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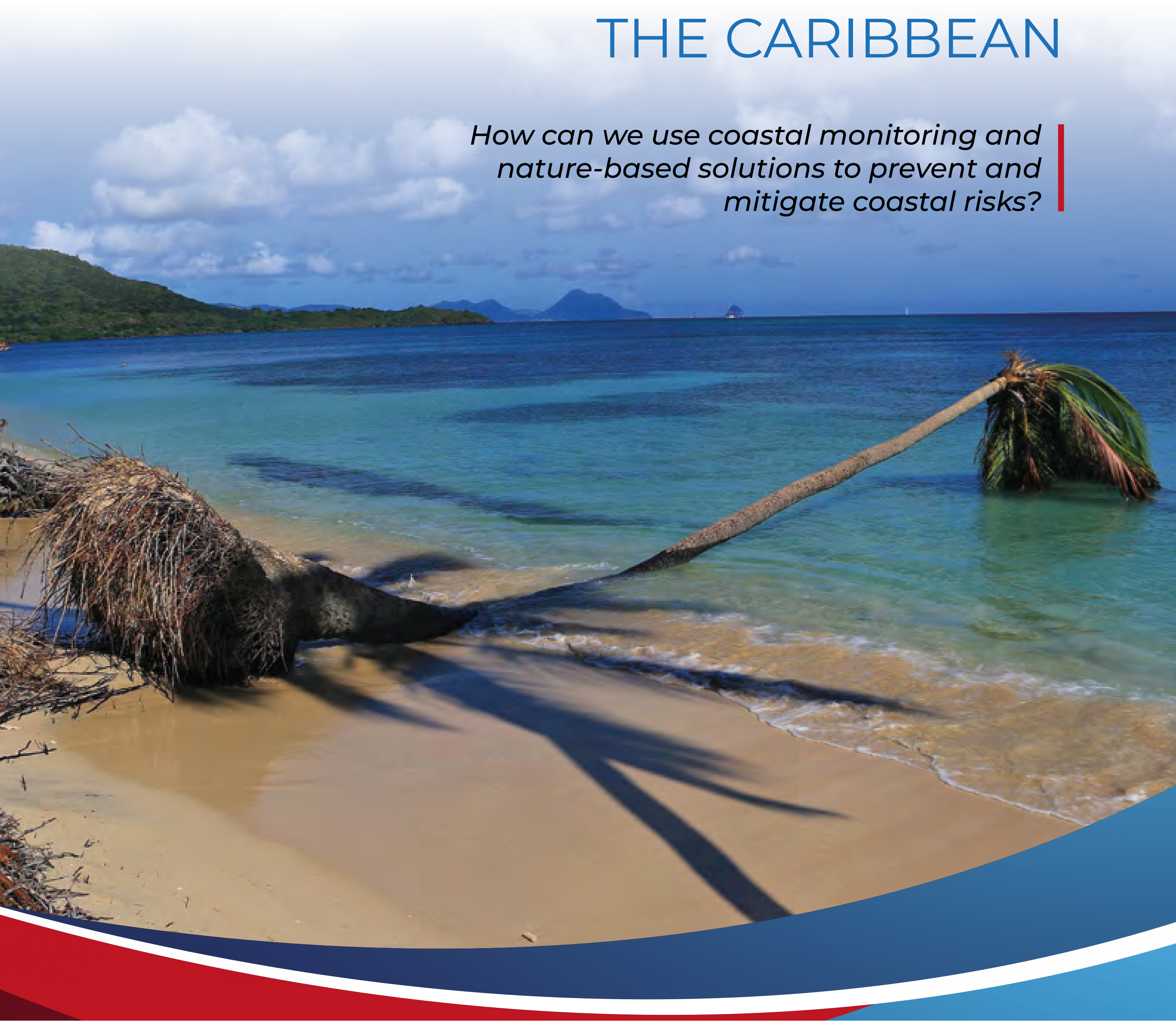
GUIDE FOR COASTAL EROSION MANAGEMENT IN THE CARIBBEAN

How can we use coastal monitoring and nature-based solutions to prevent and mitigate coastal risks?



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Introduction

Coastal areas in the island states of the Caribbean concentrate the majority of the population, economic activities, economic activity and infrastructure, and their economies highly depend on tourism and natural resources exploitation. However, coastal areas in these states are very exposed to coastal hazards in connection with intense meteorological phenomena induced by cyclonic activity on a regional scale and the rise in sea level in connection with climate change on a global scale.

This document aims to provide general recommendations for the development of coastal risks management strategies and to promote nature-based solutions (NBS) to mitigate coastal risks. It is intended for decision-makers and managers in Caribbean island states exposed to coastal erosion and marine submersion as well as the challenges of adapting to the effects of climate change in coastal areas. It is not intended to provide technical design advice but rather to introduce approaches that can be implemented in coastal areas of the Caribbean region.

This guide, specially adapted to the Caribbean region, was produced as part of the European regional cooperation project Interreg CARIB-COAST, the Caribbean network for the prevention of coastal risks related to climate change, with the support of the Bureau of Geological and Mining Research (Bureau de recherches géologiques et minières / BRGM), the National Forests Office (ONF) and the Regional Activity Center for the Protocol concerning Specially Protected Areas and Wildlife in the Greater Caribbean Region (SPAW-RAC). It was produced on the basis feedback from the work carried out in the framework of this project as well as on the basis of international recommendations.

1

Caribbean island context

GEOGRAPHIC CONTEXT

The Caribbean islands extend over an arc between northern Venezuela and southern Florida in the tropical zone of the northern hemisphere. There are also generally two groups among these islands. The Greater Antilles, made up of four main islands (Cuba, Jamaica, Hispaniola, and Puerto Rico) and the Lesser Antilles are organized into two island arcs. An external arc, from Barbados to Anguilla and extended north to the Bahamas made up of low and limestone islands. An internal arc, from Grenada to the northern islands, made up of mountainous and volcanic islands.

GEOLOGICAL AND MORPHOLOGICAL CONTEXT

The two main types of morphology of the Caribbean islands are associated with different geological contexts. The most recent islands, predominantly volcanic (Dominica, Martinique, Saint-Vincent and the Grenadines, for example), have significant relief with steep slopes. These islands are generally exposed to landslide. The presence of fringing reef is quite limited. The coastal plain is generally undeveloped and concentrates a large part of the population. The older islands, which are predominantly limestone, are generally associated with reef formations resting on an ancient volcanic bedrock (Antigua and Barbuda and Anguilla for example). They have a more or less elevated tabular/plateau morphology depending on the influence of tectonics with steep cliff coasts or extensive coastal plains. Finally, there are mixed islands, with both volcanic and limestone origin such as Guadeloupe and the Greater Antilles.

CLIMATE CONTEXT

Located in the tropical zone, the Caribbean islands are subject to a relatively stable climate in terms of temperature. The amounts of rainfall vary however according to the islands, altitude, and exposure. The rainfall regime is associated with a dry season from December to April and a wet season from May/June to October/November with transition periods. The trade wind regime is constant in direction and varies from the south-east to north-east area. The trade winds strengthen from June to July and December to March. Mid-latitude depressions can also affect the Greater Antilles, particularly during the winter period from October to April. The Caribbean islands are also located in the area of hurricanes which develop in the tropical zone of the North Atlantic and move west between June and November with a peak in intensity of hurricane activity observed in September.

HYDRODYNAMIC CONTEXT

The tidal range in the Caribbean is low with variations between 0.3 and 0.5 m for spring tides. Most of the islands experience a diurnal unequal tidal regime, that is to say that there are significant variations between the height of high tides and low tides on the same day. The waves are mainly generated in the Caribbean Sea and North Atlantic areas and with variations ranging from the south-east to north-east area depending on the trade winds, which are relatively constant throughout the year. There is thus a distinction between the coastal areas, windward in the east, which are more exposed, and those leeward, which are more protected, in the west of these islands. During the winter period of the northern hemisphere, mid-latitude depressions can generate powerful waves from the northern area generally during the period from December to March. Finally, cyclones can generate episodes of very intense waves that can impact any coastal area between June and November.

COASTAL ENVIRONMENTS AND ASSOCIATED ECOSYSTEMS IN THE CARIBBEAN

There is a great diversity of coastal environments in the Caribbean associated with the structure and geological characteristics of these islands. These are steep cliffs, low rocky platforms, barrier beaches or mangrove wetlands.

Barrier beaches and upper beach vegetation

The morphology of the beaches in the Caribbean islands (Figure 1) includes long strips, which can extend over several kilometers, as well as small pocket beaches of only a few hundred meters, at the bottom of the bay and delimited by cliffs or rocky promontories. The variety of sediments in terms of size and nature is also significant, depending on the lithology of the coast, the presence or lack of rivers or coral reefs. In the low limestone islands, sediments are originally biogenic (calcareous sands and shells) generally coming from the surrounding reef platforms. For the high volcanic islands, beaches are composed of sediments of volcanic origin (black sands and pebbles), brought to the coast by rivers and resulting from the erosion of volcanic rock formations.

Barrier beaches are constantly changing, under the effect of meteorological, geological, and anthropogenic factors. The energy of incident waves, the presence or lack of coral reefs represent the most significant natural factors in controlling the morphology of Caribbean beaches.

Beaches represent a high socio-economic value, particularly in the Caribbean with economies geared towards tourism and provide ecosystem services for local populations as well as an ecological role for emblematic species such as sea turtles for example. Naturally present on sandy coastlines, high-beach ecosystems are found throughout the Caribbean. The vegetation that composes them, which can be described as dry coastal flora, is adapted to the harsh conditions of the Caribbean coast. These plant species are thus capable of maintaining themselves on sandy, permeable, saline, and unstable soil and above all of resisting swell and spray.

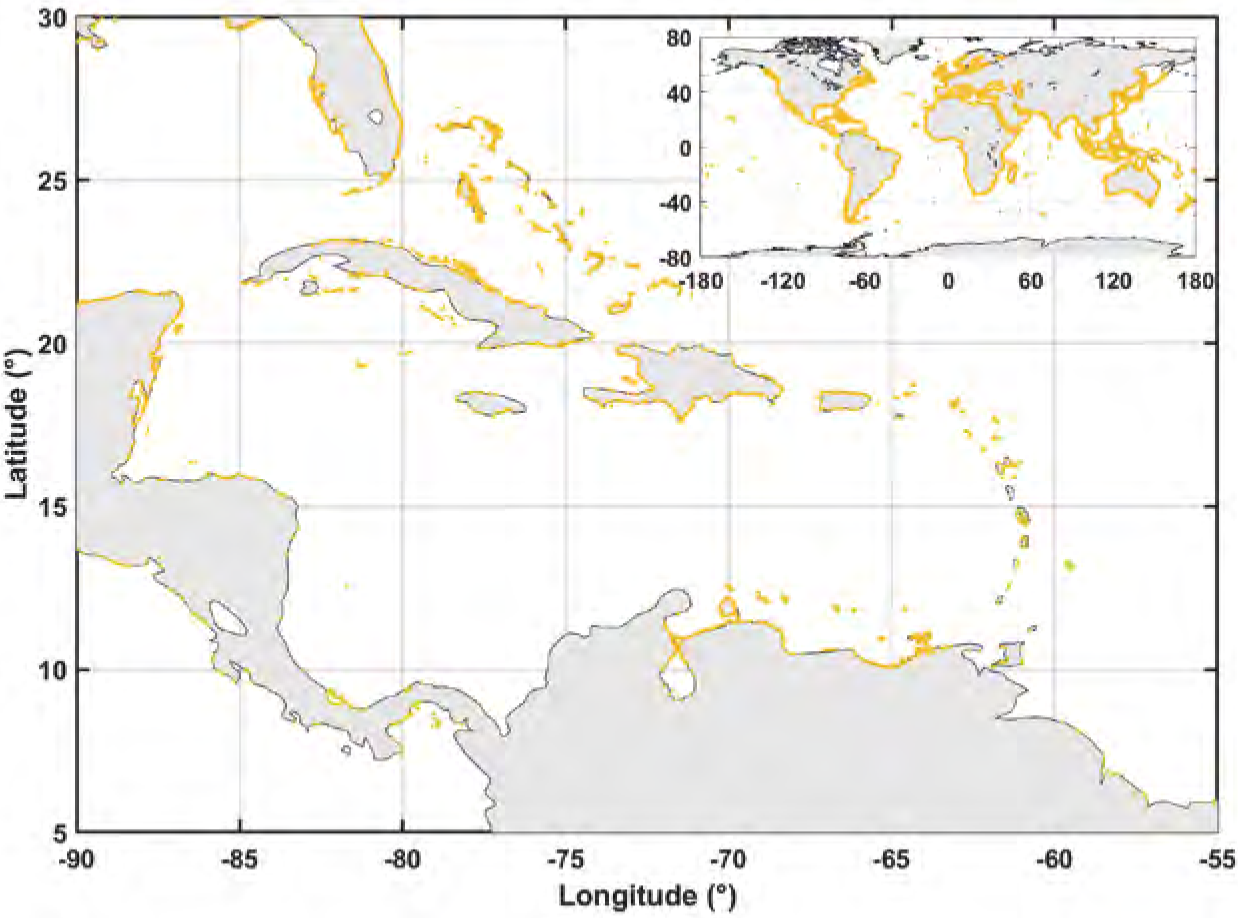


Figure 1: Distribution of beaches in the Caribbean according to Vousdoukas et al., (2020)

This dry coastal forest, when in good condition, is made up of three plant strata:

- An herbaceous stratum, composed mainly of creeping species, characterized throughout the Caribbean by bayhops *(Ipomoea pes-caprae)*, beach bean *(Canavalia rosea)* and seashore dropseed *(Sporobulus virginicus)*
- A shrubby stratum, again made up of a typically Caribbean floral procession, with White Alling *(Bontia daphnoides)*, Prickly Glorybower *(Volkameria aculeata)*, Bay Lavender *(Tournefortia gnaphalodes)*, Bay Cedar *(Suriana maritima)*, Gullfeed *(Scaevola plumieri)*
- A tree stratum, whose common and emblematic essences are, among others, Seagrape *(Coccoloba uvifera)*, Pink trumpet tree *(Tabebuia heterophylla)*, Portia tree *(Thespesia populnea)*, Button mangrove *(Conocarpus erectus)*, and, rarer these days because exploited for its wood, Guaiacwood *(Guaiacum officinale)*.

The ecological functionality of these upper beach ecosystems is enabled by the presence of these three strata. Unfortunately, anthropogenic pressures, and in particular the overcrowding of beaches, have led to the disappearance of herbaceous and shrub layers on many beaches. The tree layer itself has locally been replaced by coconut trees, symbol of heavenly beaches and "postcards" that many visitors are looking for. On many Caribbean beaches, the coastal forest barrier can no longer play its role in mitigating coastal risks.

Coral reefs

Coral reefs represent an important ecosystem for the protection and formation of beaches in the Caribbean (Figure 2). Reefs generally grow in shallow areas close to the coast. Their presence plays a fundamental role in controlling the agitation and the associated currents in the near coastal area. Reefs also play an important role in producing sandy sediments.

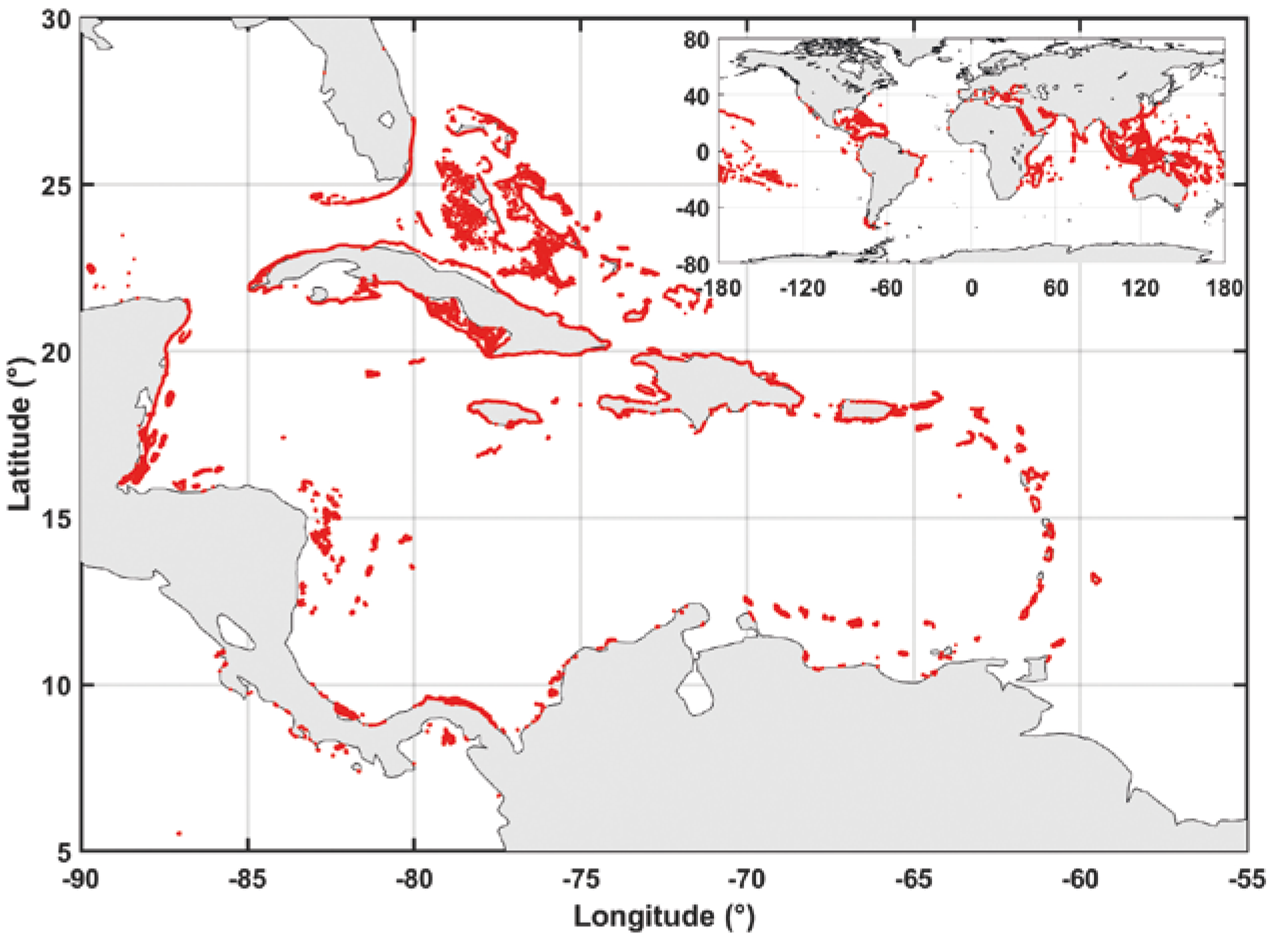


Figure 2: Distribution of coral reefs in the Caribbean according to UNEP-WCMC et al., 2021)

In the Caribbean, reefs are estimated to cover more than 26,000 km² (Miloslavich *et al.*, 2010). Fringing reefs, presenting a reef platform that borders the coast, represent the most widespread morphology in the region. There are also barrier reefs, which are more distant and separated from the coast by the presence of a reef depression (lagoon) or a channel. Finally, there are reef formations in the form of isolated massifs of only a few meters in diameter, presenting less organized morphologies than the previous types of reefs.

Coral reefs represent the richest marine ecosystem in terms of biodiversity. In the Caribbean, it is estimated that a total of about 30,000 species of all groups reside in coral reefs (Reaka-Kudla, 2005). Reefs play an important role for many marine species. Mammals, turtles, fish, mollusks, crustaceans, worms, but also seaweed, fungi, and bacteria, take advantage of the reefs which serve as habitats, nurseries, shelters, food storage, resting places, breeding grounds, etc.

Seagrass beds

Seagrass beds are generally located in shallow areas and are often associated with the presence of coral reefs. These are not seaweed but rather flowering plants that grow mainly by a system of creeping stems under the seabed to form seagrass meadows. In the Caribbean region, seagrass beds are estimated to cover approximately 66,000 km² (Miloslavich *et al.*, 2010) (Figure 3).

