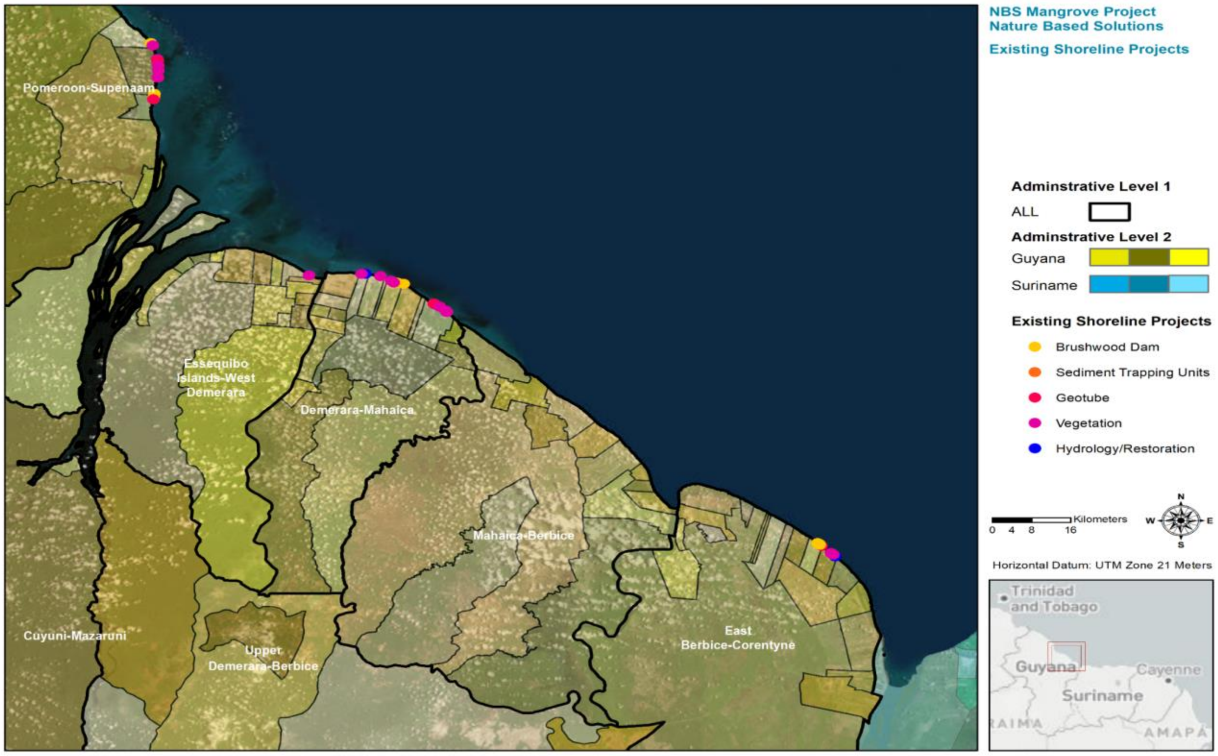


Figure 14. Locations of Existing Coastal Protection Measures in Guyana

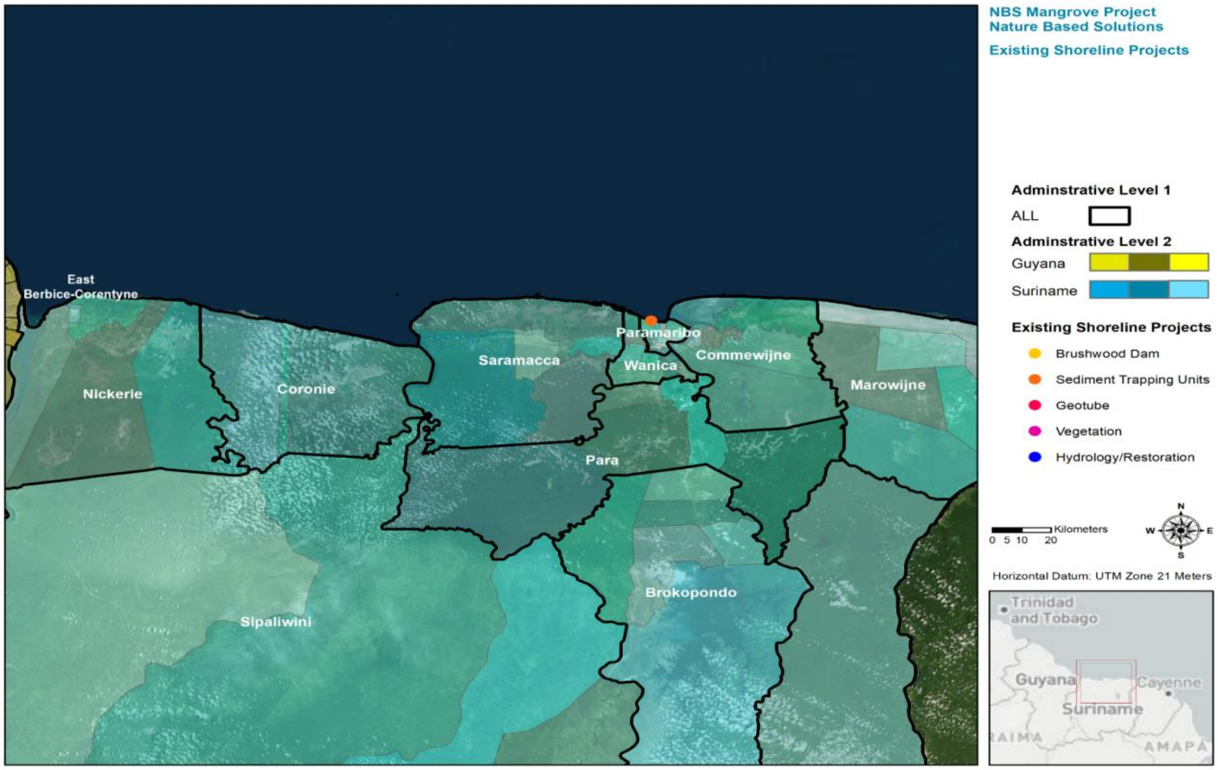


Figure 15. Locations of Existing Coastal Protection Measures in Suriname

Currently, natural infrastructure coastal defense projects include the following strategies:

Geotextile Tube (gryone) and Shoreline Plantings

- Geotextile tubes are filled with sand slurry and placed on bamboo rafters. Geotextile scour aprons may be placed adjacent to the geotextile tubes.
- The tubes dissipate wave energy and help trap sediment, resulting in reduced coastal erosion. As sediment is trapped, the foreshore elevation will increase and support mangrove establishment when target elevations are reached.
- Shoreline plantings (e.g., *Spartina brasiliensis* spp.) can be implemented in tandem with the geotextile tubes to promote soil consolidation.
- Supplemental activities include sand placement to create a beach-like foreshore and construction of a rafter-like structure using iron rods to enhance soil stability.

Brushwood Dams

- Brushwood dams support shoreline stabilization and promote mangrove establishment through sediment capture and consolidation. They are a lower cost solution compared to more engineered gray structures such as rubble mound breakwaters or groynes.
- The dams consist of rows of timber of bamboo piles constructed in parallel, with similar materials used for cross members and infill between rows.
- They are designed to withstand water levels and wave heights that have a 10% annual chance of occurring.
- They have a typical lifespan of 3-7 years.

Sediment Trapping Units

- Sediment trapping units support shoreline stabilization through wave dissipation and can promote mangrove establishment through sediment capture and consolidation. Some wave energy is dissipated as waves pass through the wood material, and some wave energy is preserved to transport sediment within the sediment trapping unit for capture. Additional seaward sediment trapping units are added in phases as the initial units capture sediment and increase the shoreline elevation.
- The units consist of walaba poles with bamboo for filling material and are typically rectangular in shape.
    - Supplemental activities include sediment placement to accelerate sedimentation; offshore artificial chenier ridges (comprised of medium to coarse sand) that enhance wave protection; floating offshore breakwaters (e.g., concrete boxes, bamboo, or tires) or integrated breakwaters (e.g., bamboo or tires) to enhance wave protection in high energy environments.

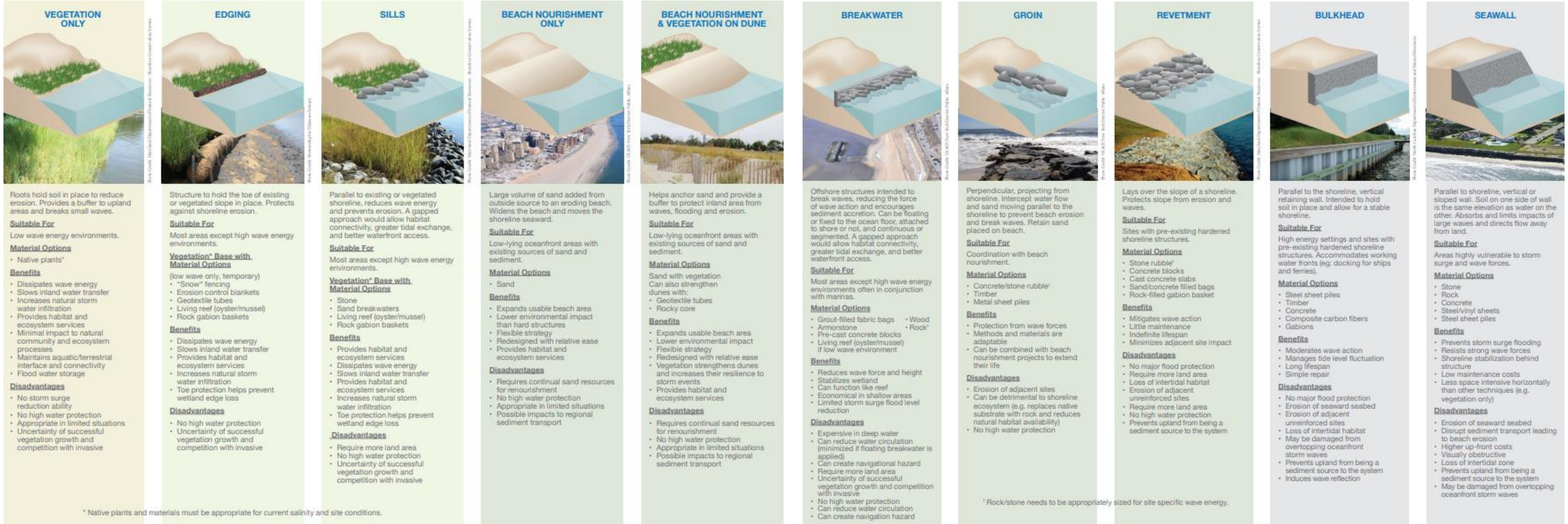
All of these strategies can be implemented quickly and are relatively low-cost. However, these strategies generally have low crest elevations and are not engineered to withstand larger, episodic storm events with high wave heights and storm surges. Extreme events can destroy or damage them, resulting in loss of the establishing mangroves and flooding of inland development.

