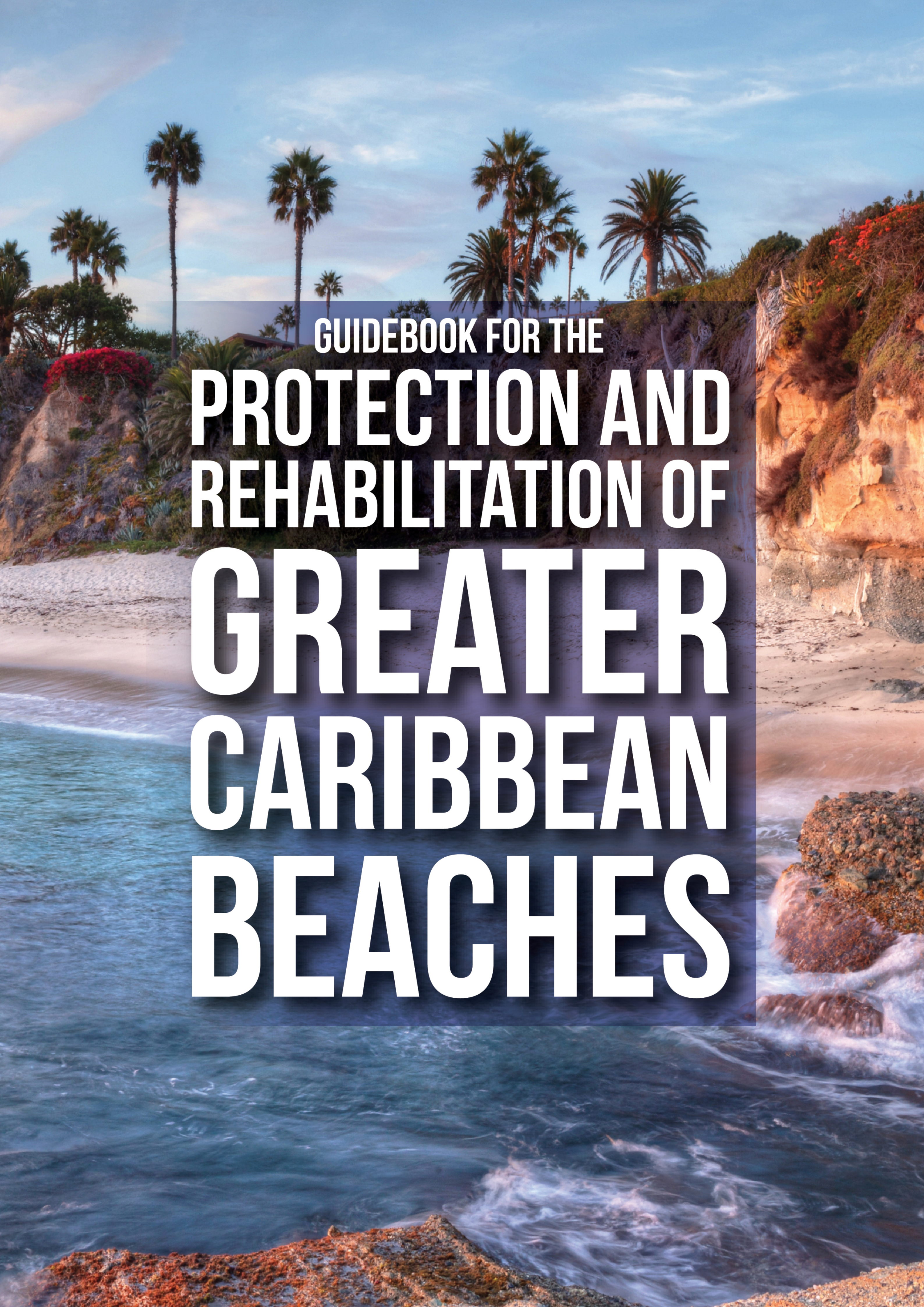

# GUIDEBOOK FOR THE PROTECTION AND REHABILITATION OF GREATER CARIBBEAN BEACHES

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mail@acs-aec.org

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Website: http://www.royards.com

# Acknowledgements

The drafting group of this guidebook has been formed by:

Dr. Miguel Canals from the UPRM Center for Applied Ocean Science at the University of Mayagüez, Puerto Rico;

Dr. Ywenn de la Torre, BRGM Guadeloupe Regional Direction;

Dr. José Luis Juanes of the Department of Physical Processes, Institute of Marine Sciences (CIMAR), Cuba;

Dr. Constanza Ricaurte Villota of the Institute of Marine and Coastal Research (INVEMAR), Colombia; and

Dr. Carlos Valdes from the Seismology Department, Institute of Geophysics of the National Autonomous University of Mexico.

They are all members of the Technical Advisory Group of the “Sandy Shorelines project (SSP)”. With the publication of this guidebook, the SSP completed COMPONENT 5 and fulfilled its Objective 6.

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# PREFACE

The Association of Caribbean States (ACS) organized the First Symposium of the Caribbean Sea Commission in the city of Port of Spain, Republic of Trinidad and Tobago, on November 23 and 24, 2015. It was attended by distinguished experts from eighteen ACS countries, and representatives of international and regional organizations.

The event was developed under the slogan “Challenges, Dialogues and Cooperation for the Sustainability of the Caribbean Sea” and focused on three issues of the marine environment with a negative impact on coastal communities and the economy of the region: the uncontrolled growth of invasive species (particularly lionfish), the arrival of sargassum, and coastal erosion.

Among other aspects, the participants in the event agreed that it was essential to have international funding to promote broader research on the topics of the symposium and in this direction the ACS Secretariat continued actions for the identification and realization of agreements with countries and institutions that had expressed their willingness to contribute with the financial support of projects in the topics addressed.

In order to analyse several project proposals, the Caribbean Sea Commission held the first meeting of its scientific and technical sub-commission in May 2016, in which the project “Assessment of the impact of climate change on the sandy shorelines of the Caribbean: alternatives for its control and resilience” was accepted for its progress. It was abbreviated “Sandy shorelines,” and was approved at the 7th Summit of Heads of State and Government of the ACS in Havana, Cuba, in June 2016.

In response to the willingness expressed by the Government of the Republic of Korea to cooperate with the financing of ACS projects, in September 2016 the “Sandy shorelines” project was presented to representatives of the Korea International Cooperation Agency (KOICA) at the ACS headquarters in Port of Spain, starting the process of implementing the project.

The general objective of the project reflected the interest expressed at the 1st Symposium of the Caribbean Sea Commission: to “improve the resilience of coastal communities to climate change and sea level rise, through the establishment of a coastal erosion monitoring network and the application of best practices in beach conservation and rehabilitation.”

The following specific objectives were included in the elaboration of the project:

Update the assessment of the intensity, extent and causes of erosion in the Caribbean region.

Establish a regional coastal erosion monitoring network.

Develop beach rehabilitation projects in priority sectors of economic and social interest.

Provide consulting and supervision for the execution of beach rehabilitation projects.

Contribute to the creation of institutional and human resource capacities for the best legal and engineering practices in erosion control.

Write a beach rehabilitation manual with scientific and engineering criteria that responds to the special characteristics of the tropical beaches of the Caribbean region.

Develop recommendations for the application of best regulatory and engineering practices in the management of the erosion process.

Provide an improved beach erosion monitoring system for practice and future applications in research to understand the causes of erosion.

In correspondence with the proposed objectives, the tasks of the project were organized through six components:

COMPONENT 1. Establishment of focal points for participating countries.

COMPONENT 2. Institutional capacity building and human resources.

COMPONENT 3. Establishment of the regional erosion process monitoring network.

COMPONENT 4. Development of 3 beach rehabilitation projects.

COMPONENT 5. Preparation of the Beach Rehabilitation Manual for the Caribbean.

COMPONENT 6. Regional Beach Preservation Conference.