They are found in three main configurations: bays or open lagoons; closed lagoons, protected by a reef barrier; and more rarely in the brackish waters of estuaries. These are generally areas with little exposure to the swell. The majority of Caribbean seagrasses are between 1 and 3 meters, but it is possible to find them down to maximum depths of

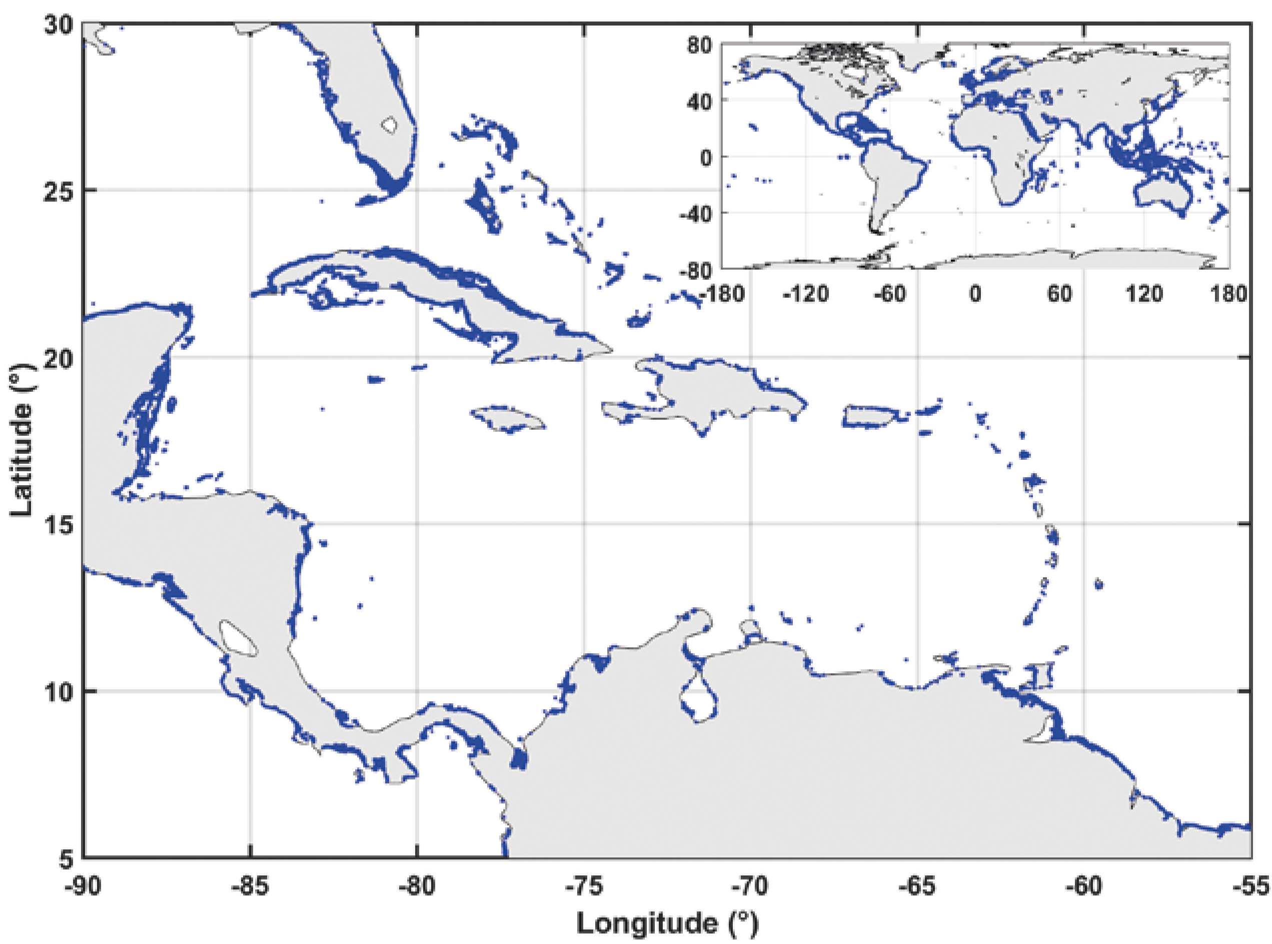


Figure 3: Distribution of seagrasses in the Caribbean according to UNEP-WCMC and Short (2021)

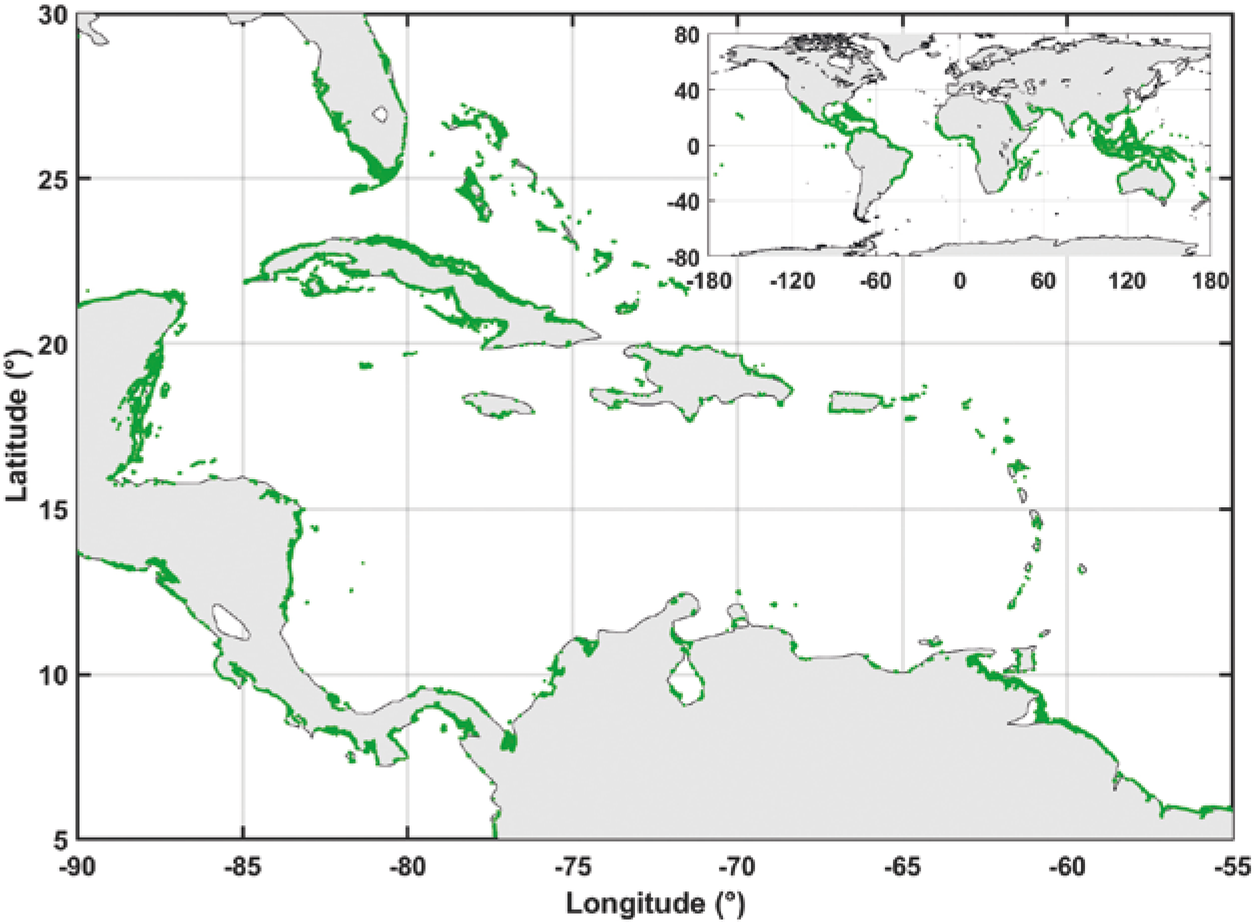


Figure 4: Distribution of the mangrove in the Caribbean according to Spalding, and Collins (2010)

around fifty meters. 7 major species are found in the Caribbean, including three main ones *Thalassia testudinum*, the most abundant, *Cymodocea filiforme And Diplanthera wightii*.

Seagrasses represent an important marine habitat for many marine animal species, especially at the larval stage of their development, and for the source of food for many emblematic and commercial species such as conches for example.

Mangroves

Mangroves typically grow in estuaries, lagoons, and wetlands behind barrier beaches typically associated with muddy sedimentation in wave-sheltered environments. These cover approximately 22,000 km² in the region, i.e. nearly 15% of the world's surface (Teutli-Hernández *et al.*, 2021) (Figure 4).

Mexico and Cuba together account for more than half of the Caribbean's mangrove surface. With the United States, Panama, and the Bahamas, they regroup 82% of the surface of Caribbean mangroves. The remaining 18% is shared between the other territories. There are about ten species in the Caribbean, 4 of them being the majority. The majority of the Caribbean's mangroves are made up of red mangroves. This is the least salinity-tolerant species. This is the reason why it is found along the coast or, near estuaries, where salinity does not exceed seawater salinity (OECS, 2009).

Mangroves represent ecologically important habitats for various marine and terrestrial species.

Cliffs and rocky shores

The presence of rocky shores is important in the Caribbean islands. Steep coasts and cliffs are the majority in most volcanic islands (Dominica for example). The tabular morphology of limestone islands can also present low rocky coasts or steep cliffs in certain areas depending on the influence of tectonics.

2. **Coastal Dynamics and Exposure to Coastal risks** in the Caribbean Region

COASTAL PROCESSES AND DYNAMICS

The coastline, at the interface between land and sea, is a mobile space that constantly adapts to environmental conditions. The factors behind the evolution of the coastline are multiple and complex. They intervene at different spatial and temporal scales to constitute what is called the coastal system (Figure 5).

Geological factors generally occur on a regional scale over periods of several thousand years. They are responsible for the vertical movements of the ground, mainly associated with tectonics in the Caribbean context.

Hydrodynamic factors associated with the wind, swell and water level play a role on a regional scale. They are the source of interannual, seasonal and event variability in the case of storms for example.

At the sediment cell scale, **coastal processes** take part in the movement of sediments in the coastal zone under the effect of coastal currents generated by swell and winds. Coastal processes are influenced by the morphology of the coast which controls the extension of the swell into the coastal area and the movement of sediments. At this scale, sediments brought by rivers also contribute, as well as cliff erosion.

Finally, at the local level, **human interventions** can also modify the coastal system equilibrium and impact sediment transport processes in connection with development or direct removal from the beaches, for example.

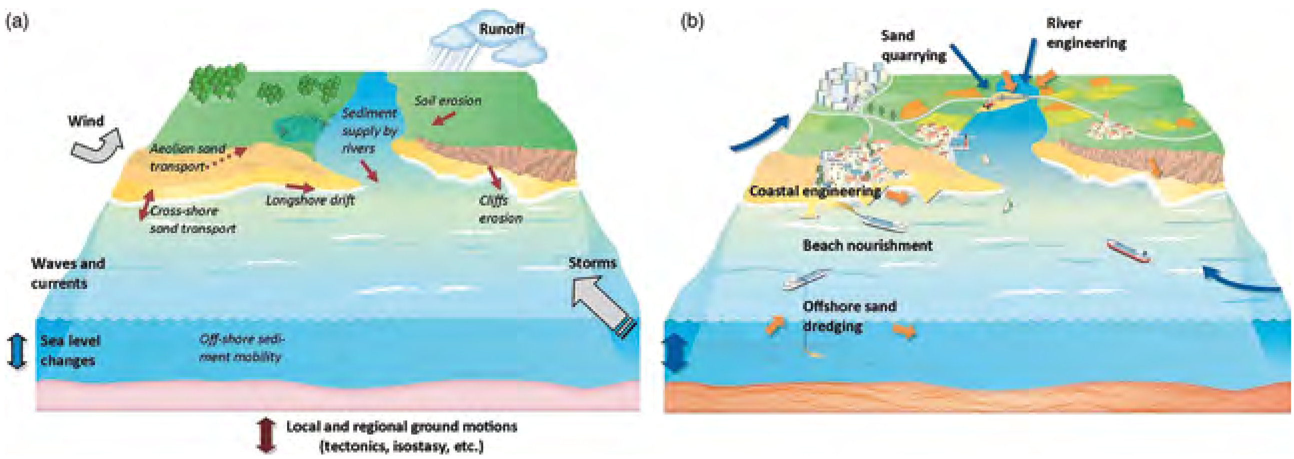


Figure 5: Processes involved in the transport of sediments in the coastal zone and the evolution of the coastline in the absence of human intervention (a) and under the influence of human intervention (b) according to Cazenave and Le Cozannet (2013)

COASTAL RISKS

Coastal erosion

Coastal erosion occurs through sediment loss under the action of the sea and results in a lowering of the beach profile and a landward shift of the coastline. The coasts most sensitive to erosion are low sandy coasts. Cliffed coasts composed of loose rocks or altered rock formations are also particularly sensitive to erosion with phenomena of landslides or rock falls, particularly on volcanic islands.

Studies carried out in Guadeloupe and Martinique indicate that approximately 1/3 of the low sandy coasts have shown a tendency to retreat since the 1950s. Cambers (2009) mentions an average annual rate of retreat of 0.5 m per year based on coastal change data analyzed on eight Caribbean islands between 1985 and 2000, mainly affected by the impact of several tropical storms on this period of observation (Anguilla, Dominica, Grenada, Montserrat and Saint-Kitts and Nevis). For example, the majority of the beaches on the islands of Sint-Marteen/Saint-Martin and Saint-Barths were affected by a sudden decline following the passage of Hurricane Irma in 2017 of between 5 meters and 30 meters with numerous related damages on coastal infrastructure (Duvat *et al.*, 2018 and Pillet *et al.*, 2019).

IMPACT OF SARGASSUM SEAWEED COLLECTION ON COASTAL EROSION

Since 2011, most of the Caribbean islands have been exposed to massive Sargassum seaweed stranding. This pelagic seaweed grows at sea, drifts under the influence of marine currents in the tropical zone of the North Atlantic and strands massively on the Caribbean coasts with significant impacts on populations, coastal ecosystems and activities carried out near the coast.

Collecting this seaweed can have significant impacts on beaches exposed to strandings. Indeed, seaweed collection can be associated with significant sand removal, which can represent up to 50% of the volumes collected. These indirect withdrawals can therefore contribute to aggravating erosion if they are not controlled. Furthermore, the use of heavy machinery can be the cause of degradation of the upper-beach vegetation (Figure 5). It is therefore essential to adapt collection techniques to avoid sand extraction as much as possible and prevent impacts on the vegetation at the upper beach. For example, the use of claws instead of buckets or of a screener when appropriate makes it possible to limit sand removal associated with the Sargassum collection.

Figure 6: Example of techniques that can limit the extraction of sand associated with Sargassum seaweed collection. On the left, a backhoe with claw bucket and on the right a screener (source: Prefecture of Guadeloupe)

As indicated above, processes associated with coastal dynamics are many and complex. They occur at different spatial and temporal scales. It is sometimes difficult to precisely attribute the factors responsible for coastal erosion. Among the factors that may be at the origin of an erosion phenomenon in the Caribbean, we can name the following:

- frequency and intensity of extreme events;
- changing climatic conditions on a seasonal or interannual scale;
- sea level rise linked to climate change occurring over long periods and on a global scale;
- local degradation of coastal ecosystems;
- changes in local conditions induced by coastal developments;
- direct removal of sediments from the coastal area for building or collecting Sargassum seaweed washed up on beaches, for example.

Moreover, although surfaces with mangrove forests tend to decrease in the Caribbean in connection with urbanization development in low coastal areas, their limit of extension is progressing at sea in many estuarine areas. Indeed, agricultural activities in watersheds promote soil erosion and increase sediment inputs in the coastal area. Consequently, coastal mudflats expand, and favor mangroves development.

Marine flooding

Marine flooding refers to temporary flooding of the coastal area by the sea associated with extreme weather conditions. In the Caribbean, marine flooding is mainly associated with cyclones, causing a sudden rise in sea level, strong swells, and strong winds. The low coastal areas or those most exposed to wave breaking represent the areas most exposed to this phenomenon (Figure 7).

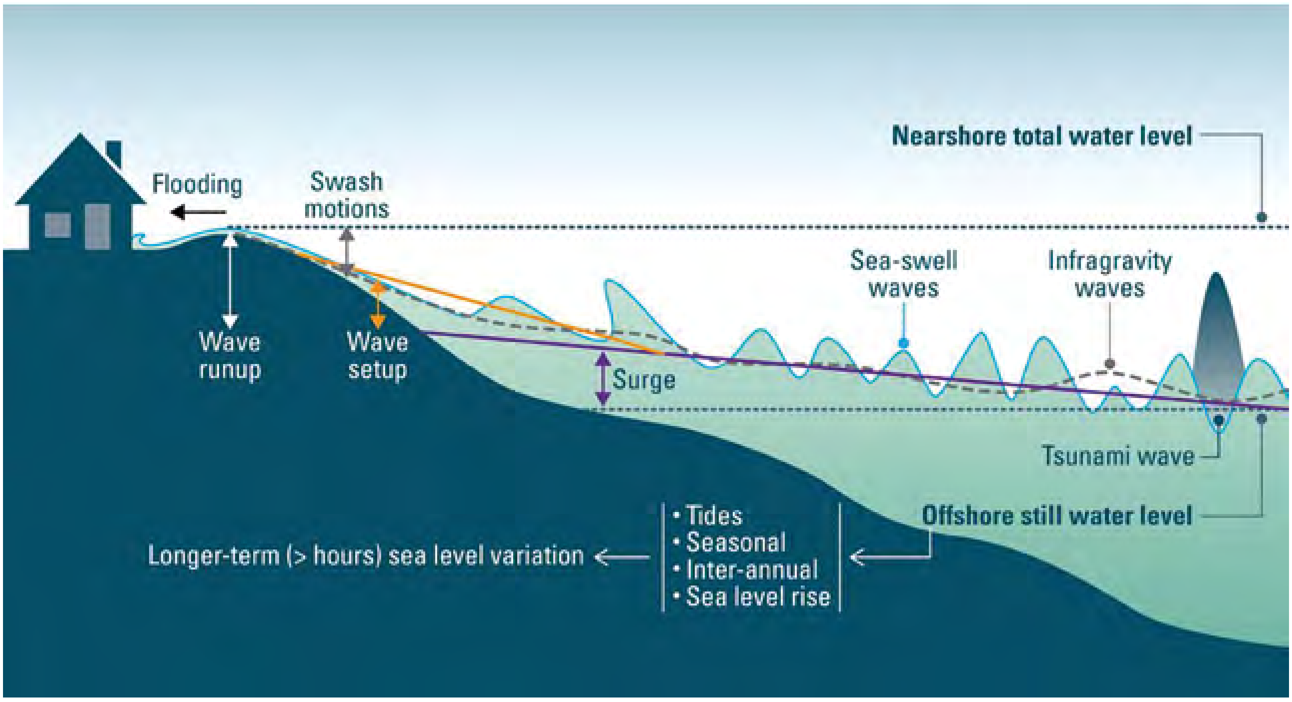


Figure 7: Contribution of hydrodynamic processes associated with marine flooding according to Morris et al., 2021 (Morris et al., 2021)

On average, a dozen tropical storms, including 6 cyclones, affect the Atlantic basin each year. According to Martin *et al.* (2022), the eastern part of the Caribbean islands receives more than 3 tropical cyclones per decade, the western part is affected on average by 1 cyclone per decade and the southern Caribbean is practically unaffected due to the trajectory displacement predominantly towards the west-northwest. The most affected islands include the Antilles, Hispaniola (Dominican Republic and Haiti) and Puerto Rico. The western part of Cuba is the area affected by the most intense tropical cyclones. Although the Lesser Antilles are not affected by the most powerful cyclones, the passage of a large number of cyclones over this area makes it one of the most exposed to their impacts. The waves generated by cyclones can reach more than 10 meters, especially on the eastern coasts of the islands exposed to the Atlantic (Antilles, Hispaniola, and Puerto Rico). The most significant surges, greater than 2 meters, are observed along the coasts of Cuba, due to the configuration of the shallow coastal waters which favor this phenomenon. The lowest values are observed on the islands located to the south of the basin. In addition to the trajectory of the cyclone which generates an area of low pressure, significant variations in surges can be observed locally due to the configuration of the coast and interactions with the wind and waves. Indeed, areas with an extensive and shallow island plateau are conducive to the generation of significant surges.

FOCUS ON THE 2017 HURRICANE SEASON

The 2017 hurricane season perfectly illustrates the way Caribbean islands are exposed to hurricanes. Among the 29 Caribbean islands, 22 were affected by at least one category 4 or 5 hurricane with devastating effects in coastal areas related to marine flooding (Irma, Jose, and Maria). For example, a major surge occurred on the island of Barbuda, where Irma made landfall as a Category 5 hurricane. A tide gauge on the island recorded a peak water level of 2.4 meters above the highest tides. The Cuban Meteorological Institute also reports that Hurricane Irma produced significant flooding along the north coast of the island due to storm surge and waves. In the province of Ciego de Avila, the sea rose from 3 to 3.5 meters and penetrated inland over more than 800 meters. Irma caused 37 direct deaths due to its strong winds, heavy rains, and waves, mainly in the Caribbean islands. For small island states, the damage caused by tropical cyclones can be very significant and have a lasting effect on their economy. For example, the damage cost associated with Hurricane Maria in Dominica is assessed at 226% of its 2016 gross domestic product.

CLIMATE CHANGE AND EXPECTED IMPACT ON COASTAL AREAS

The potential effects and impacts induced by climate change on coastal risks are many (Mycoo *et al.*, 2022). Among these effects, **the rise in average sea level** on a global scale represents the greatest threat to low-lying coastal areas below sea level, which will be directly exposed to chronic and permanent flooding (Figure 8).