9.3 Nature Based Solutions - Green-Gray Solutions

Nature based solutions, defined by the International Union for Conservation for Nature and Natural Resources (IUCN), *are actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits* (Cohen-Shacham et al. 2016). Actions can include: solutions that involve making better use of existing natural or protected ecosystems; solutions based on developing sustainable management protocols and procedures for managed or restored ecosystems; and solutions that involve creating new ecosystems (Cohen-Shacham et al. 2016). Green-gray infrastructure share characteristics across these solutions. Green-gray infrastructure combines conservation and/or restoration of ecosystems with the selective use of conventional engineering approaches to provide people with solutions that deliver climate change resilience and adaptation benefits. By blending “green” conservation with “gray” engineering techniques, communities can incorporate the benefits of both solutions while minimizing the limitations of using either green or gray infrastructure individually. The green-gray infrastructure design approach can apply in coastal, freshwater, and terrestrial settings.

In sheltered locations with low wave energy and gentle foreshore slopes, “green” or nature-based coastal defense strategies are preferred because they provide a variety of co-benefits, including enhancing or increasing biodiversity and promoting human well-being. Green solutions can be coupled with habitat restoration to meet multiple species and community goals. In locations with high wave energy and steeper foreshore slopes, more traditional “gray” or engineered coastal defense strategies are more common, especially where there is high value, high density development located very close to the coastline. Gray strategies can provide a higher level of flood protection than green strategies, but gray strategies often have ecosystem impacts, including habitat loss and disconnecting communities from the shoreline. Green and gray strategies can be integrated to develop solutions that provide coastal hazard reduction (during high water and wave events), while also enhancing habitat health. For example, by restoring mangroves and installing breakwaters, the environment and nearby communities become more adaptable and resilient than if either technique is applied alone. These hybrid “green-gray” nature-based solutions can also help preserve the connection between upland and coastal ecosystems and maintain community access to the shoreline.

Figure 16 presents a range of green to gray strategies for reducing coastal flood risk with the respective suitable site conditions, required construction materials, and the potential benefits and disadvantages for each strategy. This section discusses how these strategies can be applied to the broad shoreline typologies found in the NBS-LME region.



VEGETATION ONLY

Roots hold soil in place to reduce erosion. Provides a buffer to upland areas and breaks small waves.

Suitable For

Low wave energy environments.

Material Options

- Native plants*

Benefits

- Dissipates wave energy
- Slows inland water transfer
- Increases natural storm water infiltration
- Provides habitat and ecosystem services
- Minimal impact to natural community and ecosystem processes
- Maintains aquatic/terrestrial interface and connectivity
- Flood water storage

Disadvantages

- No storm surge reduction ability
- No high water protection
- Appropriate in limited situations
- Uncertainty of successful vegetation growth and competition with invasive

EDGING

Structure to hold the toe of existing or vegetated slope in place. Protects against shoreline erosion.

Suitable For

Most areas except high wave energy environments.

Vegetation* Base with Material Options

(low wave only, temporary)

- "Snow" fencing
- Erosion control blankets
- Geotextile tubes
- Living reef (oyster/mussel)
- Rock gabion baskets

Benefits

- Dissipates wave energy
- Slows inland water transfer
- Provides habitat and ecosystem services
- Increases natural storm water infiltration
- Toe protection helps prevent wetland edge loss

Disadvantages

- No high water protection
- Uncertainty of successful vegetation growth and competition with invasive

SILLS

Parallel to existing or vegetated shoreline, reduces wave energy and prevents erosion. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access.

Suitable For

Most areas except high wave energy environments.

Vegetation* Base with Material Options

- Stone
- Sand breakwaters
- Living reef (oyster/mussel)
- Rock gabion baskets

Benefits

- Provides habitat and ecosystem services
- Dissipates wave energy
- Slows inland water transfer
- Provides habitat and ecosystem services
- Increases natural storm water infiltration
- Toe protection helps prevent wetland edge loss

Disadvantages

- Require more land area
- No high water protection
- Uncertainty of successful vegetation growth and competition with invasive

* Native plants and materials must be appropriate for current salinity and site conditions.

BEACH NOURISHMENT ONLY

Large volume of sand added from outside source to an eroding beach. Widens the beach and moves the shoreline seaward.

Suitable For

Low-lying oceanfront areas with existing sources of sand and sediment.

Material Options

- Sand

Benefits

- Expands usable beach area
- Lower environmental impact than hard structures
- Flexible strategy
- Redesigned with relative ease
- Provides habitat and ecosystem services

Disadvantages

- Requires continual sand resources for renourishment
- No high water protection
- Appropriate in limited situations
- Possible impacts to regional sediment transport

BEACH NOURISHMENT & VEGETATION ON DUNE

Helps anchor sand and provide a buffer to protect inland area from waves, flooding and erosion.

Suitable For

Low-lying oceanfront areas with existing sources of sand and sediment.

Material Options

Sand with vegetation
Can also strengthen dunes with:

- Geotextile tubes
- Rocky core

Benefits

- Expands usable beach area
- Lower environmental impact
- Flexible strategy
- Redesigned with relative ease
- Vegetation strengthens dunes and increases their resilience to storm events
- Provides habitat and ecosystem services

Disadvantages

- Requires continual sand resources for renourishment
- No high water protection
- Appropriate in limited situations
- Possible impacts to regional sediment transport

BREAKWATER

Offshore structures intended to break waves, reducing the force of wave action and encourages sediment accretion. Can be floating or fixed to the ocean floor, attached to shore or not, and continuous or segmented. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access.

Suitable For

Most areas except high wave energy environments often in conjunction with marinas.

Material Options

- Grout-filled fabric bags
- Armorstone
- Pre-cast concrete blocks
- Living reef (oyster/mussel) if low wave environment
- Wood
- Rock[1]

Benefits

- Reduces wave force and height
- Stabilizes wetland
- Can function like reef
- Economical in shallow areas
- Limited storm surge flood level reduction

Disadvantages

- Expensive in deep water
- Can reduce water circulation (minimized if floating breakwater is applied)
- Can create navigational hazard
- Require more land area
- Uncertainty of successful vegetation growth and competition with invasive
- No high water protection
- Can reduce water circulation
- Can create navigation hazard

GROIN

Perpendicular, projecting from shoreline. Intercept water flow and sand moving parallel to the shoreline to prevent beach erosion and break waves. Retain sand placed on beach.

Suitable For

Coordination with beach nourishment.

Material Options

- Concrete/stone rubble[1]
- Timber
- Metal sheet piles

Benefits

- Protection from wave forces
- Methods and materials are adaptable
- Can be combined with beach nourishment projects to extend their life

Disadvantages

- Erosion of adjacent sites
- Can be detrimental to shoreline ecosystem (e.g. replaces native substrate with rock and reduces natural habitat availability)
- No high water protection

REVETMENT

Lays over the slope of a shoreline. Protects slope from erosion and waves.

Suitable For

Sites with pre-existing hardened shoreline structures.

Material Options

- Stone rubble[1]
- Concrete blocks
- Cast concrete slabs
- Sand/concrete filled bags
- Rock-filled gabion basket

Benefits

- Mitigates wave action
- Little maintenance
- Indefinite lifespan
- Minimizes adjacent site impact

Disadvantages

- No major flood protection
- Require more land area
- Loss of intertidal habitat
- Erosion of adjacent unreinforced sites
- Require more land area
- No high water protection
- Prevents upland from being a sediment source to the system

[1] Rock/stone needs to be appropriately sized for site specific wave energy.

BULKHEAD

Parallel to the shoreline, vertical retaining wall. Intended to hold soil in place and allow for a stable shoreline.

Suitable For

High energy settings and sites with pre-existing hardened shoreline structures. Accommodates working water fronts (eg: docking for ships and ferries).

Material Options

- Steel sheet piles
- Timber
- Concrete
- Composite carbon fibers
- Gabions

Benefits

- Moderates wave action
- Manages tide level fluctuation
- Long lifespan
- Simple repair

Disadvantages

- No major flood protection
- Erosion of seaward seabed
- Erosion of adjacent unreinforced sites
- Loss of intertidal habitat
- May be damaged from overtopping oceanfront storm waves
- Prevents upland from being a sediment source to the system
- Induces wave reflection

SEAWALL

Parallel to shoreline, vertical or sloped wall. Soil on one side of wall is the same elevation as water on the other. Absorbs and limits impacts of large waves and directs flow away from land.

Suitable For

Areas highly vulnerable to storm surge and wave forces.

Material Options

- Stone
- Rock
- Concrete
- Steel/vinyl sheets
- Steel sheet piles

Benefits

- Prevents storm surge flooding
- Resists strong wave forces
- Shoreline stabilization behind structure
- Low maintenance costs
- Less space intensive horizontally than other techniques (e.g. vegetation only)

Disadvantages

- Erosion of seaward seabed
- Disrupt sediment transport leading to beach erosion
- Higher up-front costs
- Visually obstructive
- Loss of intertidal zone
- Prevents upland from being a sediment source to the system
- May be damaged from overtopping oceanfront storm waves

Source: Adapted from SAGE (2019)

Figure 16. Range of green to gray coastal defense strategies

9.3.1 Shoreline Typologies

Classifying the shoreline typologies in the NBS-LME region informs the selection of potential green-gray nature-based solutions. Across the NBS coastline, there are stretches of mudbank that provide wave energy dissipation and promote the establishment of mangroves (see Section 7). Between the migrating mudbanks there are interbank regions that are susceptible to erosion from wave attack (see Figure 6).

Landward of the migrating mudbank and interbank regions, there is generally a wide low-lying coastal floodplain with various degrees of inland development (e.g., sparse residential, dense residential/commercial (mixed urban), or agriculture/aquaculture). Inland development can be found directly adjacent to the shoreline with either a narrow band of mangroves providing coastal protection or engineered flood protection structures. In other areas, the development is set back from the shoreline with broader mangrove forests providing coastal protection.

Figure 17 presents a classification of the usual shoreline typologies found in the NBS-LME region. The considerations for matching nature-based solutions with these shoreline typologies is presented in the following section.