The first methodological result of the project was obtained in COMPONENT 1 when the Focal Points were prepared and completed the proposal of the "Project Profile for the Elaboration of the National Plan for the Coastal Erosion Process" which reflects the organizational procedure for the conduct of tasks at the country level.

Countries participating were part of the project "Assessment of the impact of climate change on the sandy shorelines of the Caribbean: alternatives for their control and resilience" and national institutions that serve as Focal Points in each of them.

Table 1 Table showing Participating Countries and Focal Point Institutions

| Participating countries | Institutions that serve as Focal Points |
|---|---|
| Antigua & Barbuda | Point Wharf Fisheries Division. Ministry |
| Costa Rica | National University of Costa Rica |
| Cuba | Institute of Marine Sciences (ICIMAR)<br>Ministry of Science, Technology and Environment |
| Dominican Republic | Ministry of Environment and Natural Resources |
| Guatemala | Ministry of Environment and Natural Resources |
| Haiti | National Office of Environmental Assessments (BNEE) |
| Jamaica | National Environment & Planning Agency (NEPA) |
| Panama | Ministry of Environment |
| Trinidad and Tobago | Institute of Marine Affairs (IMA) |

# Chapter 1

## INTRODUCTION AND PURPOSE OF THE GUIDEBOOK

The Greater Caribbean Region (GCR), as defined in the Convention for the Protection and Development of the Marine Environment (UNEP 1983), extends from the North Eastern coast of Brazil to Cape Hatteras, off the coast of North Carolina (United States). It is one of the most geopolitically complex regions in the world, composed of 28 independent countries (between continental and small island developing states - SIDS) and 16 overseas territories of metropolitan states (Mahon et al., 2010), with differences in size and level of socio-economic development. The colonial legacy of European countries includes five official languages in the region (English, Spanish, French, Dutch and Portuguese) (Fanning & Mahon, 2017), as well as cultural elements that both indigenous and other human groups brought to America.

Much of the economy of the Greater Caribbean region is based on the tourism industry in which sandy beaches play an important role because they are marketed as an attractive sea-sand-sun product, but these are potentially threatened by the impact of anthropogenic activities (Defeo et al., 2009) and climate change that induces sea level rise (Spencer et al., 2022), coastal erosion, increased extreme wave events, and hurricanes. Coastal erosion, defined as a process by which the coastline adapts to variations in sea level, energy levels, sediment supply, and existing topography (Cooper and McKenna, 2007), is one of the greatest threats to coastal areas of the Greater Caribbean. Studies show that 70% of the beaches of the Eastern Caribbean have registered a retreat of the coastline since the 1980s with rates between -0.27 metres / year and -1.06 metres / year (UNEP, 2003).

This guidebook aims to propose scientific and engineering criteria that respond to the special characteristics of tropical beaches in the Greater Caribbean region, for the monitoring of coastal erosion of these beaches, as well as the establishment of mitigation measures of the problem. It is hoped that this guidebook can be used by the scientific community in general, by decision makers, and other stakeholders interested in assisting in the coastal situation of the region, either locally or internationally.

The guidebook has been prepared in accordance with the contents of the classes and lectures given during the training actions of COMPONENT 2, as well as the procedures and protocols applied in the establishment of the regional network for monitoring the erosion process, COMPONENT 3, and the concepts and methodologies applied in the three executive beach rehabilitation projects corresponding to COMPONENT 4.

The topics developed in each chapter include the results of a careful literature review that leads to the update on the state of the art, but always under the critical assessment of what is truly applicable and convenient in the context of the environmental and socioeconomic characteristics of the Greater Caribbean region. In this sense, special attention is paid to the contributions made in this field by the outstanding specialist of the region, Dr. Guillian Cambers, with her recognized work on erosion on the beaches of the small islands of the Caribbean. Taking into account that many topics addressed in the guidebook are developed in greater depth in specialized manuals and books, it has been decided to include commented references to these texts in order to simplify the length of the guidebook.

In Chapter 6, Lessons learned through the development of the Sandy Shorelines Project, are conceived to highlight all those elements that in the development of the project, served to identify limitations and insufficiencies in the conception of regulations and design of engineering actions for erosion control and coping with the effects of climate change, and that should be the object of attention in future coastal actions.

Finally with Chapter 7, recommendations for decision makers, a proposed methodological procedure with the logical ordering of research and monitoring actions, definition of solutions, design of actions, supervision of the execution of works and the evaluation of their effectiveness, so that a cycle is completed in coastal action, following the precepts of Integrated Coastal Management.

# Chapter 2

The word beach arose from the need that man had to differentiate in the coastal area the spaces formed by the accumulation of loose materials, where the gentle slope and the weak consistency of the soil facilitated their movements to and from the sea.

In addition to becoming the embarkation and disembarkation sites of the first navigators and fishermen, beaches were appropriate areas for the collection of food and objects of marine origin with multiple uses.

More recently beaches are recognized as the place of recreation and leisure preferred by many people, becoming a natural resource of great value for the tourism industry, which stands out in a particular way in the Greater Caribbean region.

Over the years the technical concept of beach has undergone few changes and in the specialized literature they refer to it as the contact strip between the land and the sea in which the deposition of loose materials of different origins occurs where the sand predominates with particles that, due to their size, they rank in a range of 1.0 mm and 0.062 mm, according to the Wentworth classification, Shore Protection Manual, (1984), widely used worldwide. The deposits of sand that form on the banks of rivers and lakes are also considered beaches and are used by man in various economic and social activities, although in this guidebook only reference is made to the sandy marine coasts.

As data of interest, it is estimated that sandy shorelines represent between 34%-40% (170,000 km) of the total length of the coasts, (Hardisty, 1990) and (Bird, 1996), although they essentially cover 100% of the coasts of Holland, 60% of those of Australia and 33% of those of the United States. (Short, 1999, in Shwartz, 2005), just to cite a few examples of countries with extensive sandy shorelines.

## 2.1. The Beaches of the Greater Caribbean

In the definition of "Greater Caribbean" of July 2023 that appears on the website of the Association of Caribbean States (ACS), it is clearly expressed that it is a political concept that includes the territories bordering the Caribbean Sea and other island states with similar historical, social and cultural characteristics, connecting the Antilles with countries in Central America, North America and South America.

According to this concept, the "Greater Caribbean" is composed of 25 member states and 12 associated states for a total of 37 states that together have a coastline length estimated at 25,738 km that represents only 1.6% of the world's coasts, according to data provided by The World Factbook (https://www.cia.gov/the-world-factbook/field/coastline/ ).

Despite the small extension of the coasts of the "Greater Caribbean" compared to the rest of the world, the region is internationally recognized for the hundreds of beaches it has with exceptional natural conditions for tourism activity. It should be noted that with only 1.6% of the world's coastlines, 6 of the best 20 beaches (30%) are located in the region according to a selection of "Traveler's Choice Awards" held by Trip Advisor in 2023.

Already in the report "Diagnosis of Erosion Processes in Caribbean Sandy Beaches" (UNEP/ROLAC. GPA. 2003) it was warned that "In contrast to the expansion of tourism on the beaches, erosion processes occur more frequently that cause severe damage to hotel facilities and environmental deterioration of the coast." The aforementioned report refers to investigations of the erosion process in several countries of the area initiated in the 80s in which the first inventories of the beaches of the region were elaborated.

In 1996 and through the project "Stability of the Coasts and Beaches in Caribbean Islands" (COSALC) sponsored by the Sea Grant College of the University of Puerto Rico (UPR-SGCP) and the support of UNESCO, Dr. Guillian Cambers established a Monitoring Program for the Beaches of the Small Island States of the Eastern Caribbean that facilitated the registration of dozens of beaches and the assessment of the behaviour of the erosion process in them, (Cambers, 2005, in Shwartz, 2005). The results of these monitoring were essential to demonstrate the magnitude and extent of the erosive effect of hurricanes between 1990 and 1999 in the region.