A 2018 study by the Inter-American Development Bank (IDB. 2018. Sea-level rise threats in the Caribbean), estimates that about 500,000 people live in areas less than 0.5 meter above local highest sea level and 1,000,000 occupy land below 1 meter in the greater Caribbean. The Bahamas is the territory most exposed to sea level rise with more than 40% of the population located less than 1 meter from the local high sea level (Table 1). The coastal areas of the Caribbean islands also concentrate the majority of transport infrastructure and activities.

Moreover, it is now recognized that global warming will induce with a high probability **an increase in the intensity of extreme weather events**. More powerful cyclones are thus expected in the tropical zone of the North Atlantic. These extreme events will be associated with more intense and more frequent marine flooding and coastal erosion, particularly in connection with the rise in sea level.

Finally, environmental changes associated with the **increase in surface water temperature, ocean acidification** and the rise in average sea level will also contribute to weakening coastal ecosystems, such

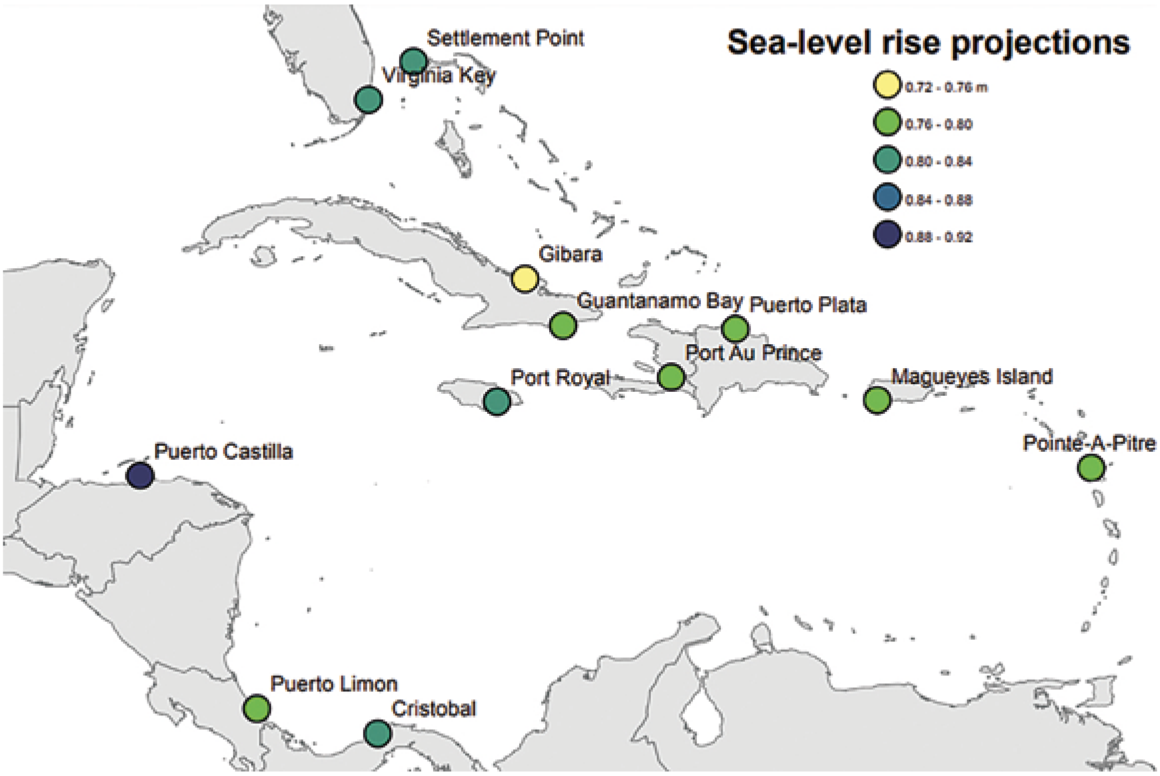


Figure 8: Median projection of sea level rise around the Caribbean basin by 2100 according to the IPCC's RCP 8.5 scenario according to Kopp et al., (2014).

Place	National Total Pop.	0.5m Tot	Pct	1m Tot	Pct	2m Tot	Pct	4m Tot	Pct
Antigua and Barbuda	86,710	1,170	1.3%	1,737	2.0%	4,236	4.9%	12,759	14.7%
The Bahamas	310,015	76,993	24.8%	128,328	41.4%	176,398	56.9%	247,435	79.8%
Barbados	285,134	240	0.1%	526	0.2%	5,643	2.0%	25,335	8.9%
Dominica	72,811	737	1.0%	1,277	1.8%	3,284	4.5%	6,316	8.7%
Dominican Republic	9,812,309	99,310	1.0%	127,179	1.3%	232,506	2.4%	574,226	5.9%
Grenada	107,817	1,021	0.9%	2,108	2.0%	4,859	4.5%	8,728	8.1%
Guyana	723,107	101,871	14.1%	191,368	26.5%	446,309	61.7%	558,477	77.2%
Haiti	9,660,438	97,241	1.0%	164,310	1.7%	405,978	4.2%	852,626	8.8%
Jamaica	2,847,231	13,700	0.5%	22,681	0.8%	75,242	2.6%	370,732	13.0%
Saint Kitts and Nevis	49,898	244	0.5%	613	1.2%	1,996	4.0%	4,310	8.6%
Saint Lucia	160,742	2,725	1.7%	8,659	5.4%	22,466	14.0%	31,838	19.8%
Saint Vincent and the Grenadines	104,218	697	0.7%	1,129	1.1%	3,650	3.5%	8,060	7.7%
Suriname	508,340	52,493	10.3%	102,318	20.1%	332,934	65.5%	435,907	85.8%
Trinidad and Tobago	1,228,676	4,426	0.4%	15,384	1.3%	66,640	5.4%	170,167	13.8%

Table 1: Population living in low coastal areas in the wider Caribbean according to the IDB (2018)

as coral reefs, which are already heavily impacted by human disturbances. These ecosystems represent a natural protection against hazards and reduce the risk in the coastal zone, especially during extreme events. These disturbances will most likely be associated with a reduction in the protection offered by these ecosystems if their natural resilience capacity does not allow them to adapt to changes in environmental conditions.

A TOOL FOR VISUALIZING SEA LEVEL PROJECTIONS

NASA has developed an interactive sea level projection tool that allows users to view and download sea level projection data from the Intergovernmental Panel on Climate Change's 6th Assessment Report (IPCC) (AR6). The purpose of this tool is to provide easy and improved access and visualization of IPCC projections (Figure 9).

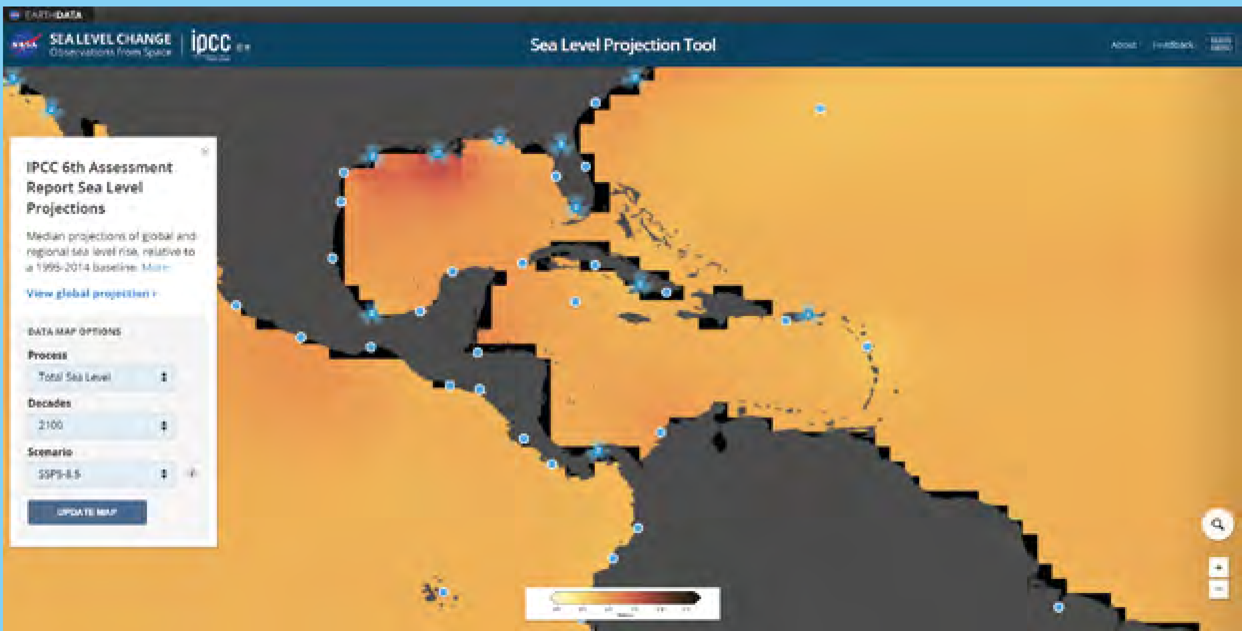


Figure 9: Visualization of the accessible sea level projection tool accessible at the following address: Sea Level Projection Tool – NASA Sea Level Change Portal

The tool allows users to visualize global and regional sea level projections from 2020 to 2150 and the related uncertainties under the different scenarios studied by the IPCC. Users can click on a point anywhere in the ocean or on reference ports to get the sea level projection for a given location. The contributions of different physical processes related to sea level rise are also presented.

3

Coastal **monitoring and physical modeling**

The collection of long-term coastline data is essential for understanding exactly how coastal processes are associated with coastline evolution. It also allows for the characterization of risks and the management actions, the characterization of the risks and the definition of management actions adapted to the local context and natural dynamics of each site. Observations are generally complementary to numerical modeling tools in order to produce analyzes for understanding coastal system functioning and hazard management (Figure 10).

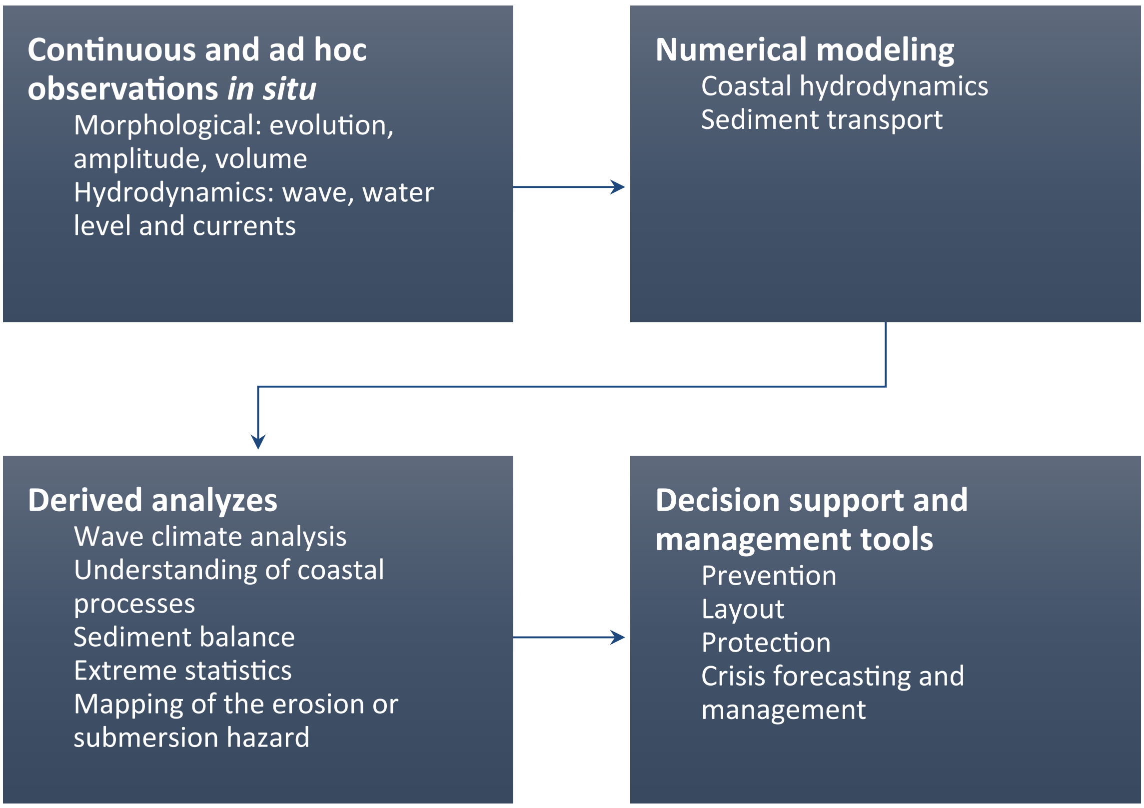


Figure 10: Main tools for analyzing the functioning of the coastal system for the implementation of management strategies

COASTAL MONITORING

Several types of observations can be used in order to collect data on the evolution of the coastline on an ad hoc or continuous basis. They can vary according to the scale of observation, precision, frequency of acquisition, technicality, and cost of implementation. These are generally topographical, morphological, or hydrodynamic data associated with coastal development indicators (coastline, beach profile, digital terrain model, parameters of exposure to hydrodynamic conditions) (Figure 11).

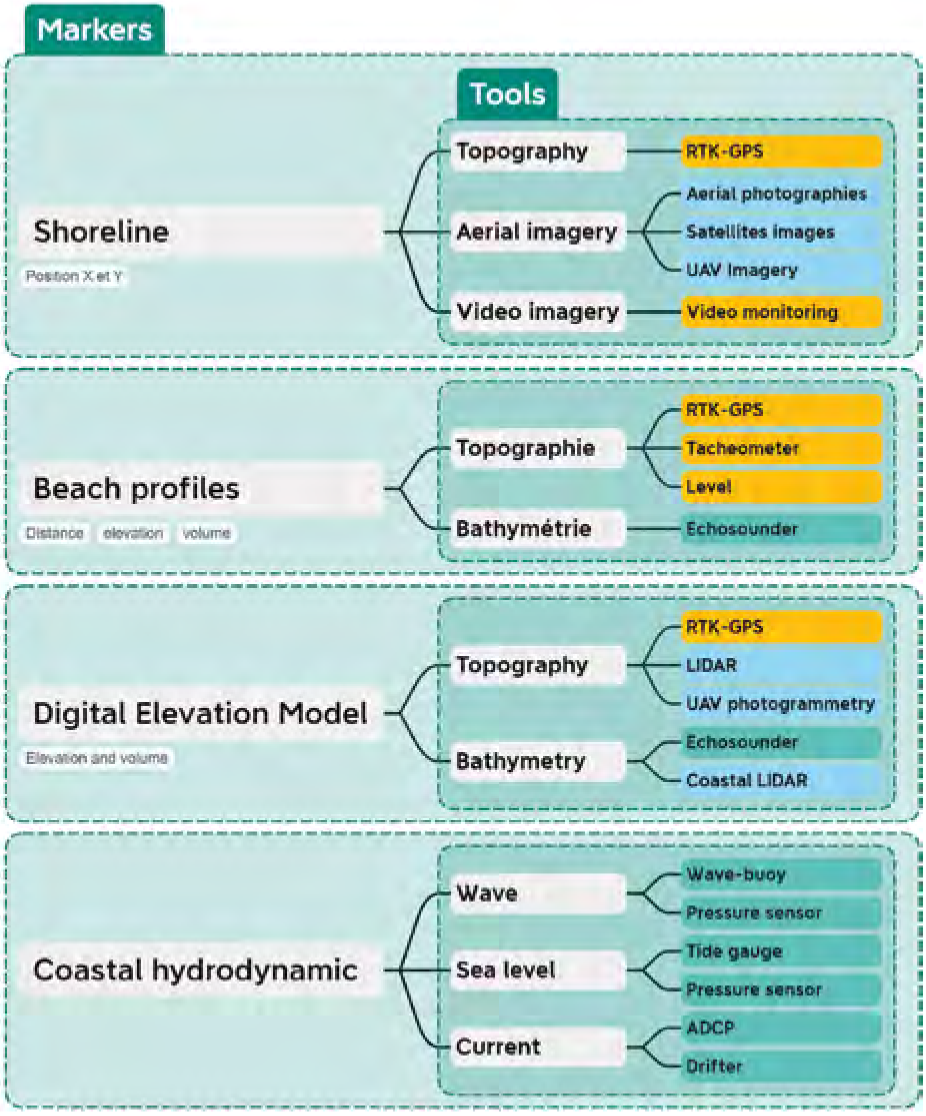


Figure 11: Main indicators and tools associated with coastal morphological and hydrodynamic observations

For example, indirect observations from aerial or satellite imagery can be used to analyze changes on a regional scale and over a long observation period (several decades). On the other hand, they can represent precision limits for analyzing local processes (resolution of less than one meter for aerial images and or several meters for freely available satellite images, for example). The frequency of acquisition can also present a limit for analyzing variability at the scale of the season or the impacts associated with events (multi-annual for aerial images or monthly for certain satellites).

Other more precise types of direct observation (using meter or a decimeter) can be used at the scale of the sedimentary cell within the framework of implementing regular monitoring programs. This monitoring generally makes it possible to better characterize the evolution of sediment stocks from data collected onsite (beach profile, position of the coastline and digital terrain model). These are usually terrestrial topographic measurements, video imagery or aerial drone tracking. These terrestrial measurements can be supplemented by bathymetric measurements in order to follow the evolution of the foreshore and analyze the sedimentary exchanges with the terrestrial compartment.

EXAMPLE OF THE NATIONAL BEACH MONITORING PROGRAM OF TRINIDAD

In 1995, the Institute of Maritime Affairs of Trinidad and Tobago launched a national coastal monitoring program to improve knowledge on the evolution of the coastline and to provide elements of decision support for the sustainable management of coastal areas. Thus 25 beaches are monitored in Trinidad and include a total of 64 topographic beach profile stations (Figure 11). The analyzes carried out concern the dynamics of the beaches in terms of changes in width and volume, but also the characteristics of the sediments.

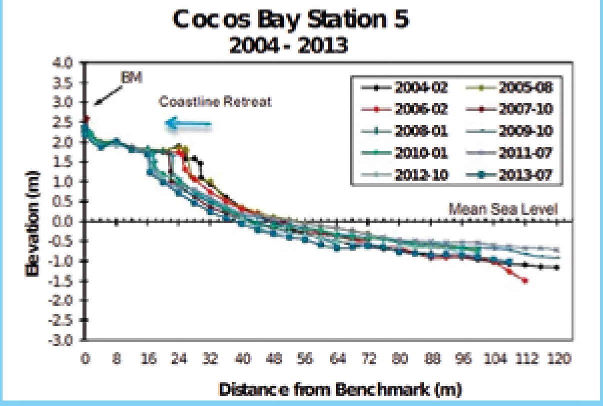


Figure 12: Mapping of the sites studied as part of the national program for monitoring the beaches of Trinidad and profile of the associated beaches (Source: Institute of Marine Affairs)

The results indicate that most of the beaches of Trinidad are in a state of dynamic equilibrium where seasonal evolutions of erosion and accretion revolve around a state of stability over the observation period. It is observed that while beaches on the north coast are less prone to erosion, high erosion rates in areas located to the east, south and west have prompted the construction of protection. While these protective structures seem effective on the sheltered west coast of the island, on the more exposed east coast, these structures are less effective.

The results of this monitoring program highlight the issues associated with a tailor-made approach for the management and protection of the coastline against erosion. This requires a continuous collection of data over the long term in order to better understand coastal processes and to provide decision support elements necessary for the implementation of a strategy for the management and adaptation of exposed coastal areas.

In addition to morphological monitoring, hydrodynamic observation data represent several interests. They make it possible to characterize the exposure conditions of a site (water level, swell and currents), calibrate and validate digital models and supply forecast and warning systems. These measurements can be taken on an ad hoc and temporary basis using sensors installed in the coastal zone (pressure sensor and current meter), or permanently (wave recorder buoy or tide gauge for example) (Figure 13).