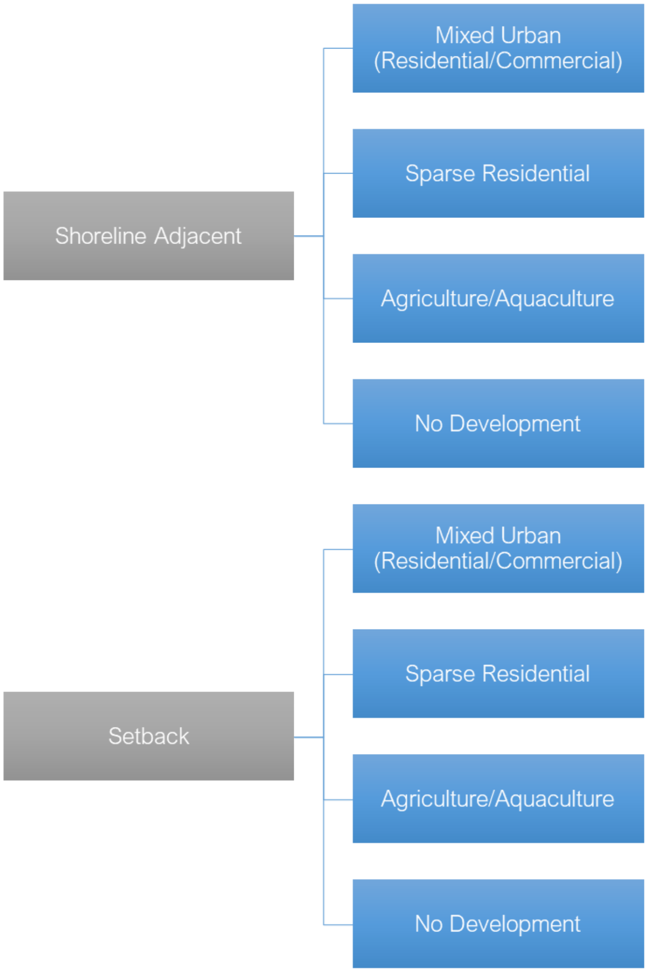


Figure 17. Classification of NBS shoreline typologies

9.3.2 Considerations for Green-Gray Strategies

Mixed Urban Development (Residential/Commercial) – Adjacent to Shoreline

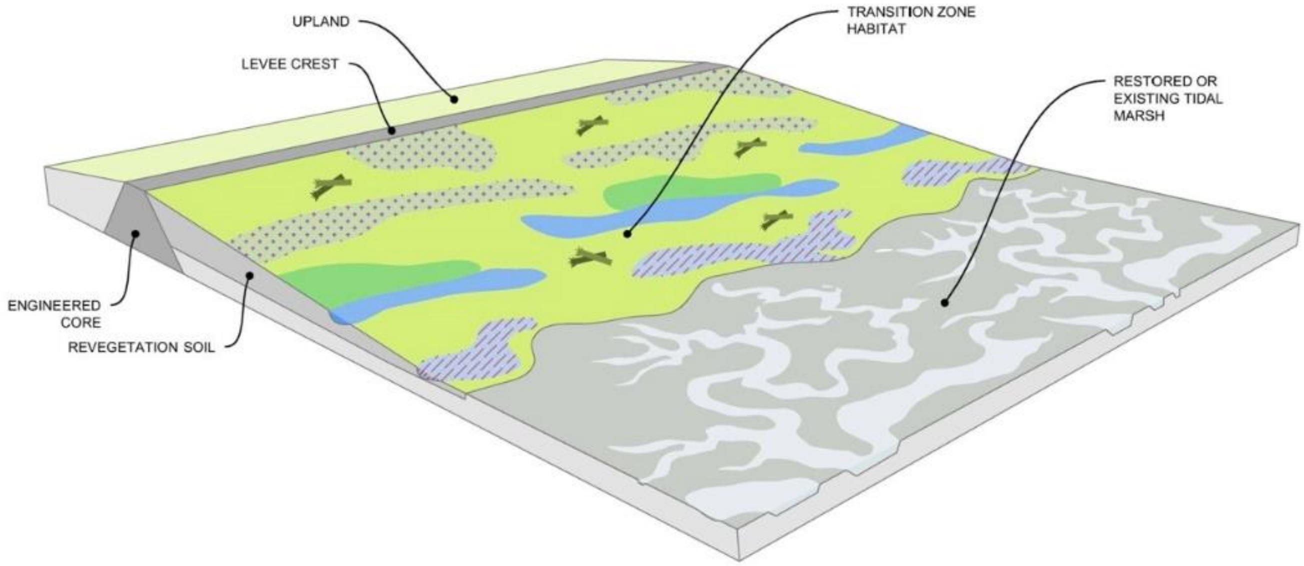
Areas with mixed urban development, including densely populated residential and commercial/industrial areas will require innovative strategies to reduce coastal hazards from high wave energy and storm surge. With rising sea levels, widespread overland flooding will occur more often as high water levels overtop large stretches of the shoreline.

Many of the more developed areas in Guyana and Suriname are near the shoreline, below mean sea level, and protected by some form of gray infrastructure (e.g., seawall or berm). In these areas, the presence of mangrove forests is often minimal or non-existent. Gray infrastructure often results in deeper coastal waters along the shoreline (e.g., through wave reflection and accelerated erosion of adjacent shoreline areas, see Section 6.2) creating conditions that are not suitable for mangrove establishment and that could cause the gray strategies to fail (Winterwerp et al. 2013). In some cases, the gray infrastructure has previously failed or is poorly maintained, resulting in increased flood risk.

Coupling the existing gray infrastructure with green strategies that can help establish mangroves could also increase the lifespan of the gray infrastructure, reduce maintenance needs, and increase the level of coastal protection provided to inland communities. These green strategies could include sediment trapping units or brushwood dams that trap sediment and increase the elevation of the foreshore to allow mangroves to establish. In high wave energy environments, supplemental gray strategies (e.g., offshore breakwaters) may be required. Layering green and gray strategies provides multiple lines of flood defense, reduces the likelihood for flood defense failure, and increases the ability to adapt the system over time to sea level rise.

Although there is potentially sufficient sediment in the NBS-LME region for mangroves to build vertically as sea levels rise, mangrove forests are also projected to retreat where landward space allows (Crooks et al. 2019). In areas where inland development is a constraint, mangrove forests will eventually be lost unless the existing shoreline is protected in place. In these areas where development constrains the landward limit of nature-based solutions, the coupling of green and gray strategies will become more important, and more substantial gray strategies may be required (e.g., more significant offshore breakwaters or shoreline revetments to reduce wave hazards). A cost-benefit analysis that considers short-term and long-term flood protection needs, multi-tiered green-gray strategies, and managed retreat, should be completed.

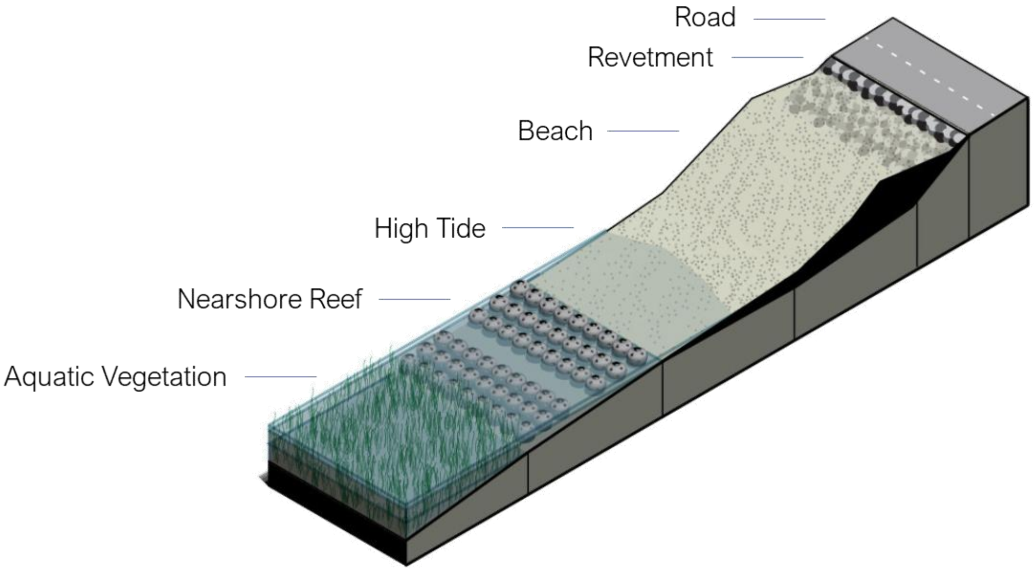
In both mudbank and interbank shoreline stretches, a living levee design may be suitable – this type of green-gray strategy provides a gentler slope than a traditional levee design and incorporates habitat transition zones between upland and tidal flat areas. An example of a living levee that incorporates multi-tiered green-gray strategies is presented in Figure 18. This strategy provides habitat restoration and flood protection, and it can be adapted to higher elevations over time in response to sea level rise and increased storm activity. This measure requires artificially extending the natural shoreline seaward in areas of coastal squeeze, so considerations of indirect impacts (e.g., sediment starvation) to adjacent shoreline areas are necessary. In developed areas behind mudbanks, a living levee design would complement the gentler foreshore slope. At interbank locations with higher wave energy, the design would likely require sediment placement and more construction materials, translating to higher construction costs. In all scenarios, design for coastal protection in the dynamic mudbank environment should consider the higher wave climate conditions (erosive conditions) that occur during interbank periods.



Source: H.T. Harvey & Associates (Accessed at https://www.greenfoothills.org/living-levees/ – 2019)

Figure 18. Living levee example

In areas with steeper foreshore slopes and very high wave energy, a living levee design may be cost prohibitive. Solutions weighted towards gray strategies may be required (e.g., traditional levee or seawall) to provide coastal flood protection. Because gray infrastructure has limited adaptability over time, structural foundations should be designed with longer-term flood protection and sea level rise in mind. The foundation would be oversized for the initial structure but would be adaptable (e.g. allow for the height of the structure to be increased) to accommodate higher rates of sea level rise. If the foundation of the structure is not sized to support incremental modifications, the entire structure may need to be demolished and replaced. Figure 19 provides another example of a multi-layered green-gray strategy that couples a gray engineered shoreline (with revetment) and green strategies (e.g., vegetation and reefs). The green strategies allow a sandy beach to provide habitat and moderate storm energy reduction, while the revetment protects the adjacent roadway from high erosion events.



Source: Adapted from SFEI (2019)

Figure 19. Multi-layered green-gray strategy for coastal protection with ecological benefits

To choose the appropriate coastal defense option, a cost-benefit analysis considering short-term and long-term flood protection needs, multi-layered green-gray strategies, and managed retreat should be completed. Managed retreat should always be a consideration for development near the shoreline. Large-scale coastal protection is costly and does not guarantee protection against larger than expected storm events. Relocating communities outside of flood hazard risk areas often provides the most effective flood protection.

Mixed Urban Development (Residential/Commercial) – Setback from Shoreline

In areas where mixed urban development is setback from the current shoreline edge, alternative approaches may be able to leverage existing natural buffers provided by mangrove forests. Green strategies can be implemented to stabilize (and possibly extend) the natural buffer between the development and shoreline. The required development setback distance can be defined by the wave heights and/or storm surge elevation that requires attenuation.

Interbank areas may have less existing natural buffer (e.g., mangrove forest width) available; however green measures such as sediment trapping units and brushwood dams can support shoreline accretion to allow new mangrove populations to establish. Along shoreline stretches with particularly high wave energy, offshore breakwaters or artificial chenier ridges (Figure 7 illustrates examples of chenier ridges) can be used to reduce wave energy on the outboard size of the mangrove fringe. If coastal protection from large storms is desired, more substantial green-gray solutions can be implemented (larger mangrove buffer coupled with a setback levee), but considerations of the setback distance available between the developed areas and the shoreline are required. A greater need for integrated green-gray solutions will be more apparent in the longer-term when considering sea level rise. Integrated solutions can provide adaptive capacity where the level of flood protection can be increased over time, either through shoreline accretion promoted by natural systems, and/or ability of levees to be raised without significant reconstruction.