The preparation of the monitoring network of the morphological and sedimentological variations of the beaches in the present project "Sandy Shorelines" has required the updating and expansion of the monitoring stations of the participating countries, which in the case of the small islands have used as a reference the previous networks established by Dr. Cambers.

In the case of the Dominican Republic, Jamaica, Costa Rica and Cuba, the monitoring networks they had established for projects initiated in the 80s of the last century have also been used, following a continuous process of updating and expansion. For example, only in Cuba, with a coastline length of 5735 km the inventory already reaches 500 beaches with a great diversity both from the morphological and sedimentological point of view.

In reality, the determination of the number of beaches is conditioned to the criteria used for their physical delimitation. For example, there is no minimum length limit to classify a sandy coastal sector as a beach.

It is common to find in the Greater Caribbean beaches with less than 100 m of extension that are well recognized by the population for their traditional use as bathing and recreation sites. However, in the numerous uninhabited keys of the region there are hundreds of small sandy areas with the same characteristics that do not present any use or are recognized as a beach in any document.

**So, how many beaches are there in the Greater Caribbean?**

Undoubtedly, there are many options and very good opportunities for the development of recreational and leisure activities, but to achieve the sustainable use of the beaches of the Greater Caribbean, it is necessary to know the particularities that characterize them from the physical and environmental point of view, as explained in the following sections of the present chapter.

## 2.2 Physical delimitation of a beach profile in the case of the Greater Caribbean

In specialized literature, various definitions exist for delineating the boundaries and

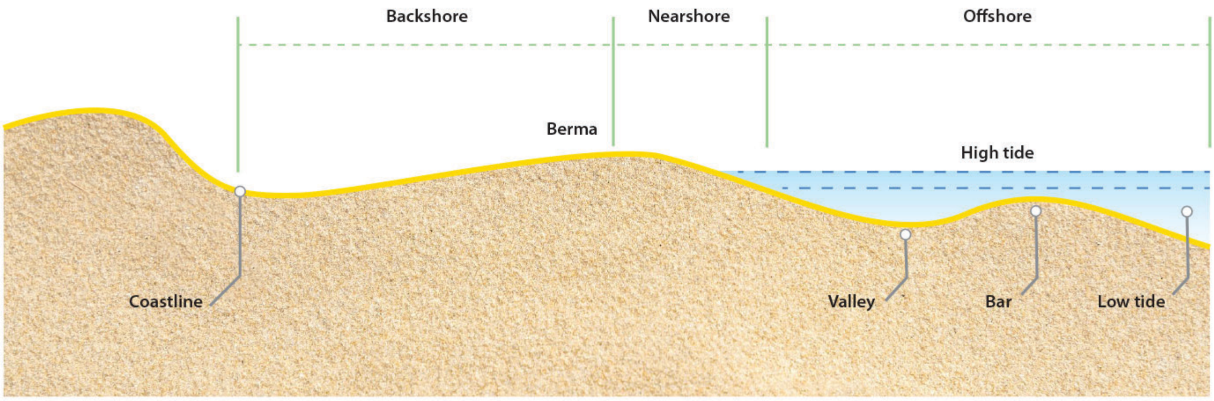



***Figure 1*** Terminology of a beach profile, Shepard (1973)

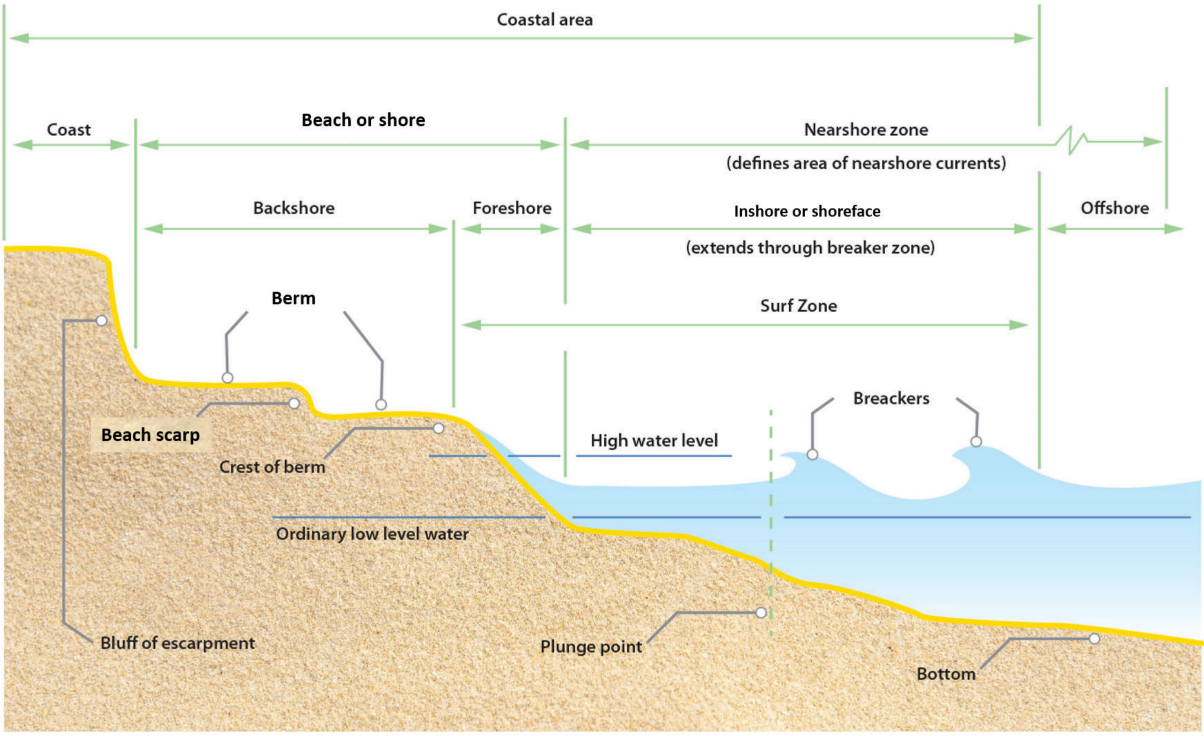



***Figure 2.*** *Terminology of a beach profile (as taken from Shore Protection Manual, 1984).*

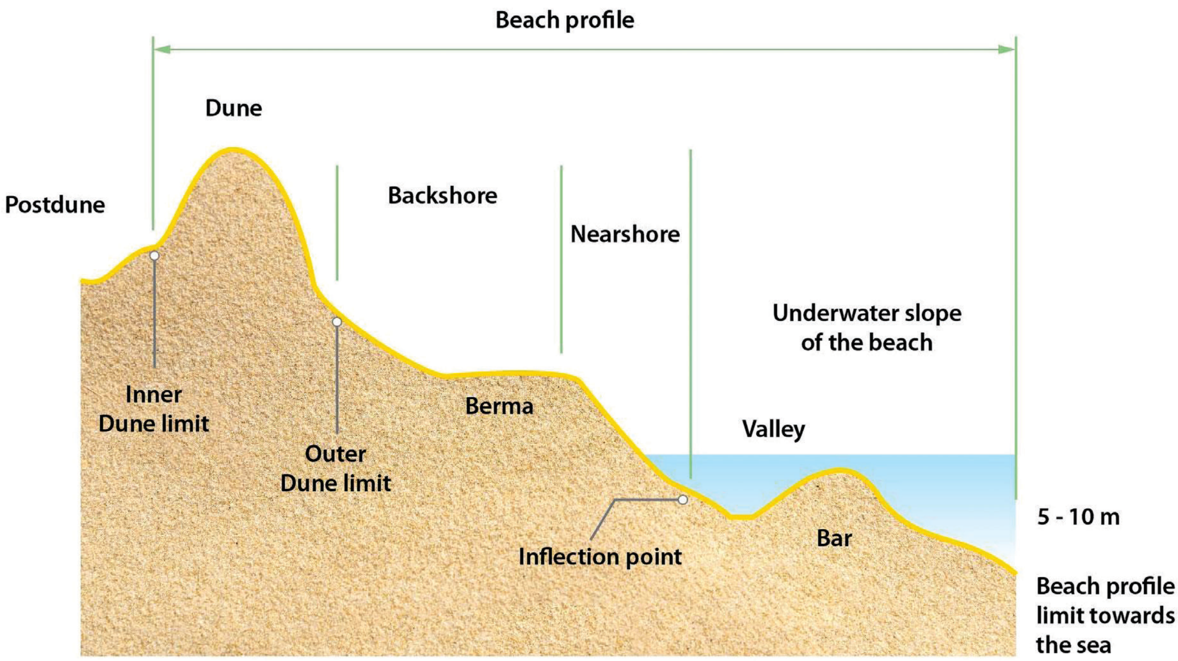



***Figure 3*** *Terminology of a beach profile. Postgraduate course of the project "Sandy shorelines." Juanes (2018, 2021 and 2022).*