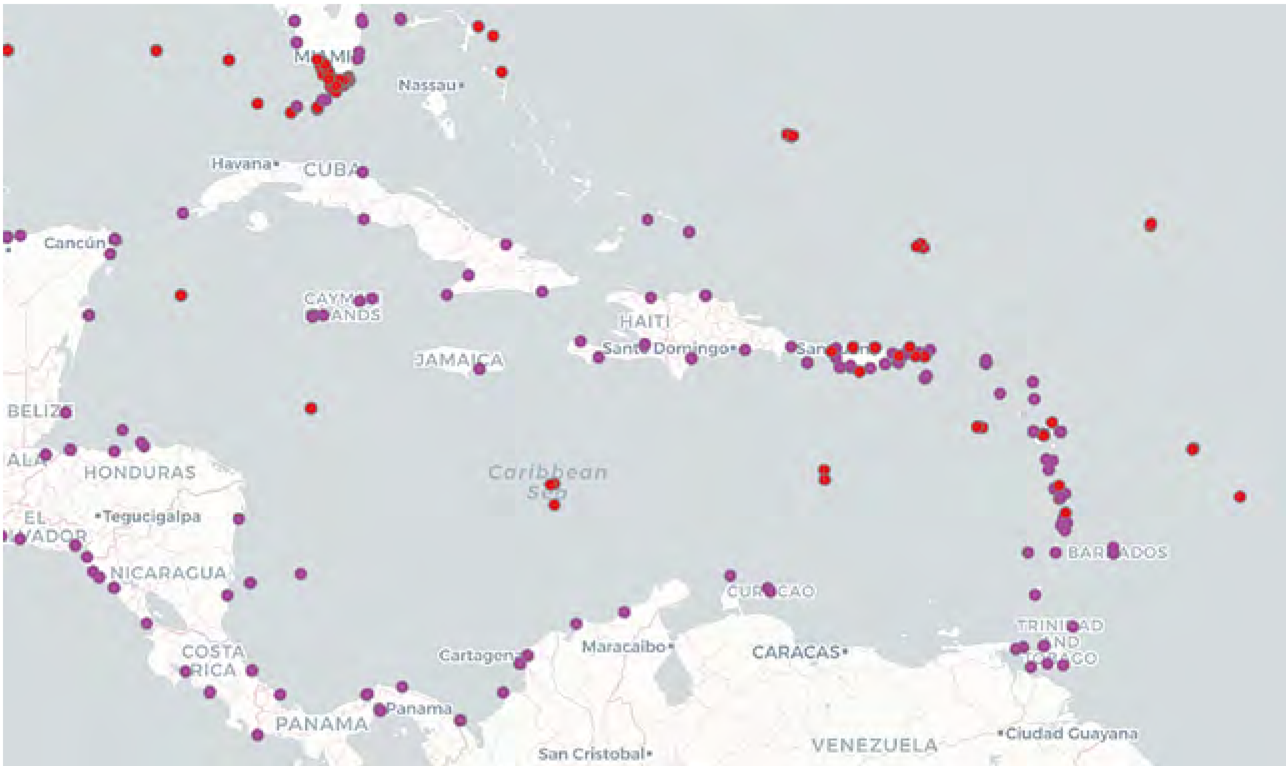


Figure 13: Location of continuous swell and water level measurement devices in the Caribbean region based on data from the EMODnet platform (https://map.emodnet-physics.eu/). Purple dots represent the tide gauges and red dots represent wave buoys

COASTAL MODELING

Numerical models can also be used in addition to observations in situ. Observations are used both to feed models but also to calibrate and validate them. Models can be implemented for various applications: simulating development scenarios and associated impacts, mapping hazards, assessing climate change impact, forecasting systems, etc. They can simulate a variety of conditions (usual, extreme, and future projections) at different scales (local, regional, or global). They are particularly useful for improving process understanding for complex situations. However, we must not forget that this is a simplified representation of reality and that each calculation code applies to a certain validation domain and is limited by the quality of the available data.

Numerical modeling is particularly useful for mapping marine flooding. It allows complex hydrodynamic processes involving waves to be considered, and the water level in the coastal area in extreme situations to simulate surges, overtopping, and associated flooding. Statistical analyzes of extreme events allows the definition of probabilistic exposure scenarios with associated return periods for modeling and mapping hazards (intensity and influence).

EXAMPLE OF THE STORMS MONITORING NETWORK AND THEIR IMPACTS IN GUADELOUPE AND MARTINIQUE

As part of the CARIB-COAST project, a network for monitoring storms and their impacts has been developed in Guadeloupe and Martinique to collect and capitalize on information relating to extreme events.

The network is based on weather forecasts from models. Several potential impact thresholds were determined based on the analysis of hydrodynamic conditions and historical impacts observed on the coast. When a foreseeable event exceeds a potential impact threshold, a bulletin is automatically generated to inform and mobilize a network of partners in order to collect qualitative and quantitative information on site (erosion, submersion, and possible damage) (Figure 14).

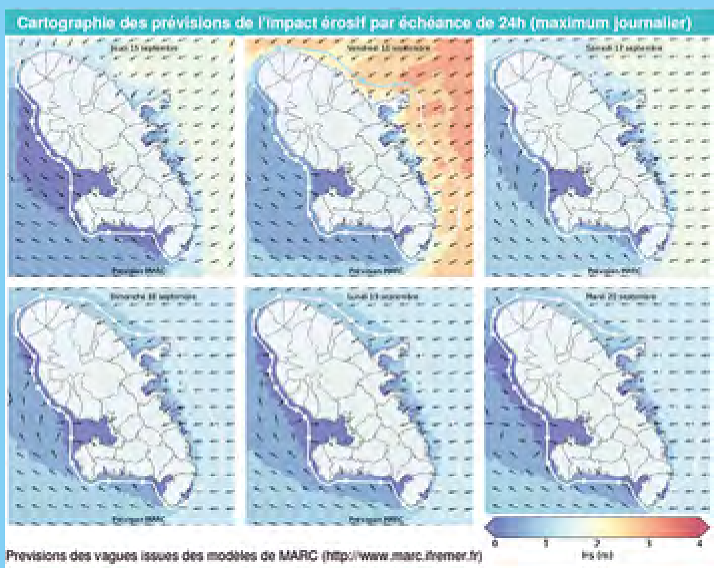


Figure 14: Extract from the bulletin of the storm network in Martinique

These observations can be supplemented by a network of low-cost autonomous cameras deployed on the coast of Guadeloupe and Martinique. These observations make it possible to carry out high-frequency observations (every hour for example) to analyze the morphological impacts on the beaches studied (Figure 15).

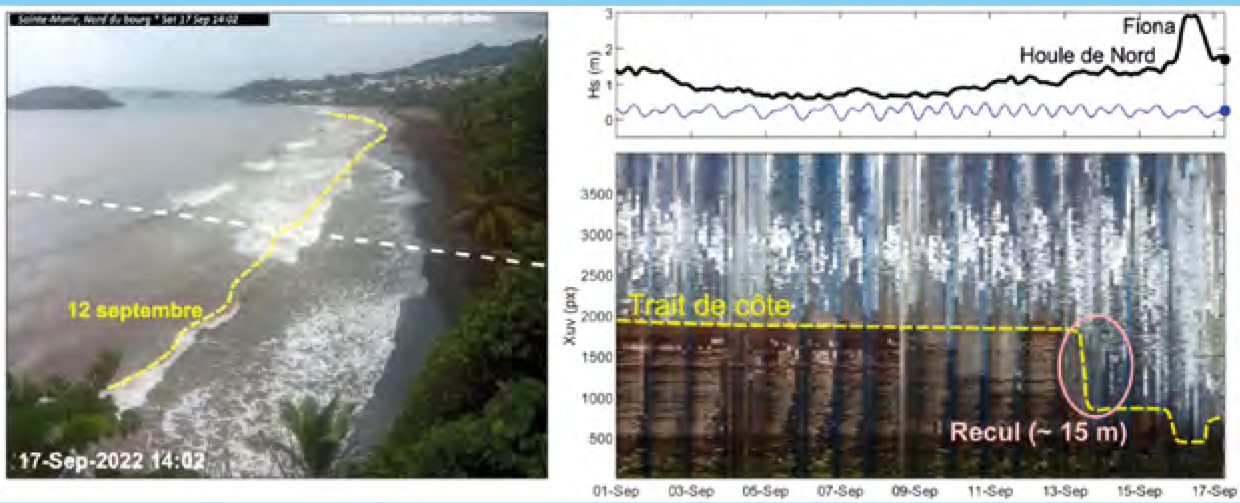


Figure 15: Observation by autonomous camera carried out before and after the passage of tropical storm FIONA on September 16, 2022 on the Sainte-Marie site in Martinique

Ultimately, the aim is to standardize and pool observations on the impacts associated with storms, capitalize information, and improve understanding of coastal processes associated with extreme phenomena. This type of network can also involve the public as part of a participatory science approach to collect information on site. This information is particularly useful for better understanding the territory's exposure to coastal risks, improving forecasting systems and supporting the authorities in implementing management strategies.

4

Coastal risks management

Climate change through sea level rise, increase in extreme events intensity, and the weakening of coastal ecosystems will contribute to increasing the exposure of populations to coastal risks in an already vulnerable area. To guard against the consequences of coastal risks, adaptation actions can be implemented at different scales to preserve human lives, reduce the cost of damage and the time needed for recovery. Among these actions, we can distinguish two main categories.

The first category involves **actions aimed at reducing hazard exposure**. They can be structural actions based on the construction of protective works or **nature-based solutions** (NBS) that build on the characteristics of natural ecosystems to enhance the protection of coastal areas.

The second category involves **non-structural actions aiming to act on issues to reduce their vulnerability and exposure**. These may be measures of **prevention** by informing the population to develop hazard awareness and disseminate behavioral instructions. There are also measures related to the **land-use planning** to limit the development of new issues in exposed areas through town planning regulations, which may go as far as relocating existing issues outside exposed areas.

The **adaptation measures** aim to reduce the vulnerability of stakes located in high-risk areas in order to enhance people's safety, reduce damage and the time required for recovery (elevating buildings and sensitive equipment, for example). Finally, non-structural actions include forecasting systems and organizational measures to protect the population (forecast, warning, protection, and recovery plan) (Figure 16).

Prevention	Adaptation of issues	Hazard Protection	Crisis management
Information and awareness Land-use planning Relocation	Reduction of building vulnerability Adaptation of infrastructures and networks	Coastal engineering works Nature-Based Solutions	Monitoring and forecasting Warning and safety Recovery

Figure 16: Typology of actions aimed at reducing exposure to coastal risks

These management actions can also be classified according to several degrees of intervention (Figure 17). The first level consists of not intervening if the stakes do not justify it. Next appears the non-structural preventive and organizational actions (for example, regulation of land use, warning system and safeguarding the population). Third, measures intervening on the issues aiming to reduce their vulnerability by adapting them or by relocating them outside risk areas. Finally, protective measures aimed at reducing exposure to hazards through nature-based solutions and protective works. Each of these intervention options can be combined at different spatial and temporal scales to improve the effectiveness of hazard management in a territory.

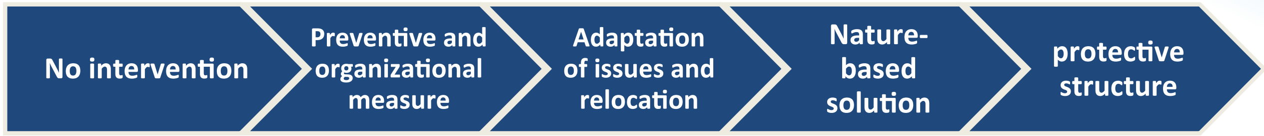


Figure 17: Degrees of coastal hazard management options

Indeed, all of these actions can be implemented through a strategy aimed at developing a global approach to coastal hazard management. The IPCC presents 6 types of adaptation strategies for low-lying coastal areas: inaction; protection works; adaptation of issues; relocation; sea or land elevation and nature-based solutions (Figure 17). The choice of strategy must be based on an analysis of the hazard, an assessment of the level of exposure of the issues as a whole as well as an analysis of the constraints and advantages that each of these options represent for the territory involved.

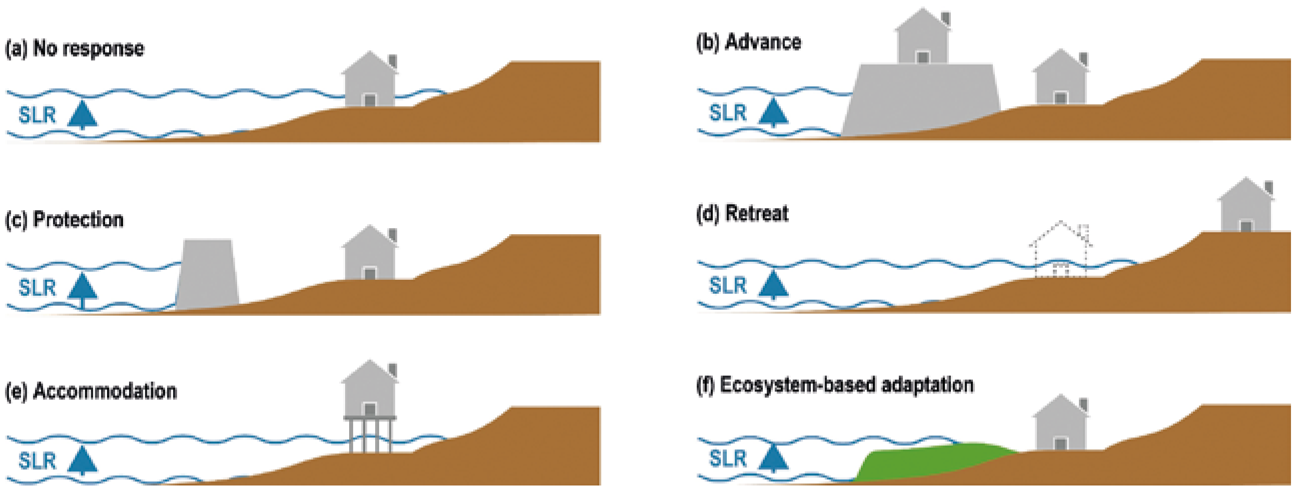


Figure 18: Typology of different types of possible adaptation strategies in response to exposure to coastal risks and sea level rise (IPPC, 2019)

The selection of strategies and their timing of implementation must be studied in their entirety by multi-criteria analyzes involving all the human, economic, technical, environmental, socio-economic, and cultural issues.

Hybrid strategies can be implemented involving one or more management options. Strategies are also likely to evolve over time in what are called adaptation paths. That is, a strategy can be considered sustainable up to a certain point in time, after which other types of strategies can be implemented. For example, it may be considered that a protective structure is effective under current conditions, but that for reasons of changing conditions associated with sea level rise, it will be preferable to relocate the exposed issues. This may save time in organizing the relocation over the long term.

EXAMPLE OF A MIXED OR *GREY-GREEN* SOLUTION

The establishment of mixed structures combining heavy engineering techniques with ecological engineering techniques based on plants are likely to constitute credible alternatives to development projects initially envisaged only in a mineral version.

Thus, the mangroves planted in Kingston Bay in Jamaica are associated with rock and plant fiber protections that allow the attenuation of wave energy until the mangroves grow sufficiently and fulfill this role (Figure 19).

Figure 19: Plantation of red mangroves (Rhizophora mangle) in Kingston Harbour (Source: Adam Gibaud (National Forests Office - ONF), 10/10/2019)

The main steps recommended for the developing and implementing a management strategy are represented in the following graphic and detailed below in an iterative process (Figure 20).

Figure 20: Conceptual diagram presenting the generic phases involved in the development of a strategy for coastal risk management and adaptation to the effects of climate change

1

Identifying the scope of intervention, associated stakeholders and available data

- Defining the scope and objectives of the strategy
- Delimitating the intervention scope of the strategy
- Identifying the stakeholders
- Gathering stakeholder agreement and commitment
- Defining governance to involve them in the development process
- Collecting the information and needs of each stakeholder
- Organizing data collection, carrying out a knowledge assessment and assessing needs to improve knowledge.

2

Assessing the hazard

- Analyzing coastal processes
- Defining scenarios
- Characterizing hazards
- Assessing current and future exposure in relation to climate change
- Assessing current protection measures and their potential impacts
- Analyzing and mapping the risk and associated future projections.

3

Assessing the issues and associated risks

- Identifying human challenges (construction, activities, infrastructure, networks) and natural issues exposed to hazard
- Qualifying the importance of the issues (heritage and cultural/social, economic/environmental)
- Determining the level of exposure of the issues and the associated consequences
- Assessing the impacts for the territory to justify hazard management actions.

4

Defining a management strategy

- Defining a consultation method to get the support and opinion of all stakeholders
- Segmenting the scope by hazard area
- Defining management objectives by hazard area
- Examining the feasibility of different management alternatives
- Analyzing the effectiveness and constraints of management options in relation to the objectives sought (cost-benefit or multi-criteria analysis)
- Selecting the options best suited to the context
- Spreading the management options over time if necessary to consider possible adaptations according to the constraints of implementation or the evolution of exposure to hazard.

5

Developing and implementing the action plan

- Defining the actions necessary to implement the selected management options
- Identifying one or more managers by actions and the associated stakeholders
- Estimating the cost of each action and setting up a financing plan
- Prioritizing actions and making a schedule
- Establishing the modalities of implementation
- Identifying actions needed to resolve identified uncertainties
- Organizing communication around strategy and actions
- Carrying out operational studies and works where necessary for structural actions.

6

Monitoring and assessing the plan

- Identifying criteria for assessing management actions
- Ensuring appropriate long-term monitoring on the scope of the site to assess the effectiveness of actions, monitor the potential associated impacts and improve knowledge of coastal processes
- If necessary, adapting the strategy and the action plan according to the developments observed and the changes in strategic orientations.

EXAMPLE OF BARBADOS COASTAL RISK ASSESSMENT AND MANAGEMENT PROGRAM

Barbados' Coastal Risk Assessment and Management Program relies on island-wide investigations to quantify coastal risks, identify vulnerable ecosystems and infrastructure, and develop management strategies to improve resilience of the island to climate change and coastal risks. The main objective is to build capacity in terms of integrated coastal zone management in Barbados by integrating principles of hazard reduction and climate change adaptation into the planning and development process (Figure 21).

This program is based on several components:

- Strengthening knowledge through the acquisition of topo-bathymetric LIDAR data in coastal areas, hydrodynamic and hydrosedimentary modeling, geotechnical investigations on cliffs, studies on the evolution of the coastline.
- Hazard assessment studies with the mapping of hazards and an assessment of the vulnerability of the issues.
- The development of a national information and planning platform on coastal risks, including a database on hazards, issues, and risks.
- Decision support and communication tools for authorities.
- Infrastructure design studies for several pilot projects of protections and nature-based adaptation solutions.
- Actions to strengthen public policies on coastal risk management through awareness and training plans for authorities, updating of the integrated coastal area management plan, evolution of coastal area management regulations and preparation of a strategic action plan for crisis management and adaptation to climate change.

Figure 21: Excerpt from Barbados Integrated Coastal Zone Management Plan update in relation to exposure to coastal risks

5

Nature-based solutions for mitigating coastal risks

Nature-based Solutions (NBS) are defined by the International Union for Conservation of Nature (IUCN) as *"actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature".*

They are based on the natural capacity of ecosystems in good condition to provide ecosystem services, such as protection against natural hazards. As such, the coastal ecosystems in the Caribbean (coral reefs, sea grass beds, mangroves, and barrier beaches) represent natural protection to mitigate the impacts of extreme events on the coast.

Among the actions for protecting or mitigating coastal risks, NBS have several advantages over the use of conventional structural solutions generally used to guard against these hazards (dike, riprap, vertical walls, transverse groynes and breakwaters). .

Indeed, beyond the coastal protection function offered by these ecosystems, the implementation of NBS generally presents co-benefits from an environmental, economic, and social point of view through the provision of a series of ecosystem services. Moreover, these solutions also benefit from a capacity for resilience and natural regeneration in the face of potential degradation if the environmental conditions allow it. These ecosystems are in fact capable of adapting to changes in the environment. Finally, the cost of implementing and maintaining this type of solution is often lower than the cost of coastal structures in the long term. Indeed, ecosystems have a certain capacity for resilience in the face of stress or degradation factors. If conditions allow it, they can regenerate naturally, in whole or in part.

However, NBS implementation requires time to be effective. It is generally necessary to wait several years or decades before benefitting from an effective protection capacity. Moreover, these ecosystems, to develop and adapt to changes in their environment, must have a sufficient surface area, unfortunately often constrained by both natural and anthropogenic pressures: intervention in these environments may be impossible due to a lack of available space. Finally, these ecosystems are generally subject to multiple pressures that can affect their development, so it is necessary to ensure regular maintenance and monitoring.

PROTECTIVE SERVICES OFFERED BY COASTAL ECOSYSTEMS

Thus, all the steps in favor of the preservation and restoration of these ecosystems are therefore favorable to the mitigation of the impacts of coastal risks and the adaptation to the effects of climate change in the coastal zones of the Caribbean. Indeed, the presence of these coastal ecosystems plays a protective role through several physical mechanisms.

Wave impact mitigation

Coastal ecosystems generate environments which are hydraulically rough. When waves flow over such areas, it contributes, contributes to dissipate the wave energy in the coastal area. The amount of dissipation depends on the incident wave conditions, morphology, species flexibility, habitat density and continuity of coverage.

For example, due to their configuration, reef formations strongly dissipate the energy of incident waves (up to 97%). Indeed, where the reefs are present, the waves break offshore before reaching the coast. The effectiveness of dissipation by breaking depends on the location of the reef relative to the incident waves and its relative depth to the surface.

Marine flooding mitigation

It is also accepted that certain ecosystems such as mangroves play a role in limiting the intensity of flooding phenomena by reducing the water level and slowing down the associated flow in extreme conditions. Indeed, the drag forces exerted on the flows by the presence of these ecosystems tend to lower the water level with a decreasing gradient towards the land. The presence of mangroves thus helps to reduce the impact of marine flooding.

Barrier beaches, which are located above the ground, also represent a physical barrier of natural protection against submersion. Vegetation on these barrier beaches also plays a role in slowing down flows and dissipating the energy of incident waves.

Erosion reduction and sediment retention

Beyond the role of ecosystems on wave action and water level control in the coastal area, ecosystems also participate in the stabilization of the coastline. Indeed, by interacting with surface runoff, they reduce the impact of coastal erosion and promote the accumulation of sediments. The root system developed by certain species also keeps the sediment in place.