An integrated green-gray strategy for setback development was evaluated for Paramaribo, Suriname (World Bank Group 2017). Several kilometers of mangroves were established between the shoreline edge and the developed areas, providing an opportunity to use natural infrastructure for storm risk reduction in combination with a gray measure (e.g., embankment or engineered levee). In the World Bank (2017) study, installing a flood barrier behind the existing mangroves provided the greatest cost-benefit for both the natural and built environment. A minimum mangrove buffer width of 1.5 km was found to provide the adequate setback needed to support this type of solution. In this region a buffer of less than 1.5km would be susceptible to wave-induced erosion (World Bank, 2017). Potential erosion seaward of the existing mangrove forest should be evaluated and monitored, and a supplemental solution that promotes sediment trapping and accretion (e.g., sediment trapping units or offshore breakwaters) may be required as sea levels rise.

Finally, if enough space is available landward of developed areas, managed retreat should be considered. This will provide additional space for the mangrove forest to migrate inland as sea levels rise and will reduce the need for other costly adaptation strategies to attenuate wave hazards and storm surge.

Sparse Residential

Sparse residential (i.e., rural) communities behind mudbanks and established mangrove populations that currently provide coastal hazard protection may benefit from minor green shoreline interventions to promote shoreline stabilization and accretion. Suitable actions may be similar to those outlined for mixed use development either setback or adjacent to the shoreline. However, over time more substantial solutions may be needed to protect against rising sea levels and associated high water level and storm surge events. In areas with sparse residential communities near the shoreline without natural flood protection, risk reduction through managed retreat is a viable option to consider. In the short term, new housing and development near the shoreline should be discouraged or prevented. In the longer term, relocating communities to upland areas outside of riverine and coastal flood hazard zones could provide overall cost savings when compared to the cost of implementing flood protection measures. At a minimum, rural communities should understand their flood risk and should construct their homes and infrastructure to withstand intermittent flooding. Building codes and defined flood risk zones can be effective at communicated varying degrees of flood risk when accompanied with appropriate enforcement, education, and outreach efforts.

Relocating rural communities can have other long-term benefits, such as potentially increasing their access to reliable water supplies. In Guyana, groundwater from coastal aquifers provides 90 percent of domestic water (United States Army Corps of Engineers 1998). Saltwater intrusion into the aquifer has already been a concern in the eastern lowlands (United States Army Corps of Engineers 1998), and as sea levels rise saltwater intrusion is likely to increase. This will impact potable water supplies, particularly in rural settlements that rely on well water.

Agriculture and Aquaculture

In the coastal aquifer system, there is currently brackish to saline groundwater in the northwestern corner of Guyana (United States Army Corps of Engineers 1998). Although agricultural water supplies are drawn from surface water rather than groundwater (United States Army Corps of Engineers 1998), salinity intrusion into the groundwater will impact agricultural lands. As sea levels rise, the shallow groundwater surface will also rise, and saline groundwater will push farther inland. Over time, this will turn agricultural areas into coastal swamps and create conditions that will adversely affect agricultural productivity. Freshwater focused aquaculture will also require adaptation to brackish tolerant species or be displaced to areas beyond the brackish interface.

While nature-based strategies can increase coastal protection from rising sea levels, no shoreline infrastructure can protect from rising groundwater levels. In wide coastal floodplains where the ground has a relatively shallow landward slope, a managed retreat scenario can support the continued use of agricultural and aquaculture practices in the region. The rates of groundwater rise and salinity intrusion are currently unknown, but should be monitored over time.

No Development

In undeveloped areas, no actions are likely needed. However, sea level rise without intervention will result in indirect impacts to these regions, including loss of carbon stock and landward migration of mangrove forests and fringe habitats.

9.4 Additional Considerations when Defining Green-Gray Solutions

9.4.1 Sediment Dynamics

The NBS-LME region is characterized by high sediment supply, predominantly from the Amazon river, providing a mix of clays and very fine sands that are transported westwards towards the Orinoco River in Venezuela. Sediment and freshwater are also supplied from local rivers. There are several solutions (ranging from green to gray) that will support attenuation of high wave energy, but the use of these solutions should not counteract the longshore (shore parallel) and cross-shore (shore perpendicular) sediment supply needed to support shoreline accretion and stabilization. Interrupting longshore sediment transport can starve the current shorelines of sediment and beach material necessary to accrete or maintain its current position from ongoing erosion. For example, sediment trapping at one shoreline location can increase flood risk at adjacent shorelines by disrupting the existing sediment regime. This can result in continued coastal protection from a response-based, patchwork approach, instead of evaluating coastal protection projects from a regional hydrodynamic and geomorphological scale.

Cross-shore sediment transport is also necessary to allow sediment to accrete. Sediment trapping units are an example of a strategy that reduces incoming wave energy and increases local sediment accretion without eliminating longshore sediment transport.

9.4.2 Wave Climate

In high wave energy environments, some green-gray solutions may not be suitable, and gray solutions may be required. This is important in locations where large wave heights are expected during episodic storm events (greater than mean significant wave heights), potentially resulting in severe damage to less engineered solutions. If existing projects such as brushwood dams and sediment trapping units have been implemented in this areas, additional protection may be required to prevent damage and failure. In all scenarios, design for coastal protection in the dynamic mudbank environment should consider the higher wave climate conditions (erosive conditions) that occur during inter-bank periods.

9.4.3 Tidal Range

Tidal range is an important design parameter when evaluating solutions that require establishing vegetation in the coastal zone. There is still ongoing research on whether a large versus narrow tide range results in higher coastal vulnerability. A larger tide range may bring stronger tidal currents, resulting in increased erosion forces (Gornitz 1991). A narrow tide range means periods of storm surge may have a greater probability of occurring during high tide, resulting in higher flood risk (Dwarakish et al. 2009). With sea level rise, tidal elevations will increase, and the tidal range may even widen, which could affect vegetation establishment.

9.4.4 Sea Level Change

With sea level rise expected to accelerate by mid-century, coastal interventions should consider future land use and the lifespan of potential interventions. While lower-cost solutions may be designed with short lifespans in mind, it may not be cost-effective to continually reconstruct solutions in response to episodic erosion events. Green-gray solutions may provide greater longevity, and although the initial capital cost may be higher, the long-term cost may reveal cost savings. Cost savings could come from only having to implement the solution once versus several times, and from the prevention of damage and loss due to the presence of a more substantive structure.

9.4.5 Mudbank Evolution

Mangrove establishment at the shoreline will help reduce the long-term sensitivity of the shoreline to the temporal effects of the mudbank cycles (World Bank Group 2017). Incorporating the temporal effects of mudbank dynamics on the wave climate will enhance the resilience of shoreline adaptation measures (both nature-based and gray-infrastructure). Adaptation strategies should consider the maximum wave climate and exposure that could occur during interbank periods (based on the expected lifespan of the strategy). This approach supports the protection of established natural shorelines and may reduce the sensitivity of the shoreline to the erosive mudbank forces. Adaptation strategy development should also consider triggers and thresholds for subsequent adaptation efforts, i.e., when in time, or by what future water level, will additional adaptation strategies be required to maintain the desired level of coastal flood protection. Additional adaptation strategies could also be triggered when protective mudbanks migrate away. Ongoing monitoring of water levels, shoreline conditions, and mudbank migration is required to trigger subsequent adaptation responses.

9.4.6 Evaluating Alternatives

After identifying vulnerable shoreline segments, the next step includes developing a range of potential coastal protection strategies (alternatives) and evaluating the strategies against a range of social, environmental, and economic criteria at both local and regional scales. Developing and evaluating the alternatives and the evaluation criteria should include substantive community and stakeholder engagement and input.

Defining the overall goals to be achieved with the coastal protection strategies can help build community and stakeholder buy-in and can also help secure financing for project implementation. Example goals could include benefits for governance, society and equity, the economy, and the environment. Alternatives could be developed to prioritize achieving one goal over the others, or to maximize achieving all the goals, etc. The evaluation criteria are then used to illustrate how well each alternative performs relative to the goals. This approach also helps identify potential alternative weaknesses and strengths, including potential pathways to improve the alternatives. This approach also facilitates conversations with stakeholders, and ultimately identifies the preferred strategy to move forward toward implementation.

9.4.7 Monitoring and Financing Mechanisms

In the dynamic mudbank environment, the maintenance of any green-gray strategy is critical to successful flood risk reduction. Maintenance of flood protection requires regular monitoring and an adaptation management plan. Routine monitoring is required to ensure that all natural and engineered elements are remain in the condition needed to provide flood protection. Vegetation should be well established, structural measures should remain intact, and any placed rock revetments or wave reduction measures should be secure and remain in place. Routine monitoring can be as simple as twice-yearly site visits with photo documentation for comparison to previous site visits. Additional site visits should also be completed after a storm event to check for possible damage and to initiate any necessary repairs. Providing adequate resources (e.g., funding, equipment, staff time) for site visits is an important component of flood risk reduction, especially in the dynamic NBS-LME coastal environment.

Climate change science is continually evolving, and updates to the science should also be routinely monitored. The rate of sea level rise and changing storm patterns and frequency should be tracked to allow enough lead team for additional adaptation strategies to be implemented. The adaptation management plan should identify the triggers and thresholds for future adaptation strategy needs, including upgrades or enhancements to built strategies that may be required to address higher rates of sea level rise.

Currently, there is no clear framework for financing nature-based solutions, as the appropriate funding source depends on the local conditions, governance structures, and current polices supporting these practices (Colgan et al. 2017). If available, funding opportunities may come via reallocation of post-disaster recovery funds. One of the greatest hurdles in green-gray infrastructure financing is overcoming institutional bias towards traditional gray infrastructure (Colgan et al. 2017). Having the benefits of green-gray solutions clearly identified from a cost-benefit and co-benefits perspective will greatly increase potential opportunities for these projects to be financed and accepted as a mainstream practice.

Potential financing instruments available to explore include private organizations (e.g., philanthropic grants and institutional investors), public organizations (e.g., NGOs, development banks, and domestic governments), or private businesses (e.g., businesses that are stakeholders in local communities) (World Business Council for Sustainable Development 2017).

10 Economic Significance of Mangrove Ecosystems for Flood Risk and Coastal Erosion Reduction

10.1 Key Messages

- Implementing gray solutions closer to the shoreline results in greater capital cost compared to green solutions. Increasing the shoreline setback available for these solutions results in cost reduction for both.
- Green measures may incur higher annual maintenance costs when adjacent to the shoreline, but with increasing setback distance, annual costs between green and gray solutions will converge to similar rates (World Bank Group 2017).
- Solutions that leverage the flood protection potential of existing mangrove forests will have a lower overall cost. Gray solutions that incorporate existing mangrove forests into the design will achieve the greater cost reduction (due to the higher initial cost of gray infrastructure).