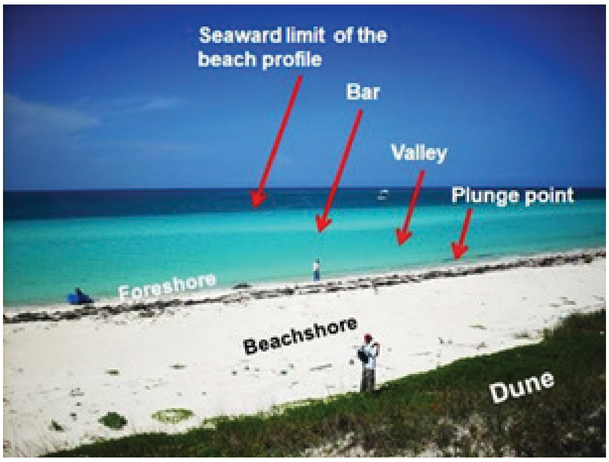



***Figure 4*** *Illustration of beach profile terminology. Postgraduate course of the "Sandy Shorelines". Juanes (2018, 2021 and 2022)*

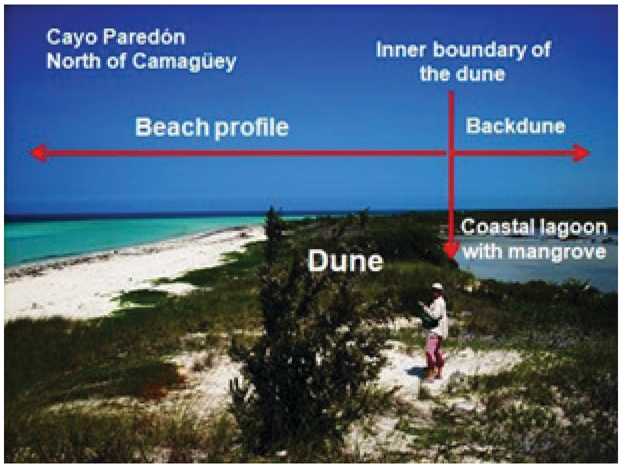



***Figure 5*** *Illustration of beach profile terminology. Postgraduate course of the "Sandy Shorelines". Juanes (2018, 2021 and 2022)*

components of a beach profile; however, there is a fundamental similarity in the treatment of basic elements across these definitions. Figure 1 shows the classification proposed by Shepard (1973) that is limited to exposing the elements of the profile in a simple way and is widely used by numerous authors.

In the case of Figure 2 the classification proposed in the Shore Protection Manual (1984) is shown offers in-depth insights into the distinct segments of the profile, categorizing them based on morphology and the impact of waves and tides. Additionally, it is noted that the inner section of the beach is defined by an escarpment, marking the boundary between the beach and the coastline.

Note that in both classifications there is no reference to the case in which the inner part of the beach constitutes an active dune participating in the processes of erosion and accumulation typical of the dynamics of the beach profile.

Considering that the erosion process in many Caribbean beaches affects the dunes (GPA, UNEP, 2003), the postgraduate course Coastal Processes and Methodological Criteria for Beach Recovery facilitated as part of the training component of the "Sandy Shorelines" project (Juanes, 2018, 2021 and 2022) the terminology of the beach profile shown in Figure 3 is proposed.

This proposal defends the idea of including the dune as part of the terminology of the dynamic profile of the beach, also valuing the role played by vegetation as an energy dissipating element during extreme waves and as a retaining barrier for the sand

***Figure 6***
*Beach leaning on a cliff. El Holandés Beach. Guahanacabibes Peninsula, Cuba. Postgraduate course of the project "Sandy Shorelines". Juanes (2018, 2021 and 2022)*

***Figure 7*** *Gently sloping beach with herbaceous and arboreal formations in its inner part. Postgraduate course of the project "Sandy Shorelines". Juanes (2018, 2021 and 2022). Sumidero Beach of Batabanó, province of Artemisa, Cuba.*

transported by the wind, phenomena very well observed in the Greater Caribbean.

As can be seen in Figure 3 the landward limit of the profile is located at the foot of the inner face of the dune. The limit towards the sea is defined in the position where the haulage of beach material is practically zero, which regularly occurs at depths between 5 m and 10 m.

In the Greater Caribbean, in addition to beaches with dunes in their interior part, beaches are frequently observed supported by cliffs that mark the natural limit of the profile towards land (Figure 6).

There are also numerous beaches with gentle slopes whose interior part is covered by herbaceous and arboreal formations that extend towards the sea depending on the behaviour of waves and wind (Figure 7)

The practical significance of establishing a definition for beach limits, considering the morphodynamic intricacies of various profile types, is driven by the necessity for technical criteria ensuring proper beach management. Frequently, it is observed that legal instruments for coastal management in Greater Caribbean countries lack precise definitions for beach limits. Where definitions do exist, they often prioritize land ownership criteria over the morphodynamic characteristics of the profile. It remains an outstanding task for countries in the region to develop and implement an effective standard for protecting the morphodynamic profile of beaches, a subject that will be further addressed in the upcoming chapter.

### 2.3 Types of beaches of the Greater Caribbean according to the morphology of the coast and the composition of the sand.

In the specialized literature, it is explained how the morphology of sandy shorelines is the result of the combination of geological and hydrodynamic processes, and the transport of sediments that result in linear beaches, embedded and supported at one end. Linear beaches can extend for tens of kilometres and are formed on coastal plains where the underlying bedrock does not influence their formation. These beaches are the result of the hauling of sediments that enter the coast from land or sea and are formed mainly on the continents.