For example, the root system of seagrass beds helps maintain sediments in shallow areas and promotes their accumulation by interacting with currents on the bottom. Furthermore, organisms with a calcium carbonate skeleton, such as corals, represent one of the main sources of sediment in certain coastal areas of the region and contribute to sandy beaches formation over the long term.

ROLES AND SERVICES OF CARIBBEAN COASTAL ECOSYSTEMS

Coastal beaches and dunes

Beaches, whether or not associated with dune formations, provide protection against wave overtopping and flooding. The level of protection against erosion is assessed from the sediment stock available in the active part of the beach. This is the volume of sand that can be mobilized in response to one or a series of events close in time. The level of protection against flooding is generally associated with the morphology (elevation and width) and the presence of upper-beach vegetation.

The dunes associated with sandy beaches represent sandy accumulations located on the upper beach resulting from the transport of sediments by the wind. They develop only in areas with large volumes of sandy sediments on the one hand and in conditions where the wind regime is sufficient in intensity and frequency to ensure sand transportation to the upper beach on the other hand. The role of vegetation is also essential in trapping and retaining sand. From a morphological point of view, these sedimentary accumulation formations are located above the level of the natural soil and represent a particularly effective physical barrier against flooding. However, the presence of development on the upper beach or the back beach generally constrains their development. The sedimentary stock of the dunes also constitutes a source of supply of sediments to accompany the natural reconstitution of the beaches in the event of erosion.

The most widespread action to strengthen the natural protection capacity of barrier beaches and dunes consists of beach replenishment. Depending on the protection objectives, this involves increasing the width or elevation of the barrier beach by artificial supply of sediment from a “donor” site. The sediments brought must however be compatible in terms of grain size, nature, and quality with respect to the characteristics of the sediments in the area to be recharged. In some cases, it is simply a transfer of sediments from one part to another of the same beach to achieve a rebalancing or from a supply by external samples (dredged sediments for the maintenance of channels and ports or marine sand deposits present offshore located outside the active part, for example). The factors to be considered in the recharge projects are the identification of the extraction areas, the volume and the nature of the sand, the deposit methods, the maintenance, and the long-term monitoring. Generally, the geometry of the recharge projects aims to find a natural balance profile adapted to the hydrodynamic conditions and the nature of the sediments.

Beach reprofiling is another technique which consists of mechanically transferring part of the sediment present on the lower beach to the upper beach to imitate the natural processes of sedimentary reconstitution in calm weather and modify the profile of a beach. This technique is generally used to protect infrastructures found in the backshore. However, it does not seem suitable for sites in a situation of chronic erosion or with a limited sedimentary volume. Although it is an inexpensive solution, preliminary studies to analyze the hydrosedimentary functioning are needed to identify volumes to be mobilized, periodicity and geometry of the reprofiling.

Vegetation also plays a key role in the formation and maintenance of coastal dunes. The plant species that grow on the barrier beaches trap the sand transported by the wind, promote its accumulation and the development of dune formations over the long term. It also keeps the sediment stock in place and thus promotes coastline stability. The roots maintain soil cohesion. Aerial structures of the plants (stems and leaves) attenuate the waves energy, and slow down the flow, which has the effect of reducing overtopping phenomena and promotes the retention of sediments in the event of an extreme event.

Actions aimed at restoring the upper beach vegetation promote the development and stability of barrier beaches. Certain interventions can regulate human traffic by installing designated pathways, barriers or protected enclosures, which eases pressure on coastal vegetation. Other actions aim to restore spaces for the natural dynamics of the barrier beaches, by moving roads or parking lots for example. These measures, which contribute to reducing the pressures exerted on the environment but without human intervention on the dynamics of vegetation, are passive ecological restoration actions. The simple act of reducing the anthropogenic pressure exerted on the environment by the establishment of a protective enclosure (trampling of the soil, passage of vehicles) generates a reduction in the compaction of the soil favorable to seed germination and the seedling development. (soil porosity, underground air, and water flow) and provides protection to seedlings which could otherwise be broken or torn off. This results in a gradual recolonization of plant species.

For the most damaged sites or to accelerate the regeneration of the environment, active restoration actions can also be implemented in order to regain plant coverage with species appropriate to the environment. The choice of species to be planted must be made by favoring local species with strong root anchoring (with a view to maintaining the sand stock) and non-invasive. In this regard, combatting invasive species to promote the development of native species, offering a more suitable protection service, is also an avenue to be studied depending on the context.

Finally, a last category of action is based on plant engineering techniques such as the installation of windbreaks or slats, to promote the trapping of sediments and their accumulation at the upper beach. This type of action is only suitable for dune environments where the transport of sand by the wind is the main factor causing coastal sedimentary accumulations. In the same way, plant fascines are elements of protection of the upper beach exposed to the swell. They are made up of bundles of ligated plant material held in place by stakes anchored vertically in the ground. The trellis formed by the plant material constitutes a sediment trap able to reconstitute a sandy barrier. These techniques can be used in addition to solutions aimed at restoring the vegetation coverage on damaged beaches, with vegetation playing the same role as windbreaks or fascines to trap and maintain sediment. Plant engineering would then constitute a preliminary step to an active or passive restoration action.

PLANT DIVERSITY AND COASTAL RISK MITIGATION

More than the simple presence of vegetation by the sea, it is the quality and diversity of the plant barrier that guarantees its effectiveness in terms of protection. The structure and stability of the soil can indeed be modified by the introduction of exotic species such as coconut palm *(Cocos nucifera)*, native to Asia and Oceania and now ubiquitous on the Caribbean coasts. Its superficial root system and its low capacity to resist violent winds do not offer the same capacity for resilience in the face of coastal ecosystem risks as the native vegetation, which has deeper roots (Figure 22).

Figure 22: Monospecific coconut palm plantations do not allow the maintenance of sand - Pointe Marin, Martinique (source: Adam Gibaud (ONF), November 2019)

In addition, a complex and strong root system is obtained by the interweaving of roots of different plant species. Thus, in general, herbaceous species have a root system that is more developed on the surface, while shrub species have a root system that is more deeply rooted. Similarly, the more species and strata are diversified, the more the littoral forest of a site is dense and able to retain the sand displaced by the action of the winds (Figures 23 and 24). Ecological diversity is therefore more likely to play an effective role in mitigating coastal risks. The effectiveness of this ecosystem is also linked to the width and density of the upper beach vegetation coverage.

The following examples illustrate the role of vegetation in the maintenance and accumulation of sediments at the upper beach.

Figure 23: Morphology of accumulation allowed by all the plant strata – Clugny Beach, Guadeloupe (Source: Adam Gibaud (ONF), July 2019)

Figure 24: Maintaining the sand by bayhops (Ipomea pes-caprae) - Sainte-Marie beach, Martinique (Source: Noémie Videau (National Forests Office - ONF, October 2022)

The presence of a dense and diversified vegetal barrier constitutes an effective natural protective screen by attenuating wave energy and wind energy. The upper-beach vegetation thus limits the damage caused in the event of cyclones or tsunamis. A minimum of a 30-meter vegetation coverage is necessary to act as a shield, to which must be added a strip to capture sediments coming from the sea.

The choice of restoration techniques depends on whether or not the conditions are favorable to dune formation, the availability of sediments, the space available and the state of the natural environment. It must be based on a detailed analysis of the hydro-sedimentary functioning and the associated evolution processes (Figure 25).

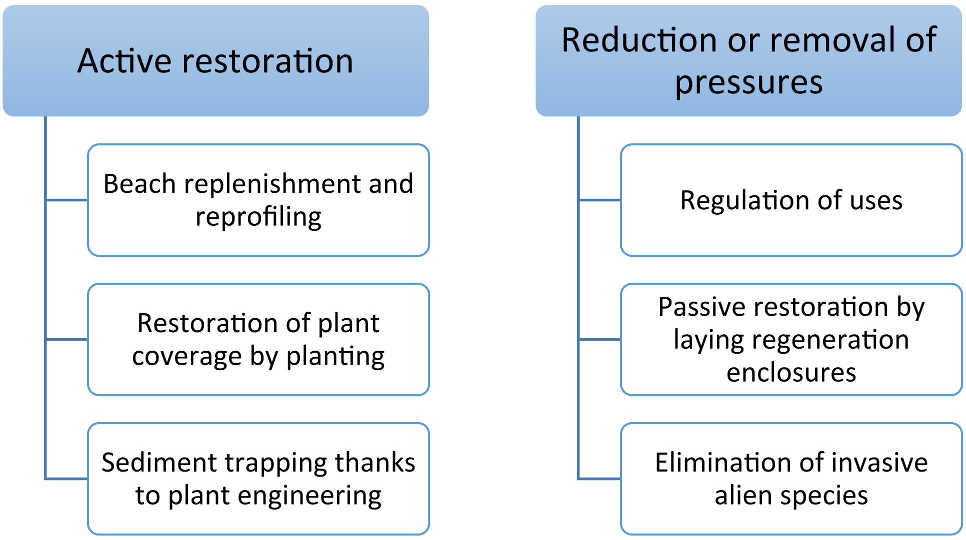


Figure 25: Synthesis of restoration actions that can improve coastal barrier protection services

ANSE MAURICE PILOT EXPERIMENTAL SITE: IMPLEMENTATION OF NATURE-BASED SOLUTIONS FOR UPPER-BEACH VEGETATION

Located on the northern Atlantic coast of Guadeloupe, Anse Maurice, in the town of Petit Canal, is the first pilot experimental site focusing on upper beach ecosystems set up as part of the Carib-Coast project. The actions implemented on this site have followed the different stages approved for the implementation of NBS described in this guide.

1. Diagnosis

The first step inherent in the choice of pilot sites for the project is the identification of exposure to coastal risks. On Anse Maurice, a decline in the coastline of 30 meters in just over 60 years (1950 - 2013) has been observed. There are many causes to this erosion (Figure 26):

- Natural coastal erosion due to swell and wind, accentuated by the Atlantic location of the site
- An alleged theft of sand for several decades
- A mechanical collection of Sargassum seaweed over the past ten years, which has accelerated the erosive process
- Altered coastal vegetation that no longer fulfills its protective role

Figure 26: Between 1950 and 2013, the vegetation line receded by 30 meters (in red, coastline in 1950; in blue, coastline in 2013)

To assess the relevance of setting up NBS and choosing the most suitable ones, an inventory of the ecosystems found on site was first carried out. There is a remainder of typical Caribbean coastal forest: several key species, such as the seas grape tree, pink trumpet tree, catalpa or even bayhops for the herbaceous stratum. This is also unevenly distributed on the beach, there is no shrub stratum, and if there is a relative diversity in the tree layer with a few seed trees, it is characterized above all by its lack of natural regeneration. There are many coconut palms, but they do not form monospecific stands.

Several pressures are exerted on this ecosystem which therefore needs to be restored in order to fulfill its protective role. The passage of machinery for collecting Sargassum seaweed and cars on busy days has compacted the soil and leaves the beach rock visible in places (Figure 27). This overcrowding, coupled with goat grazing, impacts seedlings and young trees (by cutting branches to make fires for example) and therefore prevents the natural regeneration of the forest.

Figure 27: Compaction of the sand due to Sargassum collection (Source: Adam Gibaud (National Forests Office - ONF) ; 11/20/2019)

Restoring this ecosystem therefore involves reducing these pressures, but first and foremost, the possibility of intervention must be analyzed. This is made possible by the land management of the site, located in the state forest of the coast, and managed by the National Forests Office (ONF). The space behind the beach is also sufficient to allow vegetation development and make it an effective barrier.

2. Actions

The diagnosis stage validated the necessity and feasibility of implementing NBS. Before starting concrete ecological restoration actions, a consultation stage to reduce the pressures described above was necessary. The municipality of Petit-Canal and the urban community were quite involved from the start of the project, which made it possible to stop the collection of Sargassum seaweed from 2019. The owner of the back beach restaurant was also contacted regarding his goat grazing management.

Following this approach, several ecological restoration actions were implemented in response to each problem. Before deploying active restoration measures, actions to reduce the pressures described above were carried out, to regain environmental conditions favorable to the deployment of NBS.

First of all, 39 tuff blocks along the parking lot and the coastal path were laid to prevent cars from entering the beach (Figure 28). Soil loosening was implemented in very compacted places to restore a substrate favorable to environmental recovery. The storm water drainage ditch was cleaned out to reduce the loss of sediment by runoff (Figure 29).

Figure 28: Laying boulders to prevent car traffic on the beach (Source: Adam Gibaud (ONF) ; 10/22/2020)

Figure 29: Substrate count in regeneration enclosures (Source: Adam Gibaud (NFB) ; 08/05/2020)

Once these pressures were managed upstream, passive restoration actions could be implemented. 8 regeneration enclosures have been set up, allowing the protection of 4130 m² of beach (Figure 30). The objective of these enclosures is to avoid vegetation trampling and grazing to promote natural regeneration of the coastal barrier. The type of protection with mesh is suitable for the presence of goats: in other contexts, and in particular in the case of a sea turtle nesting site, enclosures would have been suitable for the passage of turtles, closed by a single wire sufficiently high on the seafront. The location of the enclosures was selected according to the presence of seed trees in their area, ensuring a bank of seeds conducive to natural regeneration. Access to the beach has also been considered, special attention has been paid so that the enclosures are not located on the usual passages of users, and that they are thus better respected.

Figure 30: Regeneration enclosure (Source: Adam Gibaud (ONF) ; 11/05/2020)

These passive ecological restoration measures were supplemented by planting and sowing native species to support natural regeneration and also enrich the environment with species that had locally disappeared. These plantations were carried out two months after the installation of the enclosures in partnership with a local association. About 40 citizens participated in the planting of 170 seedlings of 12 different species and were thus made aware of the fragility of the coastal forest (Figure 31).

Figure 31: Participatory planting (Source: Anaig Dantec (ONF) ; 12/05/2020)

3. Assessment and follow-up

To assess the effectiveness of the actions implemented, photographic monitoring of the enclosures was carried out, first every two months for the first year, then every six months. The success of the plantations was assessed by counting the plants and calculating the mortality rate every six months also (Figure 32).

Although it is difficult at this stage, after only two years' follow-up, to have well-documented feedback on this pilot site, the follow-ups carried out have nevertheless delivered initial results. In 7 out of 8 enclosures, we observe strong recovery of the herbaceous coverage only a few months after setting up the enclosures. A single enclosure does not show any regeneration because its soil, very stony, prevents the development of seedlings: Only 1 plant survived in this enclosure.

Figure 32: Evolution of a regeneration enclosure: top left, 10/20/2020; bottom left, 12/23/2020; top right, 08/18/2021; bottom right, 01/06/2022 ; (Source: ONF)

From the first count of the plants, the mortality rate approaches 50%. It is also quite unequal depending on the species.: for some, like Allspice, it is 100%, while Seagrape shows 100% success. This mortality rate is explained by the planting period, in December, shortly before the dry season from March to May. There was no watering and the plants suffered from drought.

From this first assessment could be drawn the following conclusions:

- over the planting period: it is necessary to favor the rainy season and plant between June and October
- on watering: it is necessary to plan watering the first year during the dry season
- on the choice of species: the Seagrape tree, the Catalpa or even the Pink trumpet tree have shown a success rate of over 90%. These classic species of the Caribbean coast are therefore to be favored in plantations to ensure minimal ecological restoration.

Finally, although it is a bit early to judge the effectiveness of the regeneration enclosures at Anse Maurice today, this type of enclosure was installed by the ONF more than 10 years ago, particularly on Clugny beach, the project's second pilot site. Vegetation recovery can be easily observed from an aerial view (Figure 33). The ecological restoration of the littoral forest has been successful where the enclosures have been set up and respected, allowing for the mitigation of severe erosion on this beach.

Figure 33: Recovery of vegetation following the establishment of regeneration enclosures in 2008 – Clugny Beach (Sainte-Rose, Guadeloupe) in 2004 (top) and in 2017 (bottom) (Source: BDOrtho IGN 2004 & 2017)

Mangroves

Mangrove forests are particularly effective in mitigating coastal flooding and erosion hazards (Figure 34).

Mangroves are known for their ability to effectively attenuate the energy of incident waves (between 15 to 65%), slow down flows during flooding phenomena and reduce the impact of waves formed by tsunamis and cyclones by forming natural barriers (Spalding *et al.*, 2014). This role is well known and has been demonstrated on various occasions in the area with the passages of Hugo (1989), Andrew (1992), Ivan (2004) and more recently Maria and Irma (2017).

In addition, they allow adjacent coral reefs to recover their biodiversity more quickly after such disasters (Mumby and Hastings, 2008).
The aerial parts also weaken the winds, allowing to protect the surrounding infrastructures and to limit the formation of waves.
Mangroves also have a “sponge” role during floods. These vast wetlands can capture large volumes of water and thus limit the impacts on the infrastructures of the mainland.

Thanks to their root system, mangroves can fix large volumes of sediment (mainly sand and mud), over large areas (Guannel *et al.*, 2016). This promotes sedimentation through sediment settling. An Australian study estimates that 80% of sediments coming from the coast are trapped during their passage through mangrove (Furukawa *et al.*, 1997). This makes it possible to provide quality water allowing good development of adjacent seagrass beds and corals.

By the fall of their branches and their leaves, mangroves allow direct organic contribution to the environment which is added to the sedimentary contribution. Not only are sediments trapped, but mangroves can also raise the ground level significantly (Lee *et al.*, 2014) which can vary between 1 and 10 mm per year (Furukawa *et al.*, 1997 ; McIvor *et al.*, 2013).

This ability of mangroves to adapt to rising water levels is nevertheless limited when they are blocked by constructions or physical barriers that prevent them from expanding.

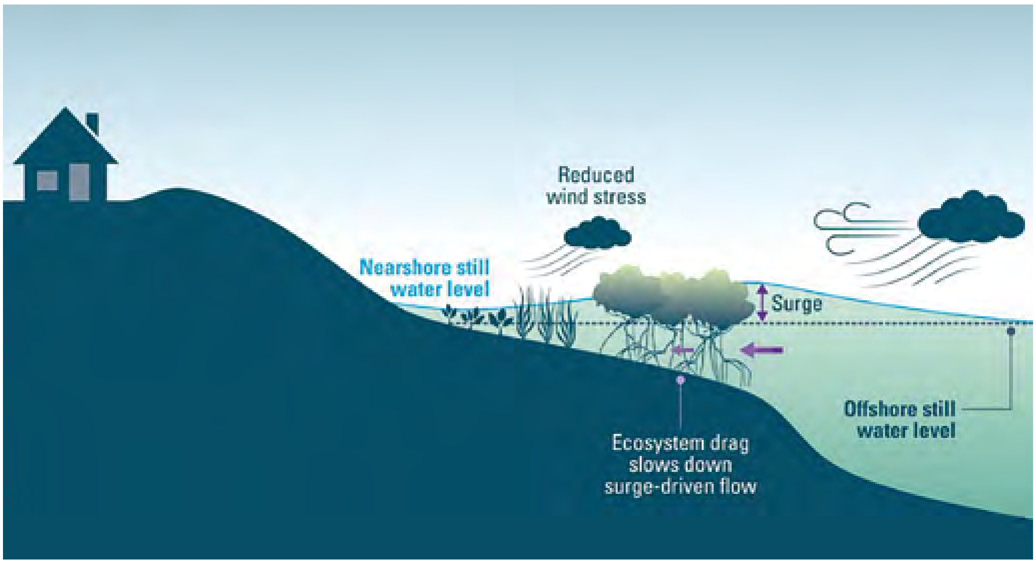


Figure 34: Role of mangroves in reducing the level of sea surges by slowing down flows according to Morris et al. (2021)

The mangrove’s protective capacity is determined by the width of the forest, its density, and the vegetation coverage. Root biomass, trunk diameter and tree canopy are also parameters contributing to reducing waves and marine flooding.

Mangroves require special environmental conditions for their development and not all mangrove species have the same tolerance. General parameters affecting the development of mangroves include salinity, level and duration of sea flooding and agitation. These factors affect the distribution of mangrove species. Other factors such as nutrient availability, the presence of favorable substrate or temperature also play a role in their expansion.

Apart from direct destruction by urbanization development, one of the most frequent causes of mangrove disappearance is related to hydrological conditions modification (frequency of exposure to flooding and increased agitation following coastal developments or the destruction of the mangrove itself, for example). Mangrove disappearance generally promotes feedback processes that are not favorable to mudflats recolonization (increased agitation and erosion).

When possible, that is to say if the mangrove itself produces enough propagules, natural recolonization is to be favored. In this case, it is necessary to ensure that conditions are optimal, particularly in terms of abiotic parameters: physico-chemical (substrate salinity, pH, temperature, etc.), hydrodynamic (wave energy, flooding, and irrigation), topographic (slope , sedimentation) and water quality (pollution) (Tropical Wetlands Relay Pole, 2018). This approach is often advocated by experts in restoration to promote the ecosystem's natural dynamics, especially when there are signs of mangrove self-regeneration and or when the area to be restored is large (>100 ha) (Teutli-Hernández *et al.*, 2021).