10.2 High-Order Cost Comparison

Table 14 and Table 16 present a range of costs for individual green and gray solutions. Capital and annual costs for individual solutions presented in Table 14 are derived from the Natural and Structural Measures for Shoreline Stabilization brochure[8] created by the Systems Approach to Geomorphic Engineering (SAGE) group, in partnership with the U.S. Army Corps of Engineers and the National Oceanic and Atmospheric Administration. The costs presented in Table 16 are derived from the Coastal Resilience Assessment for Paramaribo, Suriname, published by the World Bank Group. The differences in cost magnitude for similar solutions (e.g., seawall) across Table 14 and Table 16 are likely attributed to the costs in Table 14 including higher design fees, permitting fees, and material costs associated for coastal activities in the United States.

---

[8] Accessed: http://sagecoast.org/docs/fastfacts/LivingShorelineBrochurev26_forprint.pdf

Table 14. Relative costs for natural and gray infrastructure solutions (from global sources)

Shoreline Measure	Initial Construction Costs (USD$ per linear meter)	Annual Operations and Maintenance (USD$ per linear meter)
Vegetation Only	<$300	<$30
Edging	$300 - $600	<$30
Sills	$300 - $600	<$30
Beach/Sediment Nourishment Only	$600 - $1,500	$30 - $150
Beach/Sediment Nourishment and Vegetated Dune	$600 - $1,500	$30 - $150
Breakwater	$1,500 - $3,000	>$150
Groyne	$600 - $1,500	$30 - $150
Revetment	$1,500 - $3,000	$30 - $150
Bulkhead	$600 - $1,500	$30 - $150
Seawall	$1,500 - $3,000	>$150

Source: SAGE (2019)

Table 15. Relative costs for natural and gray infrastructure solutions (from other sources)

Shoreline Measure	Cost (USD$ per linear meter)	Annual Operations and Maintenance (USD$ per linear meter)
Living Levee	$450	NA

Source: (Sea-Level Marin Adaptation Response Team; Marin County Community Development Agency n.d., Sea-Level Marin Adaptation Response Team and Marin County Community Development Agency 2017)

Table 16. Relative costs for natural and gray infrastructure solutions (from local sources)

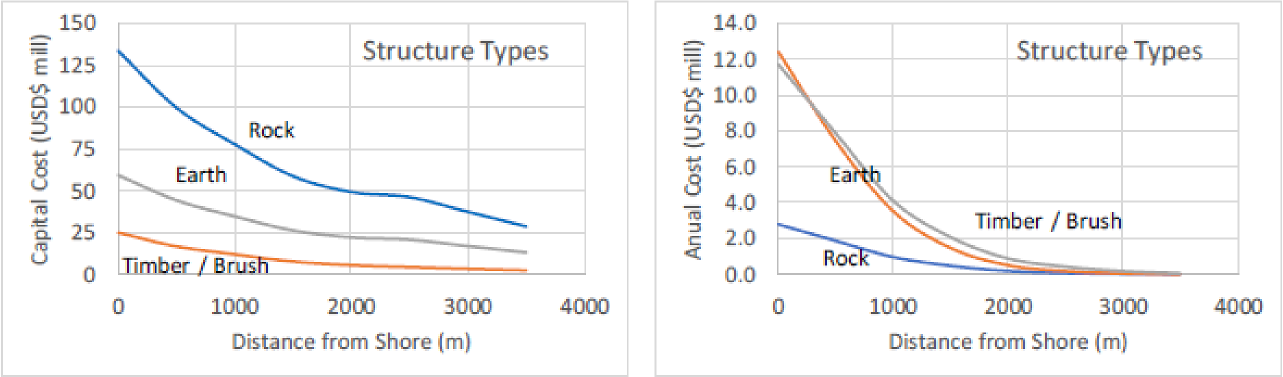
Shoreline Measure	Capital Costs (USD$ per linear meter)	Annual Operations and Maintenance (USD$ per linear meter)
Mangrove Restoration	$230 – $220,000[1] (per hectare)	Unknown
Sediment Trapping Unit	$10 - $20	$2 - $4
Levee/Dyke - Earth	$1.5 - $45	Unknown
Levee/Dyke - Rock	$300 - $450	Unknown
Seawall	$140 - $450	<$1
Development Setback	Unknown	Unknown

Notes: [1]Excludes land acquisition costs. Wide range of costs are attributed to the scope of restoration, for example construction difficulty, amount of soil material needed to restore/create hydrologically suitable conditions, and propagation method (hand planting versus seed dispersal)

Source: Lewis 2001, 2005, Nijbroek et al. 2012, Anthony 2015, Burke and Ding 2016, World Bank Group 2017

10.3 High-Order Cost-Benefit Summary

Figure 20 presents a cost comparison of capital costs and annual maintenance costs of green to gray infrastructure types (for Suriname), based on the setback distance from the existing shoreline. Traditional flood protection infrastructure comprised of rock or earthen materials have the greatest upfront capital costs, but lower annual operating and maintenance costs compared to timber/brush materials. With greater setback distances, less material is required to achieve the target flood protection levels.

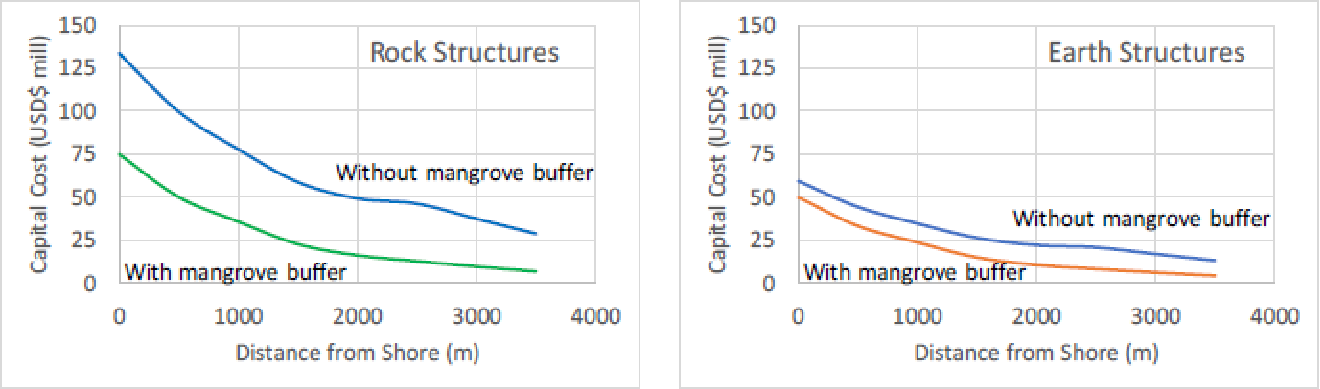


Note: Comparison graphs show cost as a function of infrastructure distance from shoreline. Width of infrastructure across shoreline is unknown.

Source: World Bank, 2017

Figure 20. Capital and annual (maintenance) costs associated flood protection materials

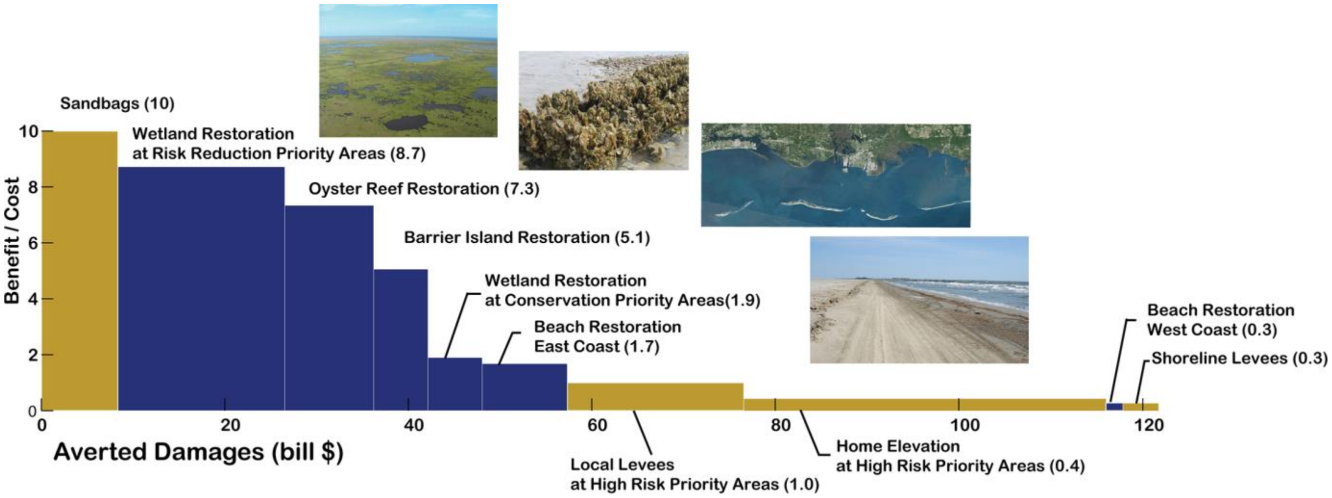
Figure 21 shows potential cost reduction in capital costs when integrating green infrastructure (e.g., mangroves) into overall flood protection solutions. Cost savings are generally constant regardless of the width of the mangrove buffer available seaward of a more traditional gray strategy. In a solution that uses a setback rock barrier coupled with a seaward mangrove buffer, cost savings of approximately 40% may be achieved compared to stand alone gray strategies. Coupling an earthen barrier behind a mangrove forest could result in cost savings of approximately 10-15% compared to a stand-alone gray strategy. This shows that leveraging the flood protection provided by mangrove forests allows for direct cost savings.



Note: Comparison graphs show cost as a function of infrastructure distance from shoreline. Width of mangrove buffer is 300 m. Width of infrastructure across shoreline is unknown.

Source: World Bank, 2017

Figure 21. Cost reduction with natural infrastructure (e.g., mangrove buffer)



Source: Reguero et al. 2018

Figure 22. Cost-benefit of adaptation strategies (green and gray)

Figure 22 shows a cost comparison of green, gray, and hybrid green-gray coastal adaptation solutions for the U.S Gulf of Mexico, which is subject to severe coastal hazards from hurricanes (and accompanying waves and storm surge). The vertical axis shows the benefit-cost ratio, with a score greater than 1.0 meaning that a measure's cost is expected to provide net positive benefits. The horizontal axis shows the potential total damage averted with each measure type, with the width of each vertical bar for each measure type denoting the scale of the benefit. The blue bars denote the nature-based or green measures, and the brown bars denote the gray engineered measures.