In the continental Greater Caribbean you can recognize with these characteristics a long sector of sandy shorelines in the Riviera Maya in the state of Quintana Roo, Mexico,

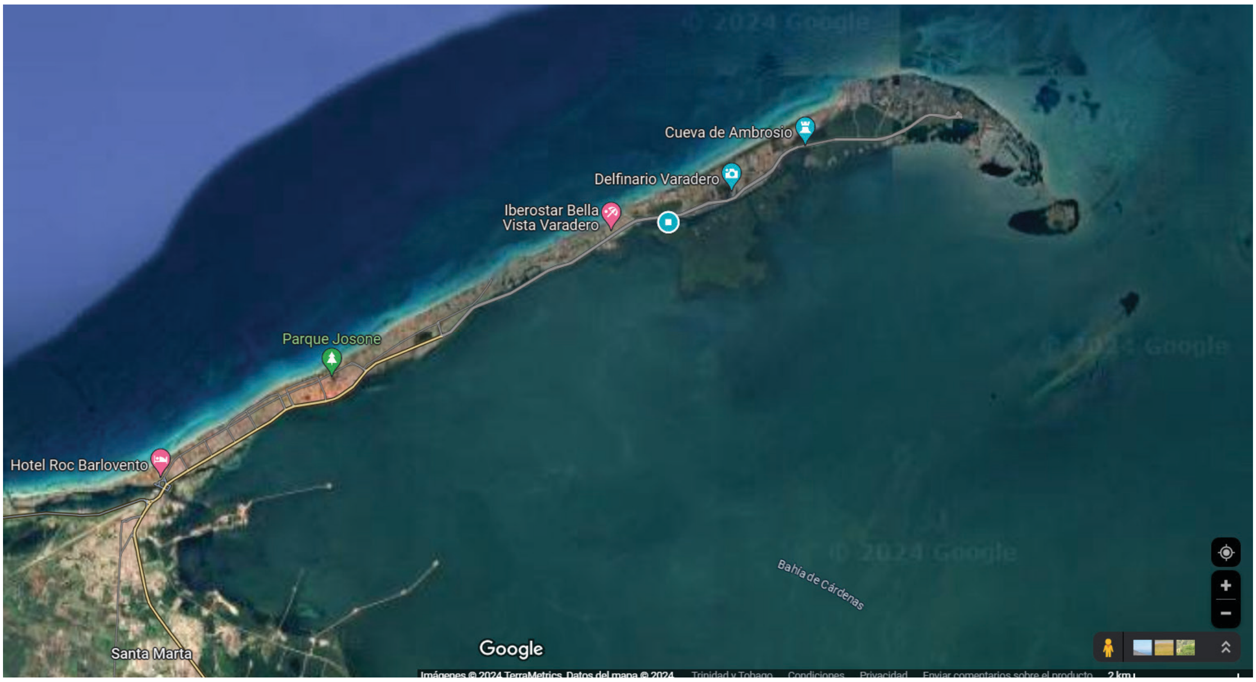



***Figure 8*** *Linear beach of the insular Caribbean with about 20 km in length. Varadero Beach on the Hicacos Peninsula, Cuba.*

about 300 km in length. Although in the insular Caribbean there are few linear beaches that reach several kilometres in length, the example of Varadero beach in Cuba with 20 km of extension can be highlighted (Figure 8).

However, the complex geological genesis of the continental coasts and the islands of volcanic origin in the Antilles arc results in a rugged morphology that facilitates the formation of numerous beaches wedged between two rocky ledges, often having a shell or cove plan configuration. Las Cuevas beach in Trinidad and Tobago serves as a notable example of this type of beach (Figure 9).

The supported beaches have support at one end, which is usually a rocky ledge although the support can be produced by the existence of artificial structures (Figure 10).

On the other hand, the classification of the beaches according to the composition of the sand is done according to both their granulometry and the genesis of the material.

Beaches formed by sediments the size of sand (2 - 0.062 mm) are the most abundant worldwide, although there are also beaches of gravel (4 - 2 mm), small pebbles (64 - 4 mm), large pebbles (256 - 64 mm) and boulders (1,024 - 256 mm), according to the Wentworth classification mentioned above.

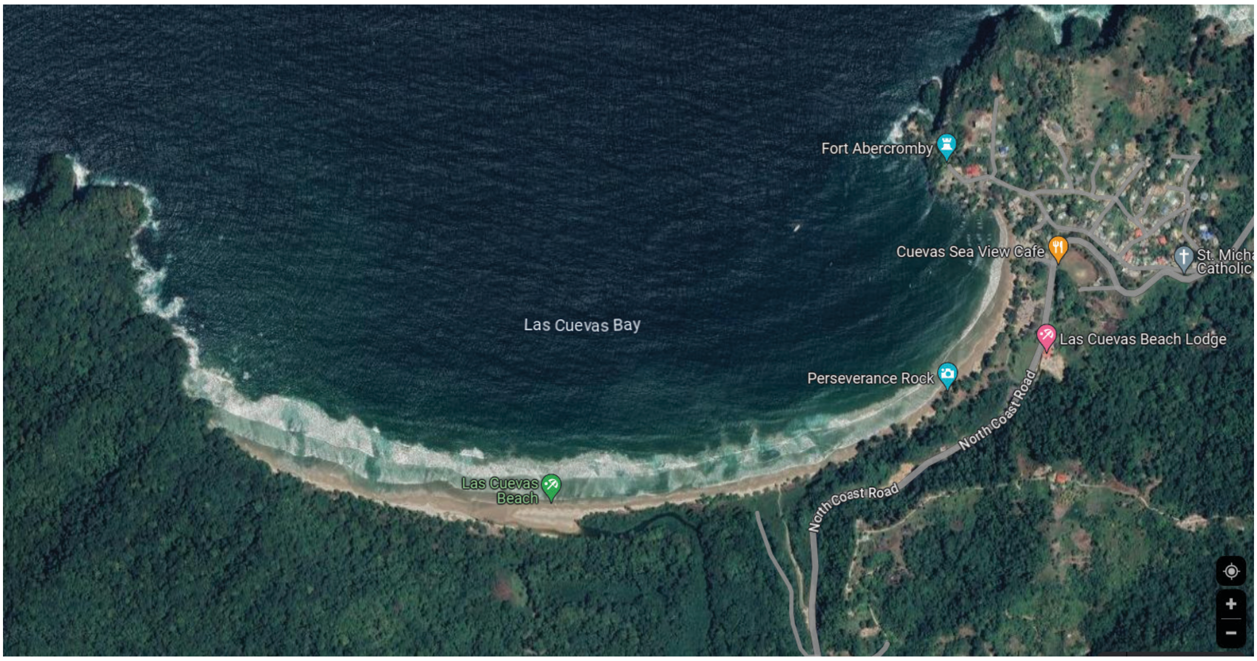



***Figure 9:** Beach wedged between two rocky ledges Las Cuevas Beach, Trinidad and Tobago.*

The evaluations presented by different authors about the volumetric indices that accompany each of the sources of sediment entry into the world ocean, show that rivers provide the greatest input of sand to the coasts.

The contribution of cliff erosion is recognized as the second major source; other

***Figure 10** Beach supported by artificial structure. Punta Cancun. Cancun Beach, Quintana Roo, Mexico*

contributions, such as submarine slope erosion, glaciers, wind transportation, volcanic eruptions, and the biogenic and chemical production of carbonates, generally present lower global volumes. However, in certain areas of the planet, they become the primary sources.

The location of the Greater Caribbean in the humid strip of the planet causes that the high rates of precipitation on the continental coasts produce important contributions of terrigenous sediments through the rivers and consequently the formation of deltas, bars and sandy beaches. In the case of the insular Caribbean, river discharges are lower due to the short extension of the basins, but in torrential times sand can be in flowed, and even gravel, pebbles and boulders. On the other hand, the rugged relief of the islands has caused the formation of sectors of steep coasts whose abrasion also generates inputs of terrigenous sandy material.

Terrigenous sand is globally abundant because granite is the main rock that forms the core of the continents and as weaker and less resistant minerals such as feldspar are eroded, they disintegrate into fine sediments leaving behind the harder grains of quartz (or silica) the size of sand along with smaller percentages of heavy minerals more resistant to abrasion.

Other terrigenous sources are sedimentary and metamorphic rocks, which contain varying percentages of sand-sized material. Erosion and weathering of all these rocks supply sediments ranging from boulders to mud. However, erosion and transport processes occur selectively so that fines are more easily transported in suspension, sands move by dragging and salting along the bottom and gravel coarser, pebbles and boulders move under the effect of river discharges associated with torrential rains.

The sand, once it reaches the coast, is quickly deposited forming bars and deltas at the mouths of the rivers. In the case of quartz sand, the high hardness of its grains allows it to be transported under the effect of the longitudinal current without major changes in its mechanical properties, forming beaches of tens of kilometres in length.