When hydrodynamic conditions have been modified (development, clearing of the pioneer front, etc.), an attempt should be made to re-establish conditions favorable to the dispersion and natural establishment of propagules. Passive restoration actions may be necessary to set up structures to limit the energy of waves, swell and tidal currents and thus limit substrate erosion (e.g. use of geotextile or bamboo structures). These actions favor the installation and maintenance of propagules in the mangrove. Actions aimed at re-establishing hydrological connections and favoring the dispersion of propagules or seeds (e.g. creation of breaches in dikes, mounds, low walls, or use of pipes or drains) should be implemented. They allow flowing of the flows linked to tidal influence and the presence of natural channels (Pôle relais zone humides tropicales, 2018, Teutli-Hernández *et al.*, 2021).

Finally, when the area to be restored does not have potential to regenerate (area to be restored too large compared to the donor site, insufficient propagule production, complete destruction of the mangrove, etc.), it is then possible to actively restore the mangrove. Reforestation is the most common technique used in mangrove restoration projects worldwide. However, if this action is carried out without adequate analysis of the environmental conditions (hydrological and physico-chemical) in which the site is located, it can lead to wasting resources and efforts and an unsuccessful attempt (Pôle relais zone humides tropicales, 2018).

There are two restoration methods by planting. The one which consists in planting directly the propagules collected on the mangroves in the site to be restored as well as the one which places them in nursery so that the propagules collected reach a certain maturity in a more or less controlled environment before planting on the site. This second method has the advantage of increasing the chances of survival during planting, as the propagules have already grown a little and developed a more substantial root system (Pôle relais zone humides tropicales, 2018). Nevertheless, the use of nursery requires careful consideration of environmental conditions so that

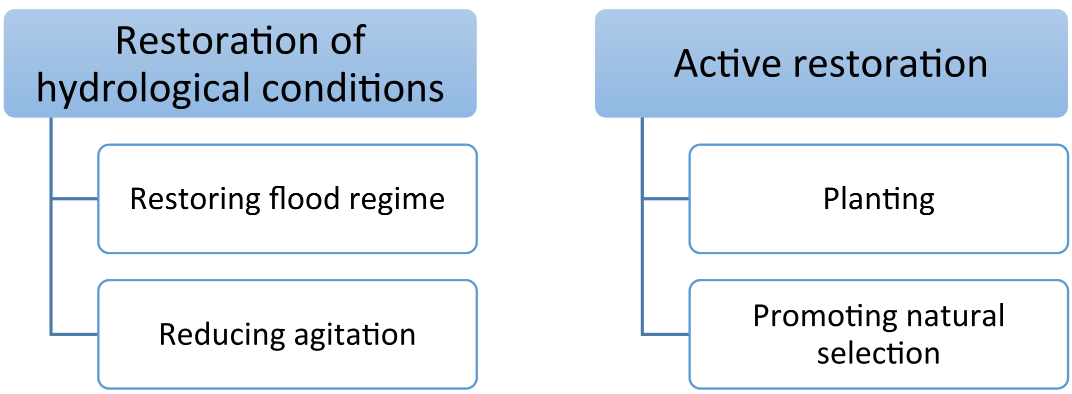


Figure 35: Summary of mangrove restoration actions that can improve protection services

they are similar (salinity, sun exposure, etc.) in the nursery and the planting site in order to maximize the transplanted seedlings' chances of survival. (Teutli-Hernández *et al.*, 2021).

In all cases, mangrove restoration projects must be based on a detailed analysis of hydrological and environmental conditions in order to select the most suitable species for planting (Figure 35).

MANGROVE RESTORATION EFFORTS IN THE BAHAMAS

As part of the Carib-Coast project, the Perry Institute for Marine Science (PIMS) implemented a mangrove restoration project on the islands of Abaco and Grand Bahama that were largely affected by Hurricane Dorian in 2019. A study released in 2020 (Steinberg *et al.*, 2020) highlighted that 73.8% of the mangrove systems on Grand Bahama and 40.1% of the mangroves in Abaco were «damaged or destroyed» by Hurricane Dorian. Estimates indicate a loss of mangroves to over 4,000 hectares across both islands with little natural regeneration or recruitment after 3 years following the hurricane (Figure 36).

Figure 36: Photo of heavily damaged red mangrove trees in Abaco after Dorian (Source: PIMS)

Following additional monitoring from aerial overflights by drone, fine mapping with high-definition imagery, as well as underwater monitoring of the ecological state of the mangroves and consultations with the local population of the two islands, PIMS could identify priority areas for restoration. These are the areas most impacted by Dorian and unable to regenerate naturally that require active restoration efforts through planting.

These elements were gathered in a strategic plan of mangrove restoration recommending the sites to be restored, the restoration techniques to be implemented, ...

From August to September 2022, PIMS was able to organize a red mangrove restoration campaign within national parks. This work involved the civil society (22 volunteers) and local authorities (6 members of the Bahamas National Trust) who were trained by PIMS in propagule collection and planting techniques.

A total of 20,408 propagules were collected (12,500 in Grand Bahama and 7,908 in Abaco) for planting at the 10 sites (6 in Grand Bahama and 4 in Abaco). All locally collected propagules were planted near their site of origin and were monitored to ensure genetic diversity in subsequent plantings (Figure 37).

Figure 37: Volunteers collecting red mangrove propagules (left) and planting them on damaged mangrove systems (right) (Source: PIMS)

After mangrove planting, baseline data were collected at planting sites and control sites where natural recovery is assessed for both Abaco and Grand Bahama (35 sites in total). Data collection at this time included high resolution site mapping. This technology will not only track the condition of the site, but also track the fate of individual mangroves (regenerating mangroves, new natural ones, and planted ones) to assess regeneration, restoration success, and determine what additional intervention will be needed.

Additional monitoring is planned after the project to assess long-term mangrove regeneration and examine changes in fish community structure and environmental parameters.

Coral reefs

According to Burke and Maidens (2004), 21% of the Caribbean coastline is directly protected by coral reefs. This is certainly the most important role of coral reefs via their ability to dissipate wave energy (Gracia *et al.*, 2018). Indeed, they very often constitute the first defense against swell. Barrier reefs are the ones that best perform this role under normal weather conditions. In contrast, during extreme weather events, fringing reefs prove to be more effective in protecting the coast (Guannel *et al.*, 2016). It is estimated that wave energy can be reduced by 97% by ecologically sound coral reefs (Ferrario *et al.*, 2014). This barrier role provides a suitable environment for adjacent seagrass beds and mangroves to thrive in calm waters.

For the wave energy attenuation effect to be optimal, it is important that a reef be predominantly composed of living corals (rather than seaweed or sponges) (Guannel *et al.*, 2016). In the context of climate change and sea level rise, «living» reefs will be able to adjust their depth to some extent. Conversely, «dead» reefs erode and eventually become so deep that their protective service no longer becomes effective.

When alive, corals provide a complex habitat structure on the reef surface. The morphology of the reef (width and slope), its structural complexity or roughness associated with the live coral cover, and its depth are the primary factors involved in shoreline protection (Figure 38). The greater the complexity or surface roughness, the greater the dissipation of wave energy.

The presence of the reef also generates a transformation of the incident waves from short waves to long waves. The dissipation capacity of incident waves indirectly intervenes on the reduction of erosion and flooding in coastal areas protected by reefs. In addition to acting as breakwaters, reefs provide calcareous sediments that can help nourish and maintain beaches over the long term. In addition, if in good health, reefs can keep up with sea level rise by maintaining their protective capacity.

In association with seagrass beds, coral reefs allow to stabilize sediments in the water. Their presence allows to keep the sand in particular, in the lagoons or close to the coasts, without which a more important part of sand would be carried away at the open sea.

Many white sand beaches in the Caribbean region originate from corals, i.e., coral limestone skeletons that turn into sand and feed the coast (Gracia *et al.*, 2018). Parrotfish in particular, are able while feeding to break off coral fragments. These are then released as sand after digestion (Ogden, 1977). The largest specimens of parrotfish can produce several tens to hundreds of kilos of sand each year. Diadem sea urchins also participate in this bioerosion and can also produce significant amounts of sand (Frydl and Stearn, 1978) and thus participate in creating and maintaining sandy beaches.

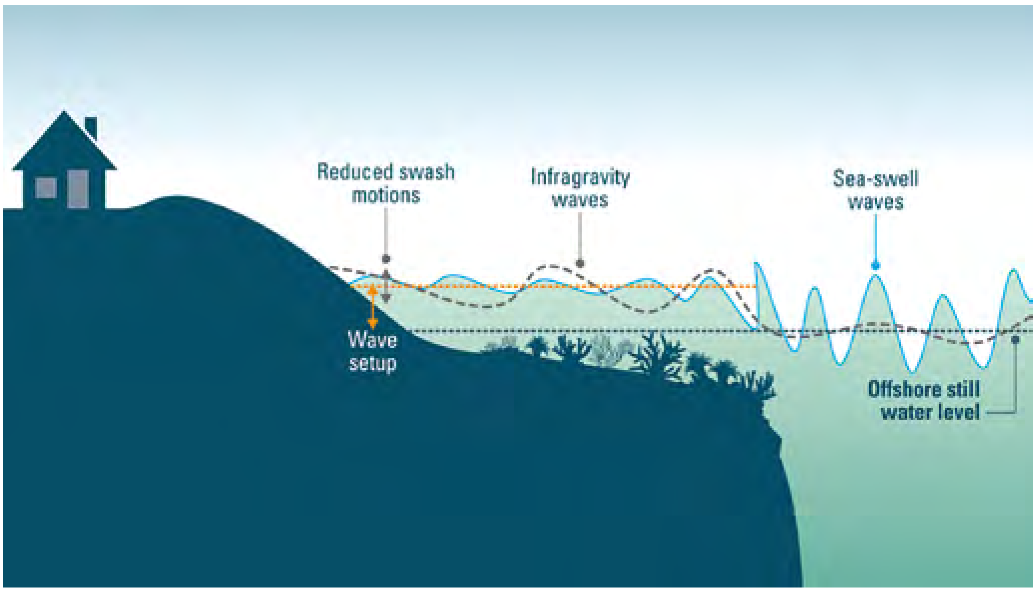


Figure 38: Role of coral reefs in reducing coastal risks in relation to attenuation of incident waves by depth and roughness associated with the presence of coral according to Morris et al. (2021)

Coral reefs develop in very specific environmental conditions. They are found in warm, nutrient-limited (oligotrophic) and non-turbid waters for optimal growth. The environmental parameters involved in the distribution, composition and growth of coral reefs are temperature, aragonite saturation, water characteristics (light, salinity, nutrient and sediment load) and exposure to hydrodynamic conditions (waves and currents). Site selection is therefore essential to intervene on coral reef restoration.

Coral reefs are particularly sensitive to nutrients and non-point source pollution from land-based sources related to urban areas and agricultural activity. Pollution sources include nitrates, phosphates, and other organic or metal pollutants. High levels of nutrients lead to increased macroalgal coverage and competition with corals. At a certain concentration level, nutrients can even become toxic to corals. Other types of metal and organic pollutants may also be associated with increased rates of disease and mortality involved in reef degradation. The presence of suspended matter increases water turbidity and attenuates light penetration into the water column and impairs coral growth. High levels of sediment supply can cause hyper-sedimentation and smother benthic organisms and tissue mortality.

It is therefore important to analyze the optimal conditions for coral reef development before selecting a site for a restoration project. Several types of actions can be implemented to improve reef protection. Conservation measures, including control of factors associated with their degradation, improvement of substrate quality and quantity, or active restoration.

Actions aimed at intervening on the causes of degradation through passive or assisted approaches consist in removing or reducing pressures to restore a functional system through: reduction of the exploitation of reef resources (no-take zone for example), enforcement of legislation in favor of conservation and reduction of nuisances. It also involves the involvement of stakeholders, awareness raising and the improvement of water quality through watershed management policies for example. All of these actions aim to strengthen the resilience of reefs to stressors and promote optimal growth.

Another category of actions aims at intervening on the stabilization and improvement of the substrate. Indeed, to develop, coral larvae need hard and stable substrate. Substrate stabilization implies the use of meshes or nets to reduce the movement of the substrate, the contribution of rocky blocks also allows to improve the quality of the substrate. Complex concrete structures can also be used to create an artificial reef where no hard substrate exists. However, it is important to study the interaction between the geometry of the artificial reef and the incident waves, as the acceleration of the currents may exacerbate the erosion locally. Measures to intervene on the substrate are often combined with other active restoration techniques.

The last category of actions is active restoration and includes various techniques. It intervenes for example when natural recruitment of coral is no longer effective. This type of restoration is often implemented in parallel with passive measures aimed at mitigating pressures and improving the quality of the substrate and water if necessary. Among the active measures, coral transplantation is the most common measure in the Caribbean. It corresponds to the removal of fragments from a donor site that are directly implanted on a reef substrate or on an artificial structure. Fragments will then reproduce asexually (cloning) on the substrate to form new colonies. It is possible to stimulate the growth of corals (25 to 50 times the normal growth rate) by micro-fragmentation which consists in cutting corals in small pieces with a specialized band saw and letting them grow on a substrate. In all cases, it is advised not to remove more than 10% of the donor individuals in order not to weaken the existing colonies.
In order to promote the growth and survival of the coral fragments as well as to better control the environmental parameters during the farming of coral fragments, it is possible to go through an intermediate phase in a nursery also called «coral gardening». This method can be carried out directly in the natural environment on artificial supports (ropes, table, blocks, etc.) or in ex-situ environments such as laboratories (aquarium).
In addition to these methods, artificial structures can be added for coral reef restoration purposes as a substrate for coral recruitment or coral planting. Electroplating is a technique of mineral accretion by electrolysis of seawater. Minerals present in the water (calcium carbonate and magnesium hydroxide ions) precipitate on a metallic support under the action of an electric current and promote the calcification necessary for the formation of the calcareous skeleton of polyps (Léocaldie *et al.*, 2020). Calcification occurs more rapidly, colonies grow faster and are reported to have better survival rates and stress tolerance (Goreau and Hilbertz, 1996).

Artificial reefs, designed to mimic natural processes and be integrated into reef landscapes, can also be used as a substrate to transplant corals, generate colonies, and form a reef. There are many ecological engineering solutions.

There are also techniques for assisted seeding and larval dispersal. Large quantities of eggs and sperm are collected in the field and brought back to the laboratory for ex-situ fertilization. The embryos and larvae are then reared in tanks before being installed on a series of artificial structures to be re-implanted on the natural or artificial reef. This technique also improves genetic diversity and natural recruitment over time but requires more time, technical skill and is more expensive compared to transplantation (Hein *et al.*, 2020).

The choice of techniques to be used in coral reef restoration projects must be based on a precise diagnosis of the factors involved in their degradation. An analysis of the environmental conditions must also be carried out for the selection of sites (Figure 39).

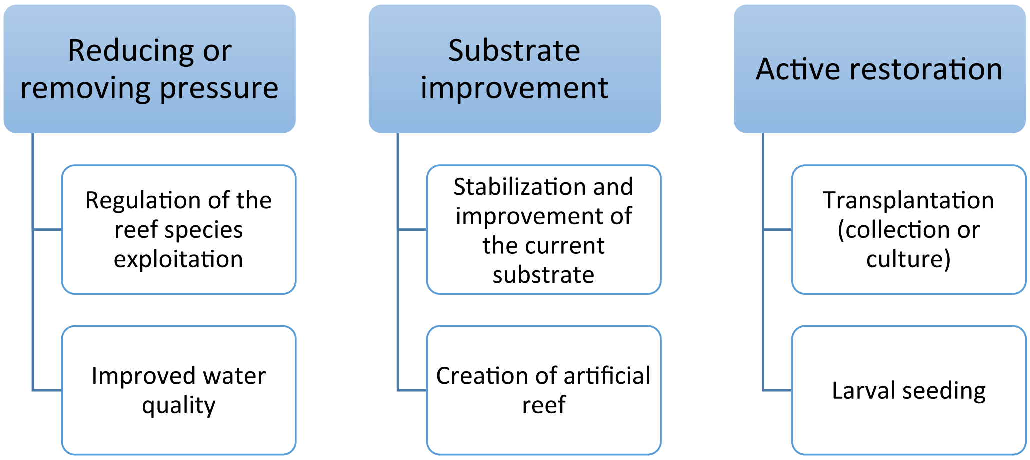


Figure 39: Synthesis of reef restoration actions that can improve the protection services of this ecosystem

ARTIFICIAL REEFS AGAINST COASTAL EROSION AND MARINE FLOODING IN GRANADA

An artificial reef was installed in 2015 off the coast of the city of Greenville, Grenada, to protect it from erosion. This is one of the few large-scale artificial reef initiatives in the region whose primary purpose is coastal protection. This project has allowed for the involvement of local communities and their feedback in its design.

Data on the evolution of the coastline, the currentology, the modification of the bottom and the state of the reefs were considered. These have highlighted the link between degradation of a portion of the reef and increased exposure to coastal erosion and marine submersion hazards (Reguero *et al.*, 2018). As a result of these preliminary studies, 4 «pilot units» consisting of rock-filled wire baskets were placed at strategic locations in the bay (Figure 40). This restoration solution is specifically designed and engineered to improve protection against erosion and flooding. It meets specific technical and ecological criteria.

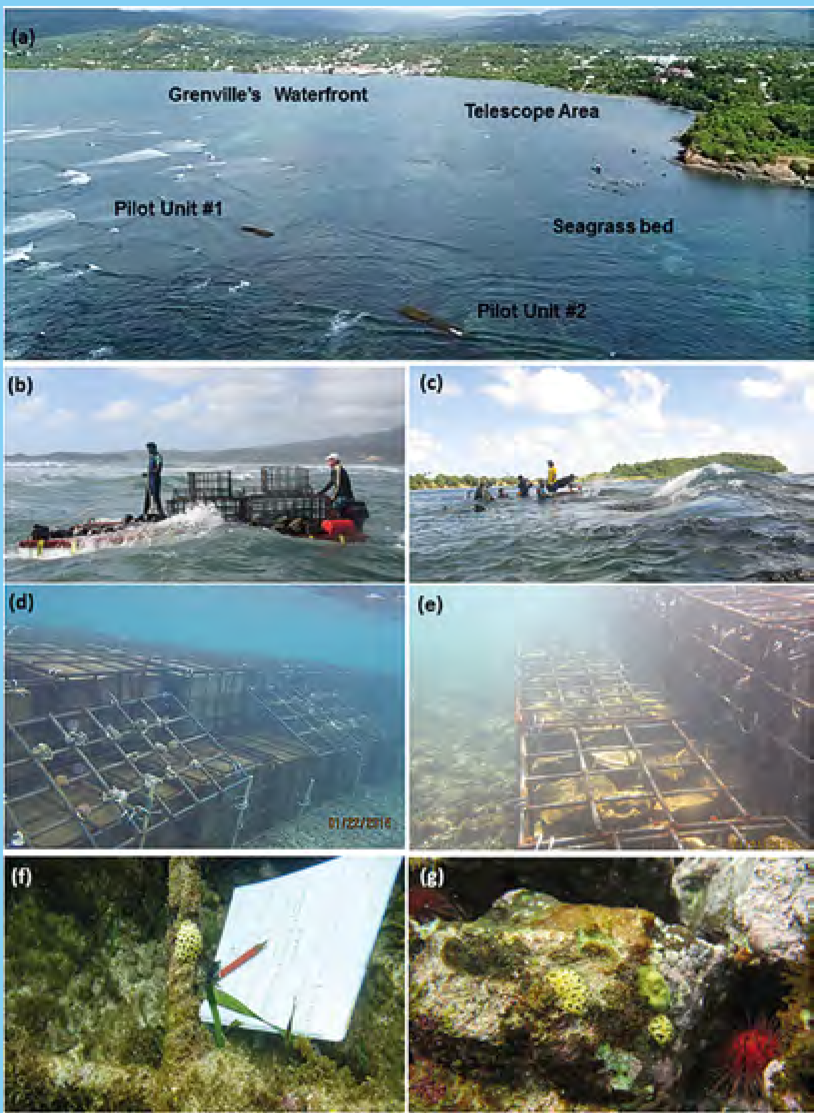


Figure 40: General overview of Pilot Units 1 and 2 in Greenville Bay (top) and submerged view of the traps installed on the damaged reef in 2015 with the coral grafts exposed on the wire mesh (Reguero et al., 2018) .

The thorough technical analysis of the site and the appropriation and commitment of the population to the design of a suitable restoration solution contributed to the project's success. This facility relies on a flexible structure and locally available materials. Based on feedback, structures are still in place and performing their role in attenuating incident waves. A long-term follow-up will eventually allow to observe a progressive return of sediments. In addition, benthic algal and coral communities are forming on the artificial structures. With time, these organisms could allow the structures to merge with the natural reef and thus become permanently established in the benthic landscape of this bay. The establishment of a coral nursery for the active restoration of the site also represents an avenue of improvement to improve the growth of coral on the substrate. In parallel, it is also a question of acting on the stress factors in order to reduce the pressures on the reef (eutrophication and overfishing). Eventually, this reef will be able to provide many ecosystem services to local populations.