Figure 22 shows that nature-based solutions are the most cost-effective measures and provide the greatest damage reduction. Sandbags provide the highest cost-benefit ratio but are only temporary measures and don't provide as much damage reduction as other nature-based solutions. Localized gray measures such as local levees and elevating individual structures may provide the highest damage reduction, but they are very costly to implement especially over wide areas, and therefore have low cost-benefit ratios. With climate change and increasing flood risk due to sea level rise, nature-based solutions are expected to have increased cost-benefit ratios, making coastal adaptation using nature-based solutions more attractive. Note that while these estimates are specific to the U.S. Gulf region, they provide a general comparison for measures that are also applicable to the NBS-LME region.

With several primary shoreline typologies in the NBS-LME region (Section 9.3.1), a detailed cost-benefit analysis[9] is needed to identify the most appropriate strategies for individual vulnerable shoreline segments. The cost-benefit analysis should consider the capital cost of designing and constructing the adaptation strategies, regular monitoring, maintenance, potential land acquisition costs, land valuation (e.g., wetland versus agricultural land), potential land loss, relocation costs (e.g., setback), and other costs as appropriate for the local conditions. The annual ecosystem services provided by mangroves has been estimated to be almost $200,000 per hectare (based on global studies, Anthony 2015).

---

[9] A detailed cost-benefit analysis includes consideration of ecosystem services and benefits provided by nature-based solutions.

11 Existing Tools/Models to Evaluate Coastal Processes

Only a few coastal modeling studies have been completed in the NBS-LME region (Toorman et al. 2018b). In Suriname, the first coastal engineering study was completed by NEDECO (Netherlands Engineering Consultants 1968) to evaluate port access and navigation. More recently, Anton de Kom University of Suriname has built research capacity to conduct field investigations and support small-scale interventions along the shoreline with local expertise. Anton de Kom University staff are currently developing a morphodynamic model for a portion of the NBS-LME coast using the TELEMAC software suite. In Guyana, several coastal engineering studies have been completed by Delft Hydraulics and NEDECO (Netherlands Engineering Consultants 1972) to support the construction of the coastal defense system. Table 17 below summarizes relevant numerical models used for evaluating coastal processes in the NBS-LME region.

Table 17. Summary of existing tools/models developed for Guyana, Suriname and French Guiana

Location	Coastal Process	Model
Guyana	Hydrodynamics	Deflt3d-SWAN
	Waves	Deflt3d-SWAN
	Currents	Deflt3d-SWAN
Suriname	Hydrodynamics	TELEMAC
	Waves	TELEMAC-TOMAWAC; SwanOne
	Sediment	TELEMAC-SISYPHE
French Guiana	Hydrodynamics	MOBEEDHYCS
	Waves	Fudaa-VAG
	Salinity/Current	TELEMAC
	Sediment	MOBEEDHYCS

Source: Chevalier et al. 2004, Nikiema et al. 2007, Winterwerp et al. 2007, Toorman et al. 2018

The numerical models in Table 17 were generally developed for specific projects and locations; therefore, the existing model simulations are likely not sufficient to evaluate coastal process across the entire NBS-LME region. A unified modeling framework with consistent boundary conditions to drive coastal processes across a wide region can benefit NBS-LME scale evaluations. Table 18 (adapted from World Bank (2016)) presents some available tools and models appropriate for evaluating coastal process, including regional scale and local scale models. Development of a regional model would support the Framework presented in Section 8.2. A regional model can also be used to support more localized high-resolution models to evaluate adaptation strategies and support the design and implementation of coastal protection projects. This coupled regional and local scale modeling approach can also help identify potential regional scale impacts of specific projects (e.g., habitat loss, hydrodynamic impacts).

Table 18. Summary of existing tools/models (by category) available to support evaluations of coastal hazards and adaptation strategies

Type of Approach	Scope/Type of Problem	Scale of Applicability	Example Models	Key Considerations
Offshore Hydrodynamics				
Analytical or semi-empirical approximations	Wave propagation	Large scales	Snell's law	Approximates wave propagation for idealized geometries. Uses analytical solutions of linear wave theory for idealized bathymetry.
Analytical or semi-empirical approximations	Storm surge propagation	Large scales	Dean and Dalrymple 1984	-
Numerical modeling	Wave propagation	Regional to local scales	Spectral wave models: Swan, Stwave	Used for wave propagation in large domains, where the wave energy distribution is the main effect to consider.
Numerical modeling	Wave propagation	Local scales	Mild slope based models: REFDIF, CGWave, OLUCA, TELEMAC-MASCARET, Fudaa-Vag	Provides accurate definition of near shore processes at smaller domains: refraction, diffraction, and breaking.
Numerical modeling	Storm surge propagation	All scales	SLOSH, ADCIRC, DELFT3D, CEST, MIKE21, TELEMAC-MASCARET, MOBEEDHYCS	Numerical models provide a robust approach for computing the surge associated with tropical and extra-tropical storms. They generate the surge from the storm's meteorological conditions (wind and pressure) in 2D and 3D domains and can capture higher resolution approaching the shoreline.

Type of Approach	Scope/Type of Problem	Scale of Applicability	Example Models	Key Considerations
Estimate Nearshore Hydrodynamics				
Numerical modeling	Wave propagation	Regional to local scales	Spectral wave models: Swan, Stwave	Used for wave propagation in large domains, where the wave energy distribution is the main effect to consider.
Numerical modeling	Wave propagation	Local scales	Mild slope based models: REFDIF, CGWave, OLUCA, TELEMAC-MASCARET, Fudaa-Vag	Provides accurate definition of near-shore processes at smaller domains: refraction, diffraction, and breaking.
Numerical modeling	Storm surge propagation	All scales	SLOSH, ADCIRC, DELFT3D, CEST, MIKE21,TELEMAC-MASCARET, MOBEEDHYCS	Numerical models provide a robust approach for computing the surge associated with tropical and extra-tropical storms. They generate the surge from the storm's meteorological conditions (wind and pressure) in 2D and 3D domains and can capture higher resolution approaching the shoreline.
Numerical modeling	Wave damping	Local scales	SWAN-Mud	Morphodynamics including wave damping due to mud

Type of Approach	Scope/Type of Problem	Scale of Applicability	Example Models	Key Considerations
Evaluate Effects of Coastal Structures (habitat) on Hydrodynamics				
Analytical or semi-empirical approximations	Wave dissipation from vegetation	Large to regional scales	Dean and Dalrymple 1984	Dissipation of waves based on vegetation parameters such as stem diameter, height, and density and relative submergence of plants.
Numerical modeling	Storm surge dissipation by vegetation	Large to regional scales	Krauss et al. 2009–9.4 cm/km; Zhang et al. 2012–40–50 cm/km	Surge attenuation depends strongly on the forest width and other factors, such as vegetation density and relative submergence or the storm velocity.

Type of Approach	Scope/Type of Problem	Scale of Applicability	Example Models	Key Considerations
Numerical modeling	Wave dissipation from vegetation	Regional to local domains	Swan-Veg, STWave, WHAFIS (1D), IH2VOF (1D)	Includes wave propagation models that incorporate wave dissipation models by vegetation.

Type of Approach	Scope/Type of Problem	Scale of Applicability	Example Models	Key Considerations
Coastal Protection (Flooding and Erosion)				
Analytical or semi-empirical approximations	Wave run-up	All scales	Beach run-up: Stockdon et al., 2006; Rubble-mounds: Van der Meer and Stam (1992)	There are several semi-empirical formulations to estimate run-up statistics for the wave conditions and the geometry of the structures.
Numerical modeling	Wave run-up & inland flooding	Small scales	SWASH, FUNWAVE, IH2VOF, DELFT3D, TUFLOW	Run-up over structures or beach profiles. Different options for models, varying in degrees of complexity and accuracy.
Analytical or semi-empirical approximations	Cross-shore evaluation	Large to regional scales	Dean 1991; Soulsby 1997	Sediment movement on a beach profile.
Analytical or semi-empirical approximations	Long-shore evaluation of sediment transport	Large to regional scales	Bijkers 1971, Engelund and Hansen 1967, CERC 1984	Sediment movement along shore due to currents, oblique incidence of waves, and wave height gradients.
Numerical modeling	Cross-shore evaluation	Regional to local scales	MOPLA, Delft3D, TELEMAC-MASCARET, Xbeach	Sediment movement on a beach profile.
Numerical modeling	Long-shore evaluation of sediment transport	Small scales	MOPLA, Delft3D, Xbeach, TELEMAC-MASCARET, CMS	Coupled models and morphological models for sediment transport along shore in 2D or 3D.

Source: World Bank 2016.

12 Data Gaps and Next Steps

12.1 Data Gaps and Validation

Data gaps were identified during the data development and discovery phase that prevented using the Framework as intended (see Table 19). Filling the data gaps would support using the Framework to identify local- and regional-scale vulnerabilities and inform the selection of adaptation responses. Filling all of the data gaps in Table 19 may not be required to use the Framework; however, filling the data gaps with a noted "High" need should take priority. Engaging local practitioners (e.g., from the Anton de Kom University of Suriname and NAREI) before undertaking any new analysis or data collection would likely be beneficial. Coordinating and partnering with experienced local practitioners would allow for knowledge sharing and support the validation of data gaps.

Table 19. Data gaps[10] in coastal vulnerability indicators

Type	Data Gap	Description	Need
Site Morphology	Coastal Elevation	Estimates of shoreline elevations. Can be obtained with GIS analysis using topographic data and existing shoreline delineation.[1]	High
	Coastal Slope	Estimates of coastal slope. Can be obtained with GIS analysis using bathymetric data.[1]	Moderate
	Shoreline Change Rate	Evaluation of historical shoreline change rates. Can be calculated using aerial imagery and GIS analysis.[1]	Low
	Shoreline Geomorphology	Evaluation of shoreline geomorphology using aerial imagery and field photographs. Can be completed in GIS.	High
	Beach Width	Calculation of beach width (if present) using aerial imagery and field photographs. Can be completed in GIS.	Moderate
	Sediment Supply	Localized rates of sediment supply across region.	Low
	Mudbank Locations	Delineation of current mudbank locations using aerial imagery and additional information. Can be completed in GIS.	High
Wave Climate	Significant Wave Height	Validation using additional data sources.	High
Coastal Hydrodynamics	Tidal Range	Local long-term (e.g., 30 years) of tide observations to calculate tidal datums or existing information on tidal datums (e.g., Mean High Water and Mean Low Water) for NBS-LME region.	High

---

[10] All data gaps are across the entire NBS-LME region, unless otherwise noted.