Another important source of sand to shores is the carbonated skeletal remains of marine organisms that live from the shallows to the inner shelf. While carbonate debris is more easily broken up and eroded by physical processes, the location of sand-producing ecosystems ensures a continuous supply, with tidal waves and currents carrying the sand and coarser material to shore. In fact, coastlines formed by carbonate sand dominate large areas of the world's tropical and temperate coasts (Short, 2002), including the

Greater Caribbean, where there are significant contributions of marine carbonate sands associated with coral reef barriers and seagrasses.

Another source of sand of interest in the tropical waters of the Caribbean is that of chemical origin product of the precipitation of calcium carbonate in the water column forming spheroid particles less than 2 mm in diameter and high degree of purity that are known as oolite.

The formation of oolite occurs when cooler waters of the open sea loaded with calcium carbonate in solution penetrate into shallow and warm waters of the shelf causing precipitation of carbonate.

The Grand Bank of the Bahamas is the largest oolithic sand reserve in the world and the Caribbean also has an extensive oolite formation area on the South Eastern shelf of the Gulf of Batabanó in Cuba, and although to a lesser extent, the oolite formation has also been identified in other littorals of the region.

As a result of the accumulation of oolitic sand, the excellent white sand beaches of the Bahamas are formed and those that extend along the southern coast of the Los Canarreos Archipelago in Cuba.

In general, it can be seen that the Greater Caribbean has a variety of beaches with morphodynamic and sedimentological particularities that make them very different from each other and constitute the main natural resource for the development of the tourism industry.

It should be understood that the correct preservation of the beaches of the Caribbean is, in addition to an action for the protection of the environment, an action for the sustainability of tourism in the region.

### 2.4 Dynamic behaviour of a beach. Tool for the correct interpretation of beach erosion causes.

Beaches constitute a dynamic system that is characterized by the permanent exchange of sand between the deposits accumulated in its emergent part (berm and dune) and the sand bars of the submerged slope, depending on the behaviour of the waves.

At the same time, the beach system works in the permanent search for balance between the sand that enters it through the different terrigenous and marine routes and the sand that leaves the system by longitudinal transport, offshore transport, wind transport, the destruction of particles and even by the mining activity of man.

Both inputs and outputs are conditioned to the behaviour of hydrodynamic factors that condition the transport of sand, mainly waves, tides, and induced currents. A simplified scheme of the operation of the beach system is shown in Figure 11.

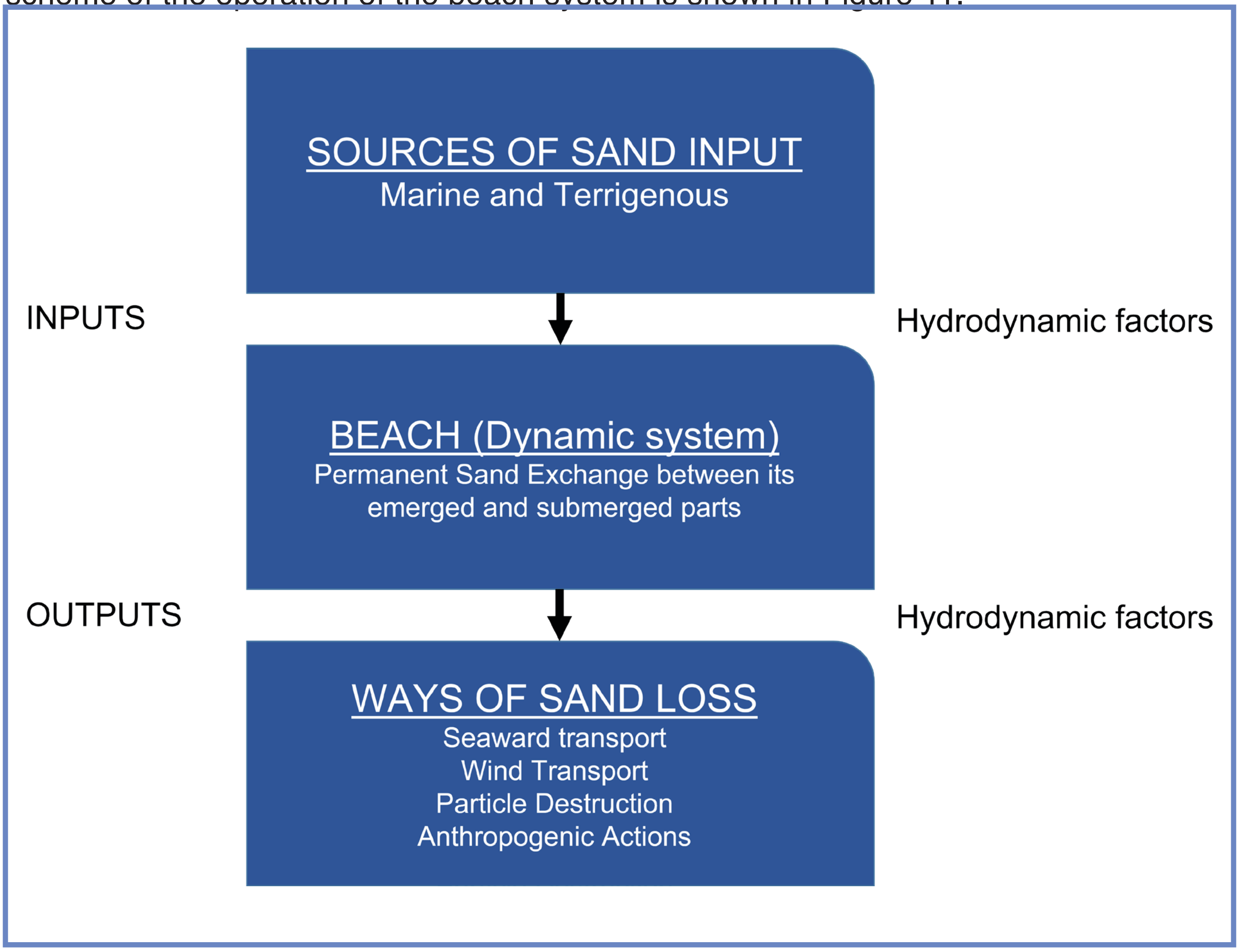



***Figure 11*** *Simplified scheme of the operation of a beach system. Postgraduate course of the project "Sandy Shorelines". Juanes (2018, 2021 and 2022)*

If, in a period of several years, the magnitude of the inflows to the system is the same as that of the outflows, it means that the system retains its sedimentary balance and the profile of the beach maintains a dynamic equilibrium.

When the balance of the system is altered by natural or anthropic causes with the disproportionate increase in discharges, the loss of sand in the profile occurs and the signs of erosion appear that mark the erosive trend in the behaviour of the beach in the medium and long term.

Signs of erosion such as escarpments in the beach profile may appear as a result of waves caused by occasional storms without necessarily meaning that the beach presents an erosive trend in the medium and long term (Figure 12). However, the continuous displacement towards land of the active escarpment in the front of the dune and the fall of tree formations with decades of existence, is clear evidence of the erosive tendency of a beach (Figure 13).

Numerous investigations on the dynamic processes of the beaches have proposed modelling of the sequence of the behaviour of the profile and the arrangement in plan of the morphology of the beach for a dominant wave of erosion or accretion and with a tidal amplitude not greater than 2m. Short, (1999), based on Short, (1979); Wright and Short, (1984); Sunamura, (1988) and Lippmann and Holman, (1990), propose the sequence shown in Figure 14.

***Figure 12:*** *An escarpment in the beach caused by an occasional storm in the Gold Coast. (David J Morgan)*

***Figure 13.*** *Displacement towards land of the active escarpment as clear evidence of the erosive tendency of a beach. Granville, Cedros, Trinidad*

The model of Short (1999), shows the different stages through which the beach transits from a dissipative profile of low wave energy to a reflective profile of high energy. As shown at the top of the left column of Figure 14 the transformation process begins with a dissipative profile where the beach exhibits a break zone and a regular coastline and bar in all its extension. With the increase in wave energy, four intermediate stages occur with the displacement of the bar towards the shore.