CORAL RESTORATION IN TOBAGO

As part of the Carib-Coast project, SPAW-RAC funded a pilot coral restoration site in Tobago from 2021 to 2022 to contribute to coastal risk reduction and climate change adaptation. Environmental Research Institute Charlotteville (ERIC) implemented restoration actions on Pillar coral (Dendrogyra cylindrus) colonies which is an iconic Caribbean hard coral species and produces unisex columnar colonies up to 4 m high (Figure 41). This makes it an important reef builder growing in shallow coastal waters and can contribute significantly to the reduction of coastal erosion.

Figure 41: Healthy colony of pillar coral (Dendrogyra cylindrus) in Tobago (Source: ERIC)

Historically, this rare species classified as vulnerable by the IUCN has a very fragmented population in Tobago. Indeed, the populations have been particularly affected by episodes of bleaching and diseases. These phenomena have greatly reduced the number of colonies around the island and their ability to reproduce.

The project mapped the remaining pillar coral colonies in Tobago, determined their gender and collected fragments for transplantation and recreation of new colonies (Figure 42). The objective of this active restoration work was to collect fragments of male and female individuals in the vicinity in order to revive natural reproduction and prevent the disappearance of pillar corals.

A total of 64 fragments were collected from donor sites (Booby Reef and Plymouth) in good ecological condition and then transplanted directly to Booby Reef. The transplantation methods used had minimal impact on the donor colonies and took place in areas with minimal human impact. Indeed, Booby Reef is located off the coast of Charlotteville, a fishing village with little pressure from tourism, water pollution or fishing practices. Moreover, this site is located within the UNESCO MAB reserve in the north-east of Tobago. A legal process has started in 2021 to designate the restoration area and other reef areas of interest as a Natural Heritage Site to form a «core reserve» for effective protection of corals in the UNESCO MAB reserve.

This active restoration project benefited from the support of the local community involved in the collection and transplantation of corals as well as their long-term monitoring.

Figure 42: Colonies of pillar coral collected and transplanted to Booby Reef (Source: ERIC)

Preliminary results are encouraging and seem to indicate that the transplanted pillar coral colonies are surviving and healthy. Additional monitoring is needed to show the success rate of the restoration work of these colonies and their ability to reproduce naturally to generate a reef capable of contributing to the reduction of coastal erosion.

Seagrass beds

Under conventional climatic conditions, the leaf surface of seagrass beds provides a simple frictional means of slowing incident waves (Ondiviela *et al.*, 2014), thereby promoting sedimentation with roots and rhizomes that prevent erosion and stabilize sediments (UNEP, 2020).

Larger species perform this protective role best (Nordlund et al, 2016). Protective performance is assessed based on meadow width, seagrass size relative to depth, density, and coverage.

Protective services differ depending on the physical conditions of the environment and are optimally delivered by seagrass beds in shallow areas with low-energy waves and where water-leaf interaction is maximal (Ondiviela *et al.*, 2014).

Due to their roots, seagrasses can fix large volumes of sediment (mainly sand and «mud») over large areas (Figure 43). This stability (also due to coral reefs) confers optimal development conditions for the adjacent mangrove (Guannel *et al.*, 2016).

Via their foliar system, they can trap particles suspended in the water and make them sediment faster. In this way, they participate in sediment accretion, in addition to fixing it, which in the long term contributes to the elevation of the seabed (Potouroglou *et al.*, 2017). This service is particularly important in the context of climate change. Indeed, seagrasses can adapt to sea level rise through soil elevation or inland migration, if unimpeded by coastal infrastructure (Duarte *et al.* 2013). This simultaneously decreases turbidity in the environment and provides favorable conditions for coral development (Guannel *et al.* 2016). Epiphytic algae also participate in this sediment capture through substances they secrete (Agawin and Duarte, 2002).

Combined, these sediment stabilization and accretion functions form favorable conditions for natural beach nourishment (sand supply) (Paul, 2018). These services would be optimal in phanerogam-dominated seagrass beds (Scott *et al.*, 2018).

Seagrass beds require specific environmental conditions for optimal development. They generally occupy shallow waters because of their need for light. Suspended matter inputs and eutrophication reduce incident light. The availability of light can have a negative impact on seagrass beds in the long term and lead to their degradation. The meadows develop both on sandy or muddy sediments. They can also develop in calm waters but also more exposed thanks to their root system. Moreover, their organism is adapted to different conditions of salinity.

With respect to their need for light, it is important to ensure that the environmental conditions are suitable before considering restoration. One of the restoration techniques is therefore to act on the

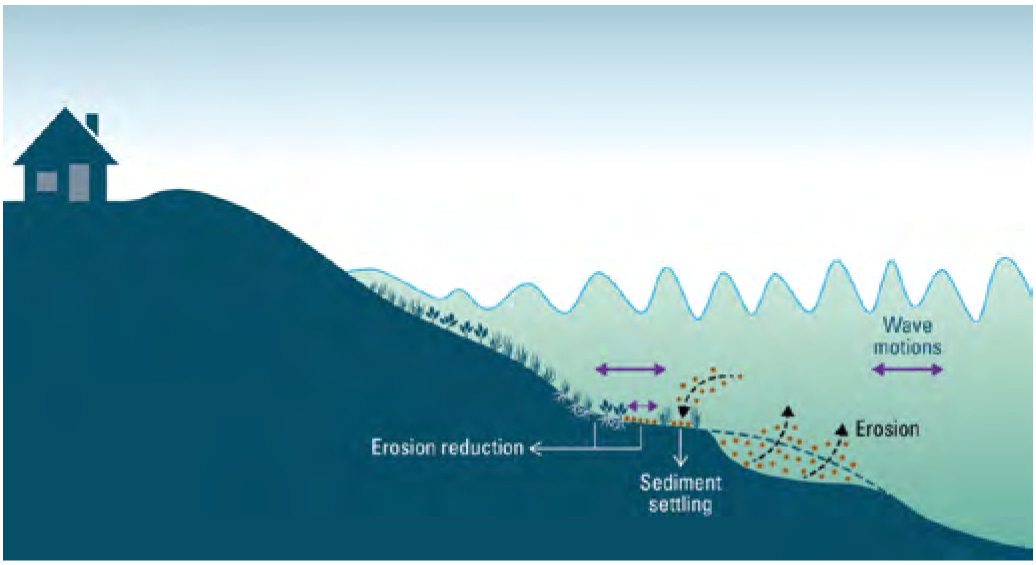


Figure 43: Role of seagrass beds in the maintenance and accumulation of sediments contributing to the stability of the coastal zone according to Morris et al. (2021)

environmental conditions by reducing the contribution of suspended matter and the diffuse sources of pollution associated with the eutrophication of the environment. In anchorage areas, meadows are also subject to direct degradation by boat anchors. It is possible to install anchor buoys and prohibit the use of anchors in protected areas, for example.

Active restoration actions involve several techniques. Transplanting seagrasses is the most common technique used in restoration projects worldwide. This method consists of collecting rhizome fragments in a meadow and fixing them in the sediments of an area to be restored at an appropriate depth. It can be done manually or mechanically. Fragments can be anchored in the sediment with weights, staples, or dowels to hold them in the bottom until new roots develop (Léocadie *et al.*, 2020). The use of root balls containing fragments and sediment around the roots is also being tested in restoration projects. This technique appears to improve plant survival by limiting stress and promoting plant anchorage.

Micropropagation is another technique that involves taking seeds or buds from the natural environment and then germinating them in a controlled environment (in vitro culture) to generate seedlings (Zarranz *et al.*, 2010). The seedlings then constitute a nursery and thus a stock of individuals that can be implanted on the selected sites. This technique does not work on all species, including S. filiforme and T. testudinum (Léocadie *et al.*, 2020).

The seed sowing technique can also be used. This approach is based on the ability of seagrasses to produce seeds that can disperse and colonize new areas (Léocadie *et al.*, 2020). Seeds are collected and transported to target areas for restoration. Seeding must be tailored to the morphological characteristics, dormancy, and germination periods of seagrass species. Indeed, it is necessary to differentiate between species with directly developing seeds and other types of species, which produce seeds at the end of the growing season and require post-harvest seed storage until growing conditions improve. Restoration results are visible long after the seeds are sown (Leocadie *et al.*, 2020).

Finally, passive management is a technique for enhancing natural recruitment by promoting the propagation and natural development of seagrass beds through the use of hessians bags placed on the ground for seagrass to cling to (colonize) (Wear *et al.*, 2006). This technique is simple to implement, inexpensive and minimally invasive, creates no impact on source sites, and allows for development in a stable sedimentary environment (Irving *et al.*, 2010) however, results are obtained relatively long after installation.

Regardless of the technique used, a pressure analysis should be performed beforehand to select the most appropriate technique. Each of the techniques can be combined to improve restoration effectiveness (Figure 44).

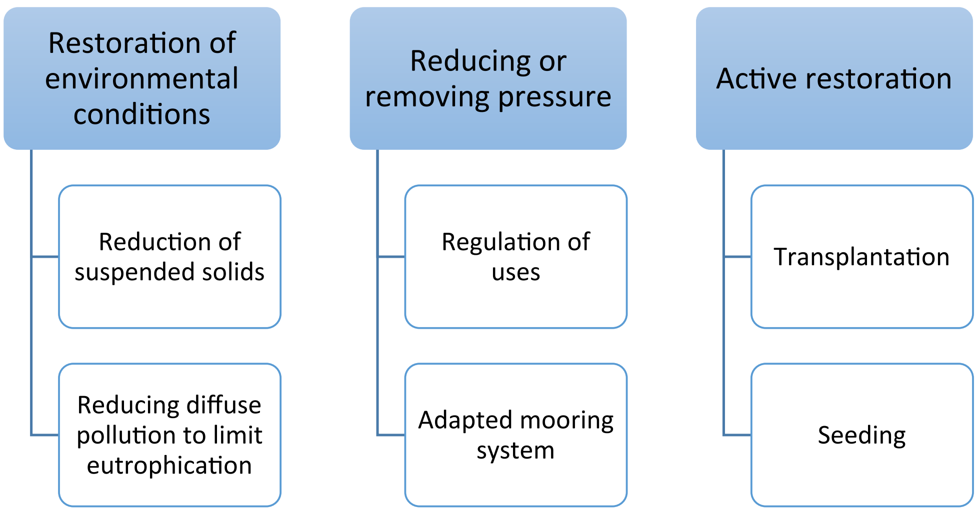


Figure 44: Synthesis of restoration actions that can improve seagrass protection services

SEAGRASS RESTORATION IN PUERTO RICO

As part of the Carib-Coast project, SPAW-RAC funded a passive seagrass restoration project working on limiting pressures on this ecosystem. The seagrass beds in Tamarindo Bay on Culebra Island have experienced a decline of almost 30% of its surface between 2010 and 2017. The coastal area is subject to high sediment loads due to the regular erosion of unpaved roads that contribute 400 metric tons of sediment to the coast per year. This situation has been intensified by the impact of hurricanes Irma and Maria in 2017 which caused significant damage to seagrass beds, coral reefs, and mangroves in the area.

Protectores de Cuencas (PDC) has developed a design project for the site to be restored located at the top of Tamarindo beach and very popular for tourism. Thus from 2021 to 2022, PDC has implemented a variety of best management practices to combat sources of land-based pollution and improve the quality of coastal waters and seagrass beds.

Figure 45: Coastal habitat restoration using native species at Tamarindo Beach, Culebra (Source: PDC)

A total of 650 native plants of 8 different species were planted to restore coastal upland habitat and form a vegetative barrier capable of blocking sediment and stabilizing soil (Figure 45). Species selected based on their ability to live in high salinity soils and require minimal maintenance.

PDC carried out ecological engineering work to stabilize the access road to Tamarindo beach, creating a permeable and ecological parking lot to stabilize the soil and drastically reduce erosion. The work also delineated the public access areas by installing new wooden posts (previously damaged) and boardwalks to both guide pedestrians to the beach without disturbing the existing coastal habitat and protect newly planted plants (Figures 46 and 47).

Figure 46: Tamarindo Beach Permeable Parking Development Process (Source: PDC)

Post-construction site monitoring ensured proper maintenance of the area and assessed its functionality. All measures implemented, including the permeable parking area, boardwalks, paved access road, and delineation with wooden posts and rocks, are working as intended. PDC has observed that visitors to the area are using the parking lot appropriately and not stepping on the coastal vegetation.

At the same time, PDC conducted an ecological study in 2022 to assess the condition of the seagrass bed in front of the Tamarindo Beach area, including associated marine organisms (macroalgae, sponges, invertebrates, and fish species). Preliminary results suggest an improvement in water quality and a reduction in sediment inputs to the seagrass beds, but additional long-term monitoring is needed to show the positive effects of the work done to better manage land-based pollution sources and restore seagrass beds. It will take several years to see seagrass beds regeneration.

Figure 47: Previously installed and damaged wooden poles (left) have been removed and replaced with new wooden poles and wooden sidewalks (right). (Source: PDC)

Most NBS-based protection projects focus rehabilitating one ecosystem. However, it is important to note that whatever the conditions, it is always the combination of the three ecosystems Reefs/Mangroves/Seagrasses that confers the most services in terms of coastal protection (Guannel *et al.*, 2016). Restoration projects can thus intervene on several ecosystems at the same time, especially since restoration actions implemented on one of the ecosystems can bring beneficial effects on the others present on the site.

In addition, NBS can be combined with structural protection works to improve the effectiveness of the respective protection measures. For example, it is possible to rely on structures to restore hydrodynamic conditions favorable to mangrove development by reducing agitation. Conversely, beach nourishment can improve the structural performance of a seawall or riprap by protecting the structure from sea action.

One of the main advantages of NBS is that ecosystems can naturally adapt to climate change over longer time scales than conventional protective structures through accretion or natural growth. It is therefore important to keep these ecosystems healthy so that they maintain their resilience by reducing anthropogenic disturbances and restoring conditions favorable to the development of these coastal ecosystems. Similarly, it is also necessary to provide space for natural development so that they can adapt to sea level rise and changing environmental conditions associated with climate change. This is an important element to anticipate in restoration projects to ensure the effectiveness of protective services over the long term, especially for barrier beaches and mangroves.

TIPS FOR IMPLEMENTING NATURE-BASED SOLUTIONS

The process of implementing nature-based solutions must follow several successive stages in order to select the intervention options and techniques best suited to the local context. It must be part of an iterative process allowing actions to be adapted to changes in the context and feedback (Figure 48).

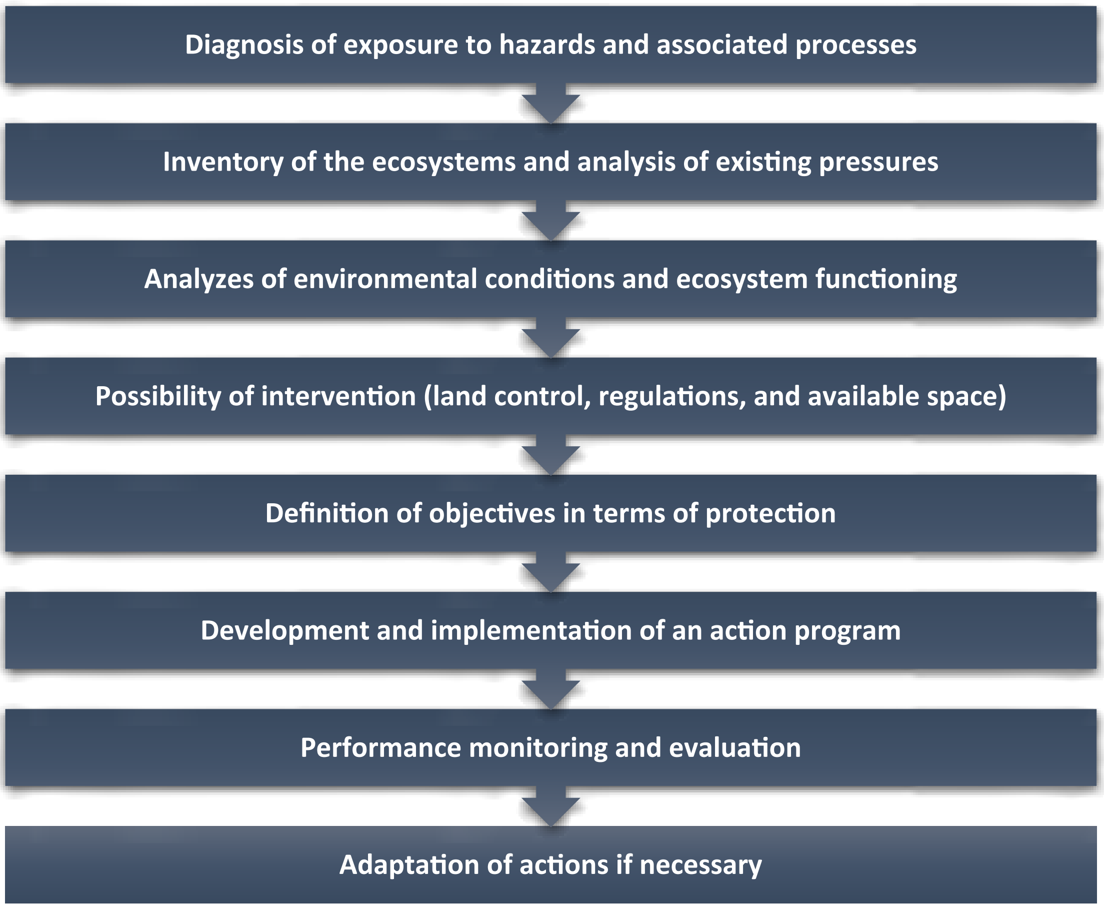


Figure 48: Generic process for implementing nature-based protection projects

Diagnosis

The diagnosis phase aims to analyze the feasibility of implementing nature-based restoration techniques. It aims to carry out a complete analysis of the physical, environmental, regulatory, historical, cultural, and social issues that may be involved in the definition and implementation of the project. This phase must also make it possible to identify all the stakeholders and the project's scope of intervention.

The phase of diagnosis of the hazard and the associated risk generally takes place upstream, during the definition of management and adaptation strategies of the territories exposed to hazard. This step aims at studying the functioning of the coastline, its evolution and the processes associated with erosion or marine submersion hazards according to the project objectives. An analysis of the stakes exposed is also carried out in order to analyze their level of exposure to the risk and the opportunities of actions to be implemented to protect them if necessary (population, buildings, activities, and infrastructures).

In order to analyze the potential actions to be implemented, including nature-based solutions, it is necessary to identify the ecosystems naturally present on the site which offer protection. This phase must also assess the state of these ecosystems, analyze the conditions involved in its current functioning, the factors involved in their degradation (anthropogenic and natural pressure) and how these ecosystems intervene in the control of the hazards of erosion or submersion. The analysis of the historical evolution of ecosystems is particularly useful for understanding the changes observed in relation to the pressures potentially present.

It is particularly essential to ensure that the environmental conditions are adapted to the development of these ecosystems. Indeed, each ecosystem has different needs and tolerance to environmental conditions. If the conditions are no longer suitable, it will be a matter of considering the implementation of actions to restore these conditions for optimal development (restoration of hydrological conditions for the mangroves or improvement of the water quality for the reefs for example). It is also important to assess the evolution of these conditions over the long term and the associated uncertainties, particularly in connection with the effects of climate change (rise in sea level for example) (Figure 49).

Figure 49: Main environmental factors involved in protection projects using nature-based solutions

Finally, one of the last important parameters is to be able to benefit from land control to act on the site. An analysis of the regulatory context, the uses and the development is therefore necessary. In particular, it is essential to provide sufficient space to restore the natural dynamics of the ecosystems if necessary. This is particularly the case for barrier beaches and mangroves which have the capacity to adapt to changes in sea level if the space is not constrained by the presence of development.

The diagnosis elements should make it possible, in association with the stakeholders, to define the objectives and assess all the intervention options to select the most appropriate strategy for the local context, considering the constraints and uncertainties. It aims in particular to select the areas on which to intervene and select the most appropriate techniques to maximize the protection services of these ecosystems.

DIAGNOSIS FOR THE RESTORATION OF MANGROVES IN THE BAHAMAS

As part of the mangrove restoration pilot project (see above), the Perry Institute for Marine Science (PIMS) carried out an important diagnosis on Abaco and Grand Bahama before setting up restoration work in 2022.

Social assessment: Community consultations

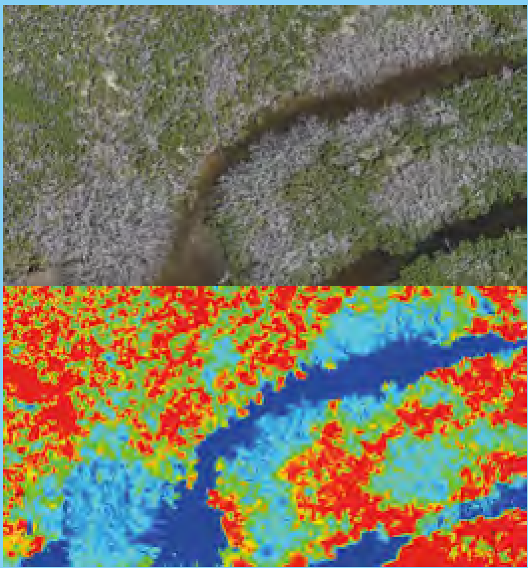
PIMS and its partners carried out 8 surveys and 12 community consultations in Grand Bahama and Abaco. These meetings involved local stakeholders to gather information on how the mangroves in the two areas were perceived, assessed, and used, as well as how Hurricane Dorian changed these factors as well as the restoration results these stakeholders hoped for. These meetings made it possible to better appreciate the socio-economic aspects and encouraged the involvement of local communities in restoration activities. A total of 20 sites (12 in Grand Bahama and 8 in Abaco) have been identified as priorities for mangrove restoration (Figure 50).