Type	Data Gap	Description	Need
Coastal Hydrodynamics	Extreme Tide Elevations	Local long-term (e.g., 30-years) tide observations and subsequent calculation of extreme water levels (25-, 50-, and 100-year storm surge), or existing extreme water level statistics for NBS-LME region.	High
	Depth of 25-, 50-, and 100-year Storm Surge (m) above Coastal Elevation	Calculation of depth of overtopping over shoreline elevations	High
	Historical Sea Level Rise	Validation of historical sea level rise using local tide station data	Low
	Future Sea Level Rise	Localized estimates of relative sea level rise projections are not currently available.	Moderate
Land Use/Land Cover	Groundwater	Evaluate groundwater rise and salinity intrusion, as these processes in the NBS-LME are currently unknown.	Low
	Coastal Land Use	Identification of primary coastal land use for all shoreline segments. Can be completed in GIS with supplemental information (e.g., building layers, land use/land cover data)	High
	Hydrologically connected areas	Delineation of hydrologically connected areas behind each shoreline segment. Can be completed in GIS.	High
	Vegetation Width	Measurement of vegetation buffer width (if present), using aerial imagery or field delineations. Can be completed in GIS.	High
	Land Use/Land Cover Connectivity	Delineation of hydrologically connected areas with similar land use/land cover. Can be completed in GIS with supplement information.	High
	Population	Population count by village	High
	Per capita Gross Domestic Product (GDP)	Per capita GDP by village	High
	Critical Facilities	Spatial identification of critical facilities	High
	Infrastructure - Repair/Replacement Cost	Spatial identification of infrastructure (buildings, structures, utilities) and associated costs of repair/replacement	High

Notes: [1]Data gap can be filled without additional datasets but requires processing time/resources beyond scope of current project.

13 Governance and Policy Strategies for Nature Based Solutions

Governance and policy-related strategies are non-structural measures for increasing the overall resilience of the NBS-LME region to climate hazards. While physical adaptation strategies may provide direct coastal protection, governance strategies can better prepare communities for emergency action and promote resilience on a regional scale. Governance strategies may include defining and enforcing building code standards, defining and enforcing land-use based flood hazard zones, and developing communication and outreach strategies to inform residents and businesses about changing flood hazards and risks over time.

13.1 Key Messages

- Flood risk reduction should be supported with governance and policy strategies (non-structural measures).
- Flood risk cannot be eliminated. However, the addition of governance and policy strategies can promote risk reduction by increasing the resilience of existing structures, setting standards for new design and construction, improving land-use zoning, and developing an emergency response plan.
- Cross-jurisdictional planning and partnerships will help achieve resilience goals on a regional scale. Implementing adaptation solutions in a silo could lead to unintended impacts to adjacent shorelines and communities

13.2 Emergency Response Planning

Emergency management systems (including forecasting, warning and evacuation) are non-structural measures that support flood risk mitigation (World Bank Group 2017). An emergency response plan should consider all potential hazards and natural disasters and should consider which hazards could be exacerbated by climate change. An emergency response plan should also detail how community officials will inform communities in advance of, or during, a natural disaster such as a large flood event. The plan should also include information on evacuation procedures, emergency shelter locations, communication protocols within the responsible agency, external communication protocols with partner agencies and local and national government contacts, messaging to the media, messaging to the impacted and surrounding communities, and an initial plan for post-disaster response activities. An emergency management agency within local government should develop and manage the plan and response activities.

13.3 Floodproofing

Floodproofing existing and new structures can reduce potential damage to a structure and its contents during a flood event. Floodproofing can be temporary (requires active management) or permanent (passive protection but requires maintenance). Temporary floodproofing can include placing sandbags or installing temporary watertight seals across structure openings in advance of a flood event.

Permanent floodproofing generally requires more substantial interventions, such as installing submarine doors and windows or constructing flood barriers.

Common approaches are classified as either dry or wet floodproofing. Dry floodproofing sealing the structure to keep floodwaters from entering the structure, and to keep the structure dry below a set flood protection elevation. Dry floodproofing works best when flood depths are less than 1 meter or flood velocities are slower than 1.5 meters per second. Wet floodproofing allows floodwaters to enter a building or structure through flood vents or other openings that help alleviate hydrostatic pressure on walls and foundations. Electrical and mechanical equipment must be elevated above projected flood elevations. Structures that are elevated on stilts or piles are using wet floodproofing methods.

The following resources provide information on floodproofing methods:

- American Society of Civil Engineers: 24-05 Flood Resistant Design and Construction (ASCE 2006), a standard referenced in the International Building Code that requires structures in a FEMA Special Flood Hazard Area to be designed using ASCE 24-05. ASCE 24-05 provides minimum requirements for design and construction of structures to support their resistance to flood loads and damage.
- American Society of Civil Engineers: Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7) (ASCE 2010) provides an overview of typical flood loads that occur when floodwaters reach buildings/structures and design requirements
- American Society of Civil Engineers: Climate-Resilient Infrastructure, Adaptive Design and Risk Management (ASCE 2018) provides guidance for coastal flooding, including design criteria, design flood elevation standards, and adaptive design considering uncertainty and risk.
- Federal Emergency Management Agency: Floodproofing for Non-Residential Buildings (FEMA 2013) has information focused on floodproofing measures appropriate for non-residential building, with a focus on dry floodproofing.
- Federal Emergency Management Agency: Protecting Building Utility Systems from Flood Damage (FEMA 2017) provides information for floodproofing and protecting utility systems and utility conduit flood pathways.
- Federal Emergency Management Agency: Homeowner’s Guide to Retrofitting (FEMA 2014) provides guidance for increasing residential buildings resilience to flooding
- New York City Climate Resiliency Design Guidelines (NYC 2019) includes a wide range of design guidance for assets and infrastructure at risk of flooding due to climate change and extreme climate events.
- United States Army Corps of Engineers: Flood Damage Reduction Matrix. Matrix of suitable flood proofing measures applicable for a range of building/structure configurations, site conditions, and flood characteristics https://www.usace.army.mil/Missions/Civil-Works/Project-Planning/nnc/)

13.4 Coastal Land Use Policies

The government of Suriname has developed regional coastal management plans and defining mixed use management areas (MUMA) with a focus on environmental resources. Coastal development setbacks have been defined, with consideration of the dynamic coastal zone and its evolution over the next 100-years. Suriname also has the Coastal Protection Act (CPA) proposed through legislation. Prior studies have proposed minimum setbacks of 3-4 km to discourage further urban expansion towards the shoreline and promote sustainability of the mangrove ecosystem (Erftemeijer and Teunissen 2009).

Coastal land use policies should consider riverine and coastal hazard zones, limit development in high hazard zones, and include or reference design standards and/or building codes in high and moderate risk zones. Unrestrained development in high hazard zones will place more structures and people at risk and will increase the need for (and cost of) coastal flood protection and adaptation.

13.5 Design Standards and Building Codes

The planning and design of new buildings and structures should consider flood hazards and climate change impacts that could occur over the course of the structures function lifespan. Many structures built today will last for 100 years or more; therefore, climate change must be considered. New buildings and structures have opportunities to streamline climate resilience and build in the ability to adapt to address future climate uncertainties.

Key considerations during the planning and design phase:

- Locate structures outside of the riverine and coastal hazard zones, with consideration for sea level rise and other climate related impacts if applicable. If facilities must be located within flood hazard zones, the design should include appropriate floodproofing elements and consider existing and future flood loads that could occur.
- Set design flood elevations that consider the functional lifespan of the structure. For example, a building that will remain in operation until 2100 that is in a flood hazard zone should set the lowest adjacent grades at or above the design flood elevation (e.g., the elevation reached by a 100-year storm surge coupled with sea level rise expected by 2100).
    - The design should also consider measures to accommodate higher than expected sea level rise occurring within the functional lifespan. Target adaptation design elevations should be set during the planning phase to accommodate future improvements such as the installation of floodproofing measures at entryways or raising electrical and mechanical equipment.
- Set potential flood entryways into facilities (e.g., vent/louvers, windows, doorways) at or above the design flood elevation.
- Floodproof at-grade flood entryways into facilities (e.g., manholes, utility/conduit spaces, and tunnel entrances) to accommodate flood depths up to the design flood elevation.

13.6 Cross Jurisdictional Governance

Coastal vulnerability and potential flood impacts across the NBS-LME region do not follow or align jurisdictional boundaries. The Framework presented in Section 8.2 helps identify existing vulnerabilities without consideration of land ownership or political boundaries. Adaptation strategy implementation must consider not only the coastal flood protection provided to inland areas, but the potential impacts and/or benefits that strategy may create for adjacent areas. A historical example of adjacent impacts is the shoreline erosion adjacent to existing seawall in Guyana. Identifying where impacts and/or benefits could occur will help foster collaborations and partnerships and could expand potential funding sources and lead to more resilient solutions.

14 References

---, A. 2016. Managing Coasts with Natural Solutions Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs.

Allison, M. A., and M. T. Lee. 2004. Sediment exchange between Amazon mudbanks and shore-fringing mangroves in French Guiana. Pages 169–190 Marine Geology.

Alongi, D. M. 2008, January 1. Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change.

American Society of Civil Engineers. 2010. ASCE 7: Minimum Design Loads for Buildings and Other Structures. Second edition. American Society of Civil Engineers (ASCE), Reston, Virginia.

Anthony, E. J. 2015. Assessment of peri-urban coastal protection options in Paramaribo-Wanica, Suriname.

Anthony, E. J. ., G. Brunier, A. Gardel, and M. Hiwat. 2019. Chenier Morphodynamics on the Amazon-Influenced Coast of Suriname, South America: Implications for Beach Ecosystem Services. Frontiers in Earth Science 7.

Anthony, E. J., F. Dolique, A. Gardel, N. Gratiot, C. Proisy, and L. Polidori. 2008. Nearshore intertidal topography and topographic-forcing mechanisms of an Amazon-derived mud bank in French Guiana. Continental Shelf Research 28:813–822.

Anthony, E. J., A. Gardel, and N. Gratiot. 2013. Fluvial sediment supply, mud banks, cheniers and the morphodynamics of the coast of South America between the Amazon and Orinoco river mouths. Geological Society, London, Special Publications 388:533–560.

Anthony, E. J., and N. Gratiot. 2012. Coastal engineering and large-scale mangrove destruction in Guyana, South America: Averting an environmental catastrophe in the making. Ecological Engineering 47:268–273.

ASCE. 2006. Flood Resistant Design and Construction (ASCE/SEI 24-05). American Society of Civil Engineers, ASCE Press.

ASCE. 2010. Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7). Americal Society of Civil Engineers.

ASCE. 2018. Climate-Resilient Infrastructure, Adaptive Design and Risk Management. American Society of Civil Engineers, Committee on Adaptation to a Changing Climate, Reston, Virginia.

Balica, S. F., N. G. Wright, and F. van der Meulen. 2012. A flood vulnerability index for coastal cities and its use in assessing climate change impacts. Natural Hazards 64:73–105.

Barbier, E. B., E. W. Koch, B. R. Silliman, S. D. Hacke, E. Wolanski, J. Primavera, E. F. Granek, S. Polasky, S. Aswani, L. A. Cramer, D. M. Stoms, C. J. Kennedy, D. Bael, C. V. Kappel, G. M. E. Perillo, and D. J. Reed. 2008. Coastal ecosystem-based management with nonlinear in ecological functions and values. Science 319.

Burke, L., and H. Ding. 2016. Valuation of Coastal Protection near Paramaribo, Suriname.

Cete. C., Haage, S.; Hardwarsing, V., Kalloe, S.; Ma-ajong, A. 2018. Mangrove Project Suriname - CIE4061-09 Multidisciplinary Project.