It should also be noted that, considering the height and period of the wave, the slope of the beach, and the granulometric characteristics of the sand, Short (1999) proposed a Nomogram that allows the numerical evaluation of the beach's tendency towards a dissipative, intermediate, or reflective morphology.

In the case of the Greater Caribbean, the abundance of beaches with biogenic sediment input makes it challenging to assess the causes that may lead to deficits in the system or increase in losses.

It is uncommon in traditional coastal engineering projects to investigate the causes

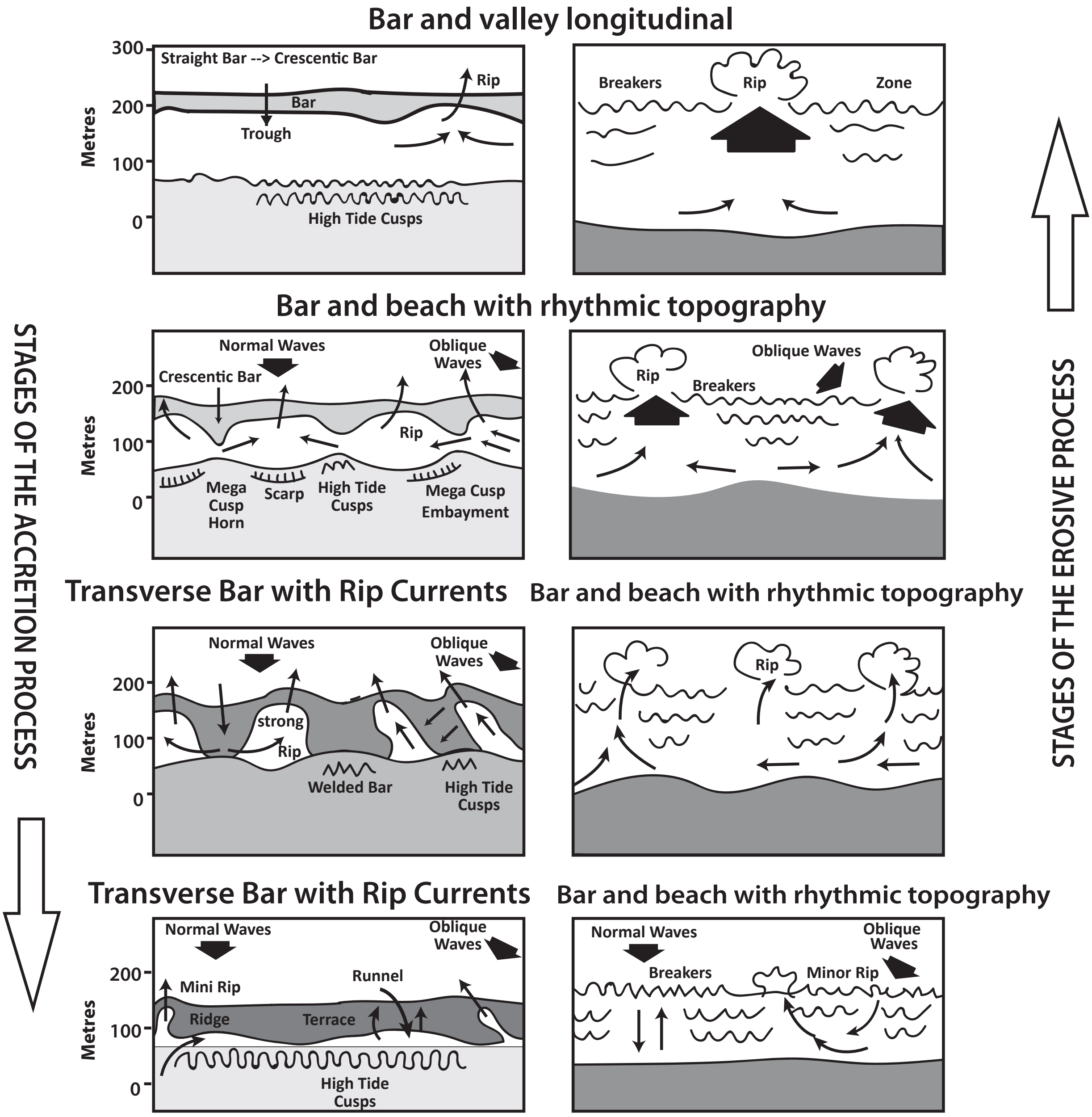



***Figure 14.*** *Plan view of the sequence of changes in the morphology of the beach and its submarine area in an accretion process (left graph) and in an erosive process (right graph) (Short, (1999), based on Short, (1979); Wright and Short, (1984); Sunamura*

of erosion related to factors affecting biogenic sand production. For instance, during a meteorological event, the calculation of lost beach sand is done to determine the volume needed for replacement using Artificial Beach Nourishment. However, there is usually no exploration into how the new natural input might decrease due to the impacts on the sand-producing ecosystem.

***Figure 15.*** *Crossbar with rip next to join the shore and form a reflective profile..*

Similarly, while it is common to attribute erosion to the rise in sea level associated with climate change, considering its impact on increased wave energy, little is known about the effects that rising temperatures and water acidification may have on marine organisms responsible for sand production. Other effects introduced by human activity to the marine environment such as water pollution, the use of trawling gear and damage to coral reefs are also poorly evaluated as causes of deficits in natural sand input on biogenic beaches.

## 2.5 The beach as part of the marine-coastal ecosystems of the Greater Caribbean.

When it comes to research on marine and coastal ecosystems, especially in the Greater Caribbean, much more attention is given to coral reefs, seagrasses, and mangroves than to sandy beaches. This discrepancy is explained by considering the extension, biodiversity, and services these other ecosystems offer to humans.

As beaches gain increased attention for their environmental services, serving as a resource for tourism development beyond irrational mining or their historical function as dry docks for fishermen's boats, there is a growing interest in understanding their functions as part of coastal ecosystems.

Brown and McLachlan (1984) note that studies of the beach ecosystem began much later than those conducted in other ecosystems, even on rocky coasts.

Currently, many flora and fauna species managing to survive in this dynamic environment have been described, thanks to their adaptation mechanisms both in the breaking zone on the underwater slope and on the emerged beach itself. It is important to note that biologists consider the dune, with its terrestrial vegetation and fauna, as part of the beach ecosystem.

However, this guidebook does not aim to delve into a detailed description of the beach ecosystem through a study of the species inhabiting it or the mechanisms of the trophic chain or energy flow.

As mentioned previously, many beaches in the region are composed of biogenic sands, formed through the mechanical destruction of calcareous remains of algae, mollusks, foraminifera, and corals, among other organisms.

In this case, it is particularly interesting to highlight the interdependence that exists between marine and coastal ecosystems as a single system, making their contribution to the formation of biogenic beaches more visible.

According to the results of Chave, et, al, (1972) cited by Zafianov (1978), the calculation of the potential production of most types of corals, green algae *Halimedas* and *Penicillus*, red algae, micro and macro molluscs and foraminifera, is very similar, which leads to the conclusion that its magnitude is of the order of 104g of $CaCO^3/m^2$/year, (10 $kg/m^2$/year).

It is striking that these organisms exhibit differences in their life cycle duration by orders of magnitude and vary in mass by about five times. What's surprising is that despite these differences, their potential production of $CaCO^3$ remains very similar. Only the coral, Acropora surpasses them, with a value of 105$g/m^2$/year.

Although methods have been established for terrigenous sources that guarantee the quantification of the volumes of entry into the sedimentary balance, in the case of biogenic sources the estimates are obtained in an experimental framework and do not appear in the manuals specific procedures for their calculation.