Figure 50: Grand Bahama mangrove areas identified by local communities as priorities for assessment and restoration. The sites circled indicate locations where the general area has been identified, as opposed to locations that have been named specifically (these areas are identified by stars). Sites identified by orange circles/stars were mentioned by several survey participants. (Source: PIMS)

Ecological assessment: Mangrove mapping

Using advanced technology (45MP camera and 10-band multispectral sensor mounted on a commercial drone flying at approximately 120 meters), PIMS mapped a total of 34 mangrove areas on Grand Bahama (19) and Abaco (15), i.e. nearly 6,700 ha.

The collected data was processed to compile photo mosaics of each mapped area, which were then assessed using different products from the visual and multispectral data, including a Normalized Difference Vegetative Index (NDVI), a metric used to indicate the amount of photosynthetic activity. NDVI values and GIS maps of mangrove habitat were used in analyzes to compare the total area of each site that consisted of living and dead mangroves as well as to assess regeneration, including mangrove regrowth damaged during Dorian or new recruits to the system and potential sources of mangrove propagules for use in replanting efforts. These data serve as a reference for long-term monitoring of the mangroves and to assess the success of restoration (Figure 51).



In addition to drone imagery, satellite data was used to provide large spatial scale maps of living mangrove coverage before and after Dorian across Grand Bahama and Abaco.

Thus, it was estimated that on Grand Bahama, 14,000 ha of mangrove (22%) were completely dead, and 9,000 ha (14%) had suffered significant damage, and that on Abaco, more than 10,000 ha of mangrove (14 %) were dead and 5,5000 ha (7%) of mangroves were impacted. These results are much more precise than those of the study produced by Steinberg *et al.*, (2020) to discriminate completely dead mangroves from those having a chance to regenerate naturally.

Figure 51: Close-up view of a mangrove system with a high-resolution image used to map living and dead mangroves at the scale of a restoration site (top) The same area (bottom) showing NDVI analysis with red areas represent healthy mangroves, light blue dead mangroves, and dark blue water (Source: PIMS)

Ecological assessment: Fish and benthic communities

PIMS assessed fish assemblages and benthic communities associated with mangroves to detect ecological changes caused by Hurricane Dorian and help determine the best approaches to rehabilitate or restore mangroves. In total, 19 sites on Grand Bahama and 11 sites on Abaco were assessed by underwater monitoring by diving (30 x 2 m transects) and water and sediment sampling. The data collected was compared to the previous assessment carried out in 2019 before Hurricane Dorian and using the same tracking method.

Analysis to prioritize the mangrove sites to be restored

A quantitative analysis of mangrove habitats was carried out using available data from community surveys, underwater surveys, aerial surveys, and access to fine satellite data. PIMS also developed a hierarchical ranking system based on the three indices and applied in a progressive way to filter the sites and select those where the impact of the restoration efforts could be the greatest: (i) damage index based on the NDVI values which resulted in a GIS map online, (ii) Resilience Index and (iii) Value Index.

This information led to the development of a Mangrove Restoration Strategy in November 2021 to conduct the most appropriate interventions on Grand Bahama and Abaco and determine the appropriate restoration methods when mangrove replanting was deemed necessary. This strategy focused on mangrove systems completely decimated due to prolonged flooding during Dorian, leaving standing dead mangroves in most cases.

In this case, PIMS favored active restoration by collecting propagules on red mangroves and planting in situ in severely degraded areas, bypassing passive restoration of the hydrological network or restoration techniques using nurseries to grow mangrove seedlings.

All restoration sites will be monitored annually using high-resolution satellite and drone imagery to track mangrove growth and survival, and underwater surveys will be conducted annually for at least five years to assess changes in fish and benthic communities and environmental characteristics.

Actions

Based on the diagnosis, possible strategies to reduce hazard should be identified and an assessment made as to whether nature-based solutions are a good alternative or complement to other management options. Several intervention strategies can be studied according to the following options:

- non-intervention if we consider that the ecosystems are fully playing their protective role in their current state;
- management measures not acting directly on ecosystems but on upstream pressures or on their protection, for example;
- restoration actions aimed at intervening directly on naturally occurring ecosystems and improving natural attenuation processes;
- active intervention actions to create new ecosystems;
- hybrid solutions involving protection works in combination with restoration actions.

These actions can thus relate to conservation, restoration, or the creation of new habitats (Figure 52). The cost and technical nature of the interventions will depend on the scope of the actions and the influence of the project. It is also considered that ecosystems in their natural state of conservation are those that offer the most protection services.

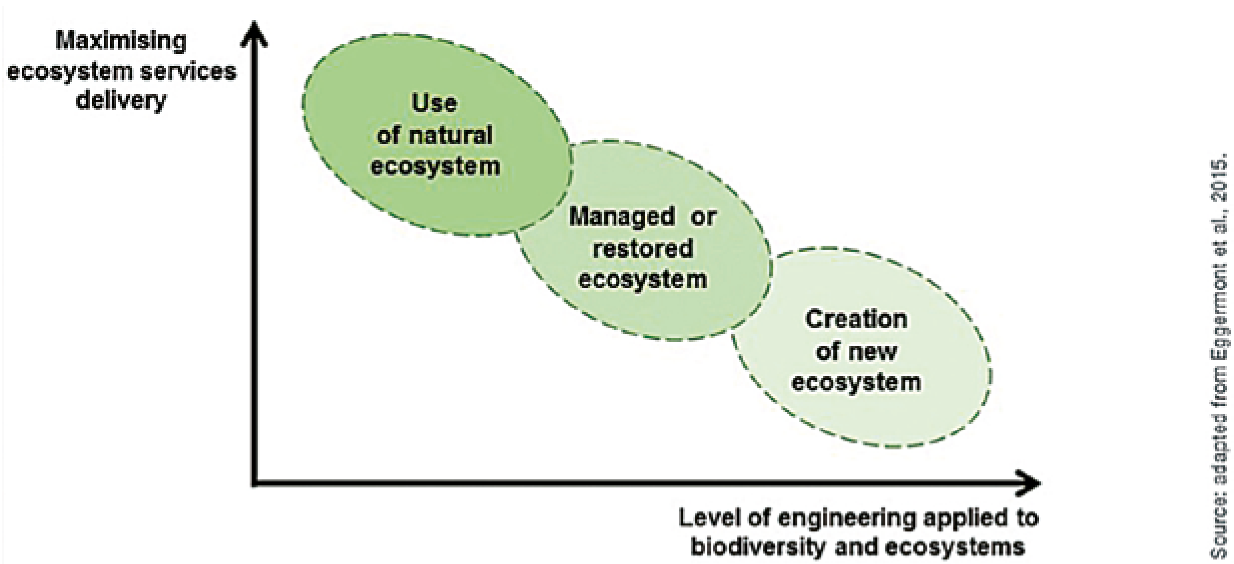


Figure 52: Typology of nature-based solutions according to the three main categories of actions on natural, restored, and new ecosystems (Cohen-Shacham et al., 2016).

Several types of action can be implemented depending on the objectives sought: active or passive measures and awareness raising (Figure 53). Active measures are restoration actions that directly affect ecosystems. Passive measures consist in acting on upstream pressures, either through protection actions or through assisted restoration actions aimed at promoting the natural development of ecosystems. The feasibility of the actions must be analyzed according to the financial and technical capacities of the project leaders and the commitment of the stakeholders.

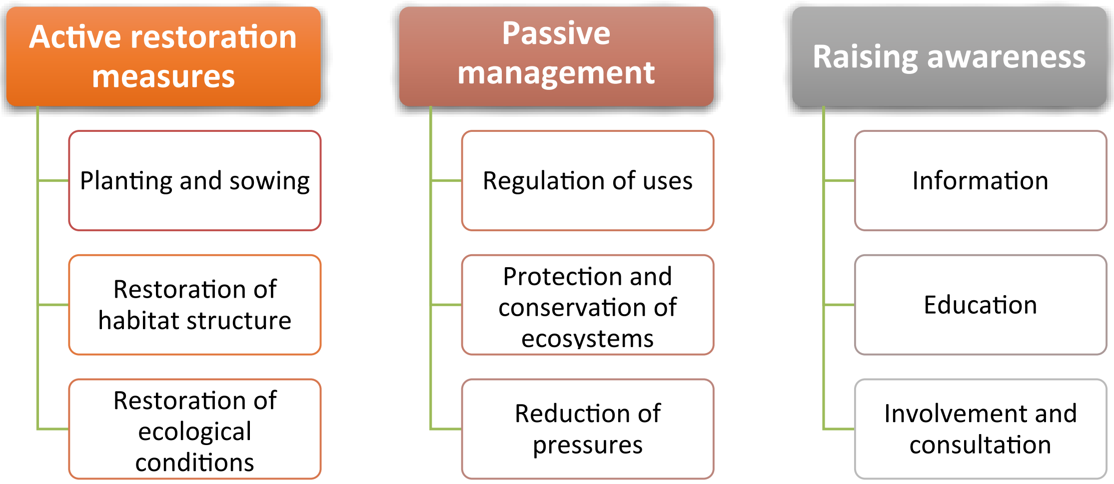


Figure 53: Typology of restoration actions to improve the protection services provided by ecosystems

The implementation of nature-based solutions generally requires time to be effective in terms of protection. It is therefore essential to plan actions to support the development of these ecosystems over long periods (several years) through maintenance actions. The cost of maintenance actions should not be underestimated as it can represent a significant part of the total budget. Long-term financial support for projects is therefore essential to ensure their success.

As a priority, it is recommended to treat existing pressures upstream before considering active restoration. Indeed, if the existing pressures or environmental conditions are not adapted, the effectiveness of active restoration actions will be limited. It is therefore generally necessary to implement several categories of actions to maximize their effectiveness in the long term.

Thus, it is necessary to involve the population and users in creating, implementing, and monitoring projects. Indeed, actions that consider the concerns of the population benefit from greater social acceptance and have a greater chance of success in the long term. Thus, the population must be involved from the creation phase and throughout the duration of the project. Public awareness, through communication activities, is also important. It aims to inform the public of the interest of preserving these environments through the multiple ecosystem services offered by these environments. Public involvement aims to reduce potential conflicts and maximize the synergies that these actions can represent in order to guarantee the sustainability of nature-based protection projects.

INVOLVEMENT OF THE LOCAL POPULATION IN THE IMPLEMENTING ECOLOGICAL RESTORATION ACTIONS ON CLUGNY BEACH, SAINTE-ROSE (GUADELOUPE)

Within the framework of the installation of Carib-Coast pilot sites in Guadeloupe by the ONF, several events involving the participation of civil society (volunteers, schoolchildren, young people in social integration, etc.) allowed them to become aware of the role of the upper beach vegetation in the fight against erosion.
On Clugny beach in Sainte-Rose, the second pilot site of the project, students from the schools and colleges of the commune participated in the ecological restoration actions from the beginning of the work (Figure 54). Each school sponsored one of the 13 regeneration enclosures installed on the site. The children produced a collective drawing that they themselves hung on their enclosure during an awareness day organized with the local nature protection association To-Ti-Jon, which brought together more than 100 participants. This initiative subsequently led to the creation of two marine educational areas around the perimeter of the school-sponsored pen (Figure 55). A year later, the children were able to return to plant Caribbean coastal forest trees in their enclosure. The seedlings were numbered and will be tracked by the students for a participatory science project.

Figure 54: Patronage of the enclosures by the students of Sainte-Rose (Source: Noémie Videau (NFB) ; 06/16/2021)

This educational work allowed to reach and sensitize a large social and generational stratum of the population of Sainte-Rose: children, teachers, parents, members of associations were directly involved. The posting of the drawings and the media communication around the project also allowed to inform other users of the site and contributed to the respect of the enclosures. Finally, the regular presence of the association and the schoolchildren on the beach also allowed them to be quickly informed of any incidents that might occur on the site.

Figure 55: Children planting in the enclosures (Source: Noémie Videau (NFB) ; 09/21/2022)

It is important to remember that project leaders must have control over the land and that they must ensure that their actions are compatible with urban planning, environmental and property regulations. For example, specific regulations may be applied due to the presence of protected species within the project's scope.

In addition, synergies may be identified with other existing strategies or action plans within the project area. For example, measures aimed at improving water quality at the watershed level can also benefit coastal coral reef ecosystems and seagrass beds by limiting pressures on these environments (improvement of urban water purification systems, adaptation of agricultural practices to limit soil erosion, waste management, etc.). In the same way, the actions implemented can be integrated with other measures involved in the conservation and protection of ecosystems.

INVOLVEMENT OF LOCAL COMMUNITIES IN THE IMPLEMENTING CORAL RESTORATION ACTIONS IN MAN'O WAR BAY, CHARLOTTEVILLE (TOBAGO)

As part of the Carib-Coast Coral Restoration Pilot Site, the Environmental Research Institute Charlotteville (ERIC) has collaborated extensively with the local community of Tobago. Indeed, to maximize and sustain the restoration of pillar corals (Dendrogyra cylindrus) in Man'O War Bay, ERIC has organized several trainings on detection, monitoring, sampling, and in-situ transplantation of coral fragments. Thus, from September 2021 to June 2022, 8 community field technicians were trained (Figure 56). This transfer of knowledge has allowed a better acceptance of this project by the local population, a reinforcement of skills as well as an important support to continue the coral restoration work and their long-term monitoring of coral health. This is an asset, especially considering the vulnerability of corals to anthropogenic activities (e.g. anchoring) and environmental stresses (e.g. bleaching, disease) as well as the time required for transplanted corals to form functional reefs capable of limiting coastal erosion.

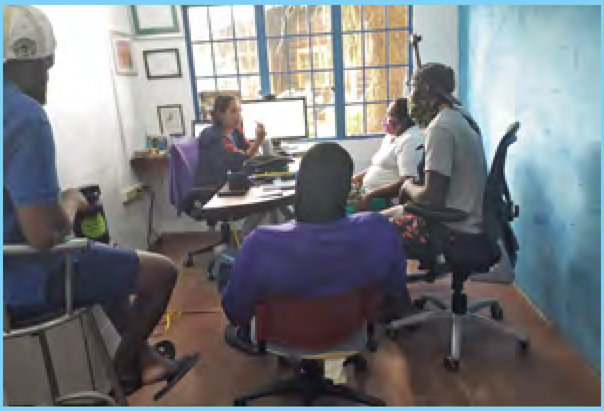


Figure 56: Community field technicians trained in restoration techniques (left) and diver sampling a healthy colony of candle corals (right) (Source: ERIC)

In parallel, ERIC made presentations in two secondary schools to 52 students to talk about the current pillar coral restoration program and their environmental and socio-economic importance.

Follow-up and adaptation

One of the success factors of nature-based protection projects is the adaptation of measures to improve the effectiveness of restoration actions. This requires assessment and monitoring at the outset of the project and over the long term. This monitoring is necessary to maintain the effectiveness of nature-based protection solutions and to provide feedback for future projects.

Monitoring and evaluation indicators should be tailored to each situation. They may include the physical environment, the state of ecosystems, their functioning, and their effectiveness in protecting against coastal risks (Figure 57). Close monitoring should be carried out during the first years of the project to ensure that the expected changes are achieved. The population and the users can be directly involved in the realization of this monitoring.

Figure 57: Example of performance factors to assess the effectiveness of coastal ecosystem protection services

Monitoring and assessing should provide information on the success or failure of projects. It should also help guide maintenance actions and determine if additional actions are needed. It is very useful to share best practices with all stakeholders involved in the implementation of nature-based protection solutions.

CAPACITY BUILDING AND KNOWLEDGE TRANSFER ON MANGROVE RESTORATION TECHNIQUES (BONAIRE)

Within the framework of the Carib-Coast project, the SPAW-RAC co-financed a regional workshop dedicated to mangrove restoration in Bonaire starts in October 2021 with the support of the Dutch Caribbean Nature Alliance (DCNA) and Stichting Nationale Parken Bonaire (STINAPA).

This workshop, organized by Mangrove Maniacs, brought together more than 60 participants (face-to-face and online) from 12 different Caribbean countries (Aruba, the Bahamas, Belize, Bonaire, Curaçao, Jamaica, Saint Lucia, Martinique, Mexico, Costa Rica), Europe (the Netherlands) and the United States.

The objective was to provide an exchange platform for researchers, conservationists, park authorities and anyone involved in the preservation of mangroves to share ideas and knowledge on techniques for restoring this ecosystem.
This 4-day workshop was one of the first of its kind on a Caribbean scale, combining both theoretical modules in the classroom and practical sessions onsite (Figures 58 and 59). It aimed to build capacity and knowledge on mangrove restoration at the regional level. Presentations covered methods of hydrological restoration of mangrove systems, identification, and management of areas of excessive sedimentation as well as the use of nurseries and active planting of mangroves to combat climate change and coastal erosion. Participants were also able to discuss cross-cutting topics such as blue carbon, restoration through innovative techniques as well as the impact of Sargassum in order to maximize conservation efforts.

Figure 58: Theoretical modules during the workshop on the restoration of mangroves (Source: Mangrove Maniacs)

Figure 59: Practical module on planting mangroves (Source: Sabine Engel)

Participants were thus able to gain practical experience while expanding their professional network.

International recommendations on the use of nature-based solutions applied to coastal risks

To conclude and to go further on the subject of nature-based solutions for the reduction of coastal risks, some suggestions for international references:

The Australian Guide to Nature-based Methods for Reducing Risk from Coastal risks
Australia's Guide to Nature-Based Solutions for Coastal Risk Reduction precisely describes the physical processes of ecosystem hazard mitigation, details ecological and technical requirements and provides a framework for implementing nature-based solutions .

Morris RL, Bishop MJ, Boon P, Browne NK, Carley JT, Fest BJ, Fraser MW, Ghisalberti M, Kendrick GA, Konlechner TM, Lovelock CE, Lowe RJ, Rogers AA, Simpson V, Strain EMA, Van Rooijen AA, Waters E, Swearer SE. (2021) The Australian Guide to Nature-Based Methods for Reducing Risk from Coastal risks. Earth Systems and Climate Change Hub Report No. 26. NESP Earth Systems and Climate Change Hub, Australia.:
Australian guidelines for the implementation of nature-based methods for coastal hazard risk reduction | Earth Systems and Climate Change Hub

Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience (US Army Corps of Engineers, 2015)
This report provides elements on the use of nature-based solutions to improve the resilience of coastal territories. It presents a classification of solutions based on the nature, the characterization of vulnerability, the development of performance measures, the integration of risk management policies, monitoring and adaptive management.

Bridges, Todd, Paul Wagner, Kelly Burks-Copes, Matthew Bates, Zachary Collier, Craig Fischenich, Joe Gailani, Lauren Leuck, Candice Piercy, Julie Rosati, Edmond Russo, Deborah Shafer, Burton Suedel, Emily Vuxton, and Ty Wamsley. 2015. Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience. U.S. Army Engineer Research and Development:
Use of Natural and Nature-Based Features (NNBF) for coastal resilience - Technical Reports - USACE Digital Library

Implementing Nature-Based Flood Protection. Principles and Implementation Guidance (The World Bank, 2017)
Principles and implementation recommendations for planning nature-based interventions related to flood protection.

Van Wesenbeeck, Bregje K.; IJff,Stephanie; Jongman, Brenden; Balog, Simone Andrea Breunig; Kaupa, Stefanie Magdalena; Bosche, Lauren Vuillemot; Lange, Glenn-Marie; Holm-Nielsen, Niels B.; Nieboer, Henk; Taishi, Yusuke; Kurukulasuriya, Pradeep H.; Meliane, Imen. Implementing nature based flood protection: principles and implementation guidance (English). C. World Bank Group.:
Implementing nature based flood protection: principles and implementation guidance

International Guidelines on Natural and Nature-Based Features for Flood Risk Management
This international recommendation guide provides comprehensive and detailed information on conceptualization, planning, design, engineering, implementation and monitoring to support flood

risk reduction in coastlines, estuaries, and waterways from nature-based solutions.

Bridges, TS, JK King, JD Simm, MW Beck, G. Collins, Q. Lodder, and RK Mohan, eds (2021). International Guidelines on Natural and Nature-Based Features for Flood Risk Management. U.S. Army Engineer Research and Development Center:
International Guidelines on Natural and Nature-Based Features for Flood Risk Management

Glossary

CARIB-COAST	Caribbean Network for coastal risks prevention related with climate change
IPCC	Intergovernmental Panel on Climate Change
NBS	Nature-Based Solutions
IUCN	International Union for Conservation of Nature

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