Chevalier, C., M. Baklouti, A. Ramamonjiarisoa, C. Chevalier, M. Baklouti, A. Ramamonjiarisoa, C. De

Luminy, and F.- Nancy. 2004. Modeling the Influence of Wind and Rivers on Current , Salinity and Temperature over the French Guiana Continental Shelf during the Rainy Season Stable URL : https://www.jstor.org/stable/4299375 Modeling the Influence of Wind and Rivers on Current , Salin 20:1183–1197.

Cohen-Shacham, E., G. Walters, C. Janzen, and S. Maginnis. 2016. Nature-based Solutions to address global societal challenges. IUCN, Gland, Switzerland.

Colgan, C. S., M. W. Beck, and S. Narayan. 2017. Financing Natural Infrastructure for Coastal Flood Damage Reduction. London.

Conger, T. 2018. Coastal Green Infrastructure As a Sea Level Rise Adaptation Measure : Assessing Environmental , Local and Institutional Contexts.

Crooks, S., B. L., M. Mak, and C. May. 2019. North Brazil Shelf Mangrove Project - Regional Biophysical Review - Draft Report.

Dalrymple, O. K., and R. S. Pulwarty. 2006. Sea-level Rise Implications for the Coast of Guyana: Sea walls and muddy coasts. Page Fourth LACCEI International Latin American and Caribbean Conference for Engineering and Technology. Mayaguez.

Dean, R. G., and R. A. Dalrymple. 1984. Water wave mechanics for engineers and scientists. Prentice-Hall, Englewood Cliffs, N.J.

Dwarakish, G. S., S. A. Vinay, U. Natesan, T. Asano, T. Kakinuma, K. Venkataramana, B. J. Pai, and M. K. Babita. 2009. Coastal vulnerability assessment of the future sea level rise in Udupi coastal zone of Karnataka state, west coast of India. Ocean and Coastal Management 52:467–478.

Environmental Services Limited. 2019. Final Draft Envionmental and Social Impact Assessment for the Nearshore Exploration Drilling Project 2019, Suriname.

Erftemeijer, P., and P. Teunissen. 2009. ICZM Plan Suriname Mangrove forest management Analysis of problems and solutions SCZM/Deltares-Teunissen Mangrove Report Final / ICZM Plan Suriname-Mangrove Report Analysis of problems and solutions for the management of mangrove forests along Suriname’s “wild coast” ICZM Plan Suriname Mangrove forest management Analysis of problems and solutions SCZM/Deltares-Teunissen Mangrove Report Final.

FEMA. 2013. Floodproofing Non-Residential Buildings (FEMA P-936). Washington, DC, USA.

FEMA. 2014. Homeowner’s Guide to Retrofitting (FEMA P-312). Federal Emergency Management Agency, Washington, DC, USA.

FEMA. 2017. Protecting Building Utility Systems From Flood Damage. Principles and Practices for the Design and Constructions of Flood Resistant Building Utility Systems. FEMA P-348, Edition 2. Federal Emergency Management Agency, Washington, DC, USA.

Flemming, B. W. 2012. Geology, Morphology, and Sedimentology of Estuaries and Coasts. Pages 7–38 Treatise on Estuarine and Coastal Science. Elsevier Inc.

Gilman, E. L., J. Ellison, N. C. Duke, and C. Field. 2008, August. Threats to mangroves from climate change and adaptation options: A review.

Gleason, S. M., and K. C. Ewel. 2006. Organic Matter Dynamics on the Forest Floor of a Micronesian Mangrove Forest: An Investigation of Species Composition Shifts1. Biotropica 34:190–198.

Gornitz, V.; Beaty, T., Daniels, R. 1997. A Coastal Hazards Data Base for the U.S. West Coast.

Gornitz, V. 1991. Global coastal hazards from future sea level rise. Palaeogeography, Palaeoclimatology, Palaeoecology 89:379–398.

Hickey, C., and T. Weis. 2012. The challenge of climate change adaptation in Guyana. Climate and Development 4:66–74.

Intergovernmental Panel on Climate Change. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Kopp, R. E., R. M. DeConto, D. A. Bader, C. C. Hay, R. M. Horton, S. Kulp, M. Oppenheimer, D. Pollard, and B. H. Strauss. 2017. Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections. Earth’s Future 5:1217–1233.

Krauss, K. W., J. A. Allen, and D. R. Cahoon. 2003. Differential rates of vertical accretion and elevation change among aerial root types in Micronesian mangrove forests. Estuarine, Coastal and Shelf Science 56:251–259.

Krauss, K. W., T. W. Doyle, T. J. Doyle, C. M. Swarzenski, A. S. From, R. H. Day, and W. H. Conner. 2009. Water level observations in mangrove swamps during two hurricanes in Florida. Wetlands 29:142–149.

Lewis, R. R. 2001. Mangrove Restoration - Costs and Benefits of Successful Ecological Restoration. Pages 4–8 Mangrove Valuation Workshop, Universiti Sains Malaysia, Penang.

Lewis, R. R. 2005. Ecological engineering for successful management and restoration of mangrove forests. Ecological Engineering 24:403–418.

Mazda, Y., and M. Magi. 1997. Mangroves as a coastal protection from waves in the Tong King Delta, Vietnam. Mangroves and Salt Marshes 1:127–135.

McIvor, A., T. Spencer, I. Möller, and M. Spalding. 2012. Storm surge reduction by mangroves. Natural Coastal Protection Series: Report 2. Cambridge Coastal Research Unit Working Paper 41. Natural Coastal Protection Series:35.

Mckee, K. L. 2011. In a Nutshell Biophysical Controls on Accretion and Elevation Change in Caribbean Mangrove Ecosystems. Page Estuarine, Coastal and Shelf Science.

McLaughlin, S., J. Andrew, and G. Cooper. 2010. A multi-scale coastal vulnerability index: A tool for coastal managers? Environmental Hazards 9:233–248.

National Agricultural Reserach and Extension Institute. 2015. NAREI - Annual Report 2015.

National Agricultural Reserach and Extension Institute. 2016. NAREI - Annual Report 2016. Page Annual Report 2016.

National Agricultural Reserach and Extension Institute. 2017. NAREI - Annual Report 2017. Page Annual Report.

Netherlands Engineering Consultants. 1968. Suriname Transportation Study - Report on Hydraulic Investigation.

Netherlands Engineering Consultants. 1972. Report on Sea Defense Studies.

Nijbroek, R. P., P. Basu, K. Archer, M. Bosman, R. Johns, and M. Miller. 2012. Mangroves, Mudbanks and Seawalls: Political Ecology of Adaptation to Sea Level Rise in Suriname.

Nikiema, O., J. Devenon, and M. Baklouti. 2007. Numerical modeling of the Amazon River plume 27:873–899.

NYC. 2019. Climate Resiliency Design Guidelines, version 3.0. New York City, Mayor’s Office of Recovery and Resiliency, New York, New York, USA.

Pantusa, D., F. D’Alessandro, L. Riefolo, F. Principato, and G. R. Tomasicchio. 2018. Application of a coastal vulnerability index. A case study along the Apulian Coastline, Italy. Water (Switzerland) 10:1–16.

Pendleton, E. ., E. . Hammar-klose, E. R. Thieler, and S. J. Williams. 2004. In cooperation with the National Park Service Coastal Vulnerability Assessment of Cape Cod National Seashore (CACO) to Sea-Level Rise U . S . Department of the Interior. Page USGS open file report.

Pendleton, E. A., E. R. Thieler, and S. J. Williams. 2010. Importance of Coastal Change Variables in Determining Vulnerability to Sea- and Lake-Level Change. Journal of Coastal Research 261:176–183.

Prevedel, L. M. 1997. Longshore Current Variations, Guyana, South America.

Reguero, B. G., M. W. Beck, D. N. Bresch, J. Calil, and I. Meliane. 2018. Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. PLoS ONE 13:1–24.

Ruh Ali, A. 2016. Scholarship at UWindsor Assessing Change and Vulnerability of the Guyana Coastline with Multi-Temporal Landsat Imagery and Survey Data.

Sea-Level Marin Adaptation Response Team; Marin County Community Development Agency. (n.d.). Appendix A Adaptation Strategy.

Sea-Level Marin Adaptation Response Team, and Marin County Community Development Agency. 2017. Marin Ocean Coast Sea Level Rise Adaptation Report Marin Ocean Coast Sea Level Rise Adaptation Report.

Serio, F. De, E. Armenio, M. Mossa, and A. F. Petrillo. 2018. How to Define Priorities in Coastal Vulnerability Assessment:1–20.

Spalding, M. D., A. L. McIvor, M. W. Beck, E. W. Koch, I. Möller, D. J. Reed, P. Rubinoff, T. Spencer, T. J. Tolhurst, and T. V Wamsley. 2014. Coastal ecosystems: a critical element of risk reduction. Conservation Letters 7:293–301.

Strauss, B., and S. Kulp. 2018. Sea-Level Rise Threats in the Caribbean - Data , tools , and analysis for a more resilient future.

Thom, B. G. 1967. Mangrove Ecology and Deltaic Geomorphology: Tabasco, Mexico. The Journal of Ecology.

Toorman, E. A., E. Anthony, P. G. E. F. Augustinus, A. Gardel, N. Gratiot, O. Homenauth, N. Huybrechts, J. Monbaliu, K. Moseley, and S. Naipal. 2018a. Interaction of Mangroves, Coastal Hydrodynamics, and Morphodynamics Along the Coastal Fringes of the Guianas. Pages 429–473 Threats to Mangrove Forests. Springer.

Toorman, E. A., E. Anthony, P. G. E. F. Augustinus, A. Gardel, N. Gratiot, O. Homenauth, N. Huybrechts, J. Monbaliu, K. Moseley, and S. Naipal. 2018b. Interaction of Mangroves, Coastal Hydrodynamics, and Morphodynamics Along the Coastal Fringes of the Guianas. Pages 429–473.

United States Army Corps of Engineers. 1998. Water Resources Assessment of Guyana.

Winterwerp, J. C., P. L. A. Erftemeijer, N. Suryadiputra, P. Van Eijk, and L. Zhang. 2013. Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts. Wetlands 33:515–526.

Winterwerp, J. C., R. F. De Graaff, J. Groeneweg, and A. P. Luijendijk. 2007. Modelling of wave damping at Guyana mud coast 54:249–261.

World Bank Group. 2017. Coastal Resilience Assessment - Paramaribo, Suriname.

World Business Council for Sustainable Development. 2017. Incentives for Natural Infrastructure - Review of existing policies, incentives and barriers related to permitting, finance and insurance of natural infrastructure. Geneva.

Wuebbles, D. J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock. 2017. Climate Science Special Report: Fourth National Climate Assessment, Volume I. Washington, DC.

Zhang, K., H. Liu, Y. Li, H. Xu, J. Shen, J. Rhome, and T. J. Smith. 2012. The role of mangroves in attenuating storm surges. Estuarine, Coastal and Shelf Science 102–103:11–23.