## Summary

Considering that the erosion process in many Caribbean beaches affects the dunes (GPA, UNEP, 2003), the "Sandy Shorelines" project proposes the terminology of the beach profile shown in Figure 3. This proposal defends the idea of including the dune as part of the terminology of the dynamic beach profile, valuing the role played by vegetation as an energy-dissipating element during extreme waves and as a retaining barrier for sand carried by the wind—phenomena well observed in the Greater Caribbean. The practical importance of having a definition of the limits of the beach, based on its morphodynamic particularities, responds to the need for technical criteria ensuring the correct management of the beaches.

According to its morphodynamic and sedimentological characteristics, the Greater Caribbean has a wide variety of beaches. In continental areas, terrigenous sand beaches predominate, mainly contributed by rivers and cliffs, with precise locations for sediment entry from land to the coast. Islands are dominated by beaches formed by biogenic carbonate sands contributed by seagrasses and reef barriers, with dispersed locations on the submarine shelf and imprecise sediment input from the sea to the coast. This particularity of biogenic beaches should be especially studied when evaluating engineering alternatives for erosion control.

It is a task for the marine science centres of the Greater Caribbean to deepen investigations into the rates of sand production in marine ecosystems and the processes that form biogenic beaches.

# Chapter 3

## EROSION ON CARIBBEAN BEACHES

Coastal erosion and accretion are dynamic and natural processes that shape the shorelines of the world's oceans and seas. In the Caribbean region, these processes have particular significance due to the reliance on tourism and the unique biodiversity present in coastal ecosystems. The purpose of this chapter is to provide a comprehensive understanding of the basic erosion and accretion processes occurring on Caribbean beaches. A thorough analysis of these processes will help elucidate the factors contributing to the observed changes in coastal environments, paving the way for effective mitigation and management strategies.

The Caribbean, with its stunning beaches, diverse marine ecosystems, and vibrant cultures, is a region that captures the imagination of many. However, these same features make it particularly susceptible to the impacts of coastal erosion and accretion. In this chapter, we will delve into the complexities of natural and anthropic causes driving these processes, as well as the seasonal erosion cycles that further influence the dynamics of the region's shorelines. This knowledge is crucial for the development and implementation of sustainable solutions to preserve the Caribbean's coastal environment and the livelihoods that depend on it.

### 3.1 Extension and intensity of erosion.

#### 3.1.1 Overview of coastal erosion in the Caribbean.

Coastal erosion is a significant issue affecting the Caribbean region and has already caused significant environmental and economic damage. The Caribbean region is vulnerable to coastal erosion due to a range of natural and anthropogenic factors. Natural factors include wave energy, wind, and water level variations, while anthropogenic factors include shoreline development, sand mining, and dredging activities. These activities can cause significant damage to the natural coastal environment and have a detrimental impact on local communities (Figure 16).

***Figure 16.*** *Catastrophic erosion and infrastructure damage in Puerto Rico due to Hurricane María*

### 3.1.2 Geographic distribution and variations.

The spatial distribution of coastal erosion in the Caribbean Sea is not uniform, as it is influenced by various factors such as geology, wave energy, sea level rise, human activity, and storm events. Coastal erosion in the Caribbean can be characterized by the following features:

- The Greater Antilles, which include islands such as Cuba, Hispaniola, Jamaica, and Puerto Rico, experience varying degrees of coastal erosion. The northern and eastern coastlines are more exposed to the Atlantic Ocean and are thus more prone to erosion caused by wave action and storm surges.

- The Lesser Antilles, a chain of smaller islands stretching from the Virgin Islands to Trinidad and Tobago, are similarly affected by coastal erosion. The eastern coastlines, exposed to the Atlantic Ocean, are more susceptible to erosion due to wave action and storm events.

- Central American coastline: The Caribbean coasts of Central American countries like Belize, Costa Rica, and Panama also face coastal erosion, particularly in areas with low-lying coastal plains and sandy beaches.

- South American coastline: The Caribbean coastlines of South American countries such as Colombia and Venezuela experience coastal erosion as well, with varying intensity depending on the local geological and oceanographic conditions.

When comparing the coastal erosion in the Caribbean Sea to other regions in the world, it is important to consider the factors that contribute to erosion, such as:

- Sea level rise. Global sea level rise affects all coastal areas, but the Caribbean is particularly vulnerable due to its low-lying islands and coastal plains.

- Storm events. The Caribbean is prone to hurricanes and tropical storms, which cause significant erosion through storm surges, heavy rainfall, and wave action. Other regions, such as the US Atlantic and Gulf coasts, Southeast Asia, and the Pacific islands, also face coastal erosion due to storm events.

- Human activity. Coastal development and land use changes can exacerbate coastal erosion. This is true not only for the Caribbean but also for other regions like the Mediterranean, the North Sea coast of Europe, and the US Atlantic and Gulf coasts.

- Geology. The underlying geology of a region plays a significant role in determining the susceptibility of coastlines to erosion. For example, rocky coastlines like those found in parts of the Mediterranean and Australia may be more resistant to erosion compared to sandy or muddy coastlines like those found in the Caribbean and Southeast Asia.

In summary, coastal erosion in the Caribbean Sea is spatially diverse and influenced by a range of factors. While there are similarities with other regions in the world, the intensity and extent of coastal erosion may vary depending on local and regional conditions.

### 3.1.3 Economic and environmental impacts of erosion.

Coastal erosion in Caribbean beaches poses significant economic and environmental challenges (Cambers, 1998; Cambers, 2009). Economically, the Caribbean relies heavily on tourism, with pristine beaches being a major draw for visitors. As coastal erosion degrades these beaches, the tourism industry faces potential declines in revenue, affecting local economies and employment opportunities. Additionally, the loss of coastal land due to erosion can impact infrastructure, including transportation, communication, and housing, resulting in considerable reconstruction and relocation costs. Environmentally, coastal erosion disrupts fragile ecosystems, particularly coastal dune systems and mangrove forests, which serve as crucial habitats for various species and act as natural barriers against storms and flooding. Moreover, the erosion of coastal areas can lead to saltwater intrusion into freshwater sources, negatively affecting water quality and availability for both human consumption and agriculture.

## 3.2. Erosion vs. accretion.

Coastal erosion and sand accretion are two opposing natural processes that can occur on beaches in the Caribbean Sea. Coastal erosion refers to the gradual loss of sediment from the beach due to natural and/or anthropogenic factors. This can result in the beach becoming narrower or even disappearing altogether over time. On the other hand, sand accretion refers to the gradual accumulation of sediment on a beach. This can occur naturally through the deposition of sand from offshore sources or through human interventions such as beach nourishment projects. Sand accretion can help to mitigate the impact of coastal erosion and can even lead to the expansion of the beach over time. While both processes can occur on beaches in the Caribbean Sea, coastal erosion is generally much more common and can result in economic losses, particularly for communities that rely on tourism as a major source of income. In contrast, sand accretion can have positive impacts on the beach environment and the surrounding community.

An important concept that helps shed light on coastal erosion processes is the sediment budget (Figure 17) In the context of coastal systems, a sediment budget refers to the balance between the inputs (sediment supply) and outputs (sediment removal) of sand and other sediments along a shoreline. This balance is determined by natural processes such as wave action, longshore currents, tides, and river discharge, as well as human activities like beach nourishment, sand mining, and construction. It is important to emphasize that sand does not simply disappear from a coastal system unless it is extracted for purposes like construction or lost to deep water where wave action can no longer transport it back to the submerged beach. When sand is removed or trapped in deep water, the sediment budget becomes negative, resulting in a deficit that can exacerbate coastal erosion. Thus, maintaining a balanced sediment budget is essential for preserving the stability and resilience of coastal environments and mitigating the impacts of coastal erosion. All causes of erosion affect the sediment budget in some way, creating a deficit of sand at a particular location for a particular period of time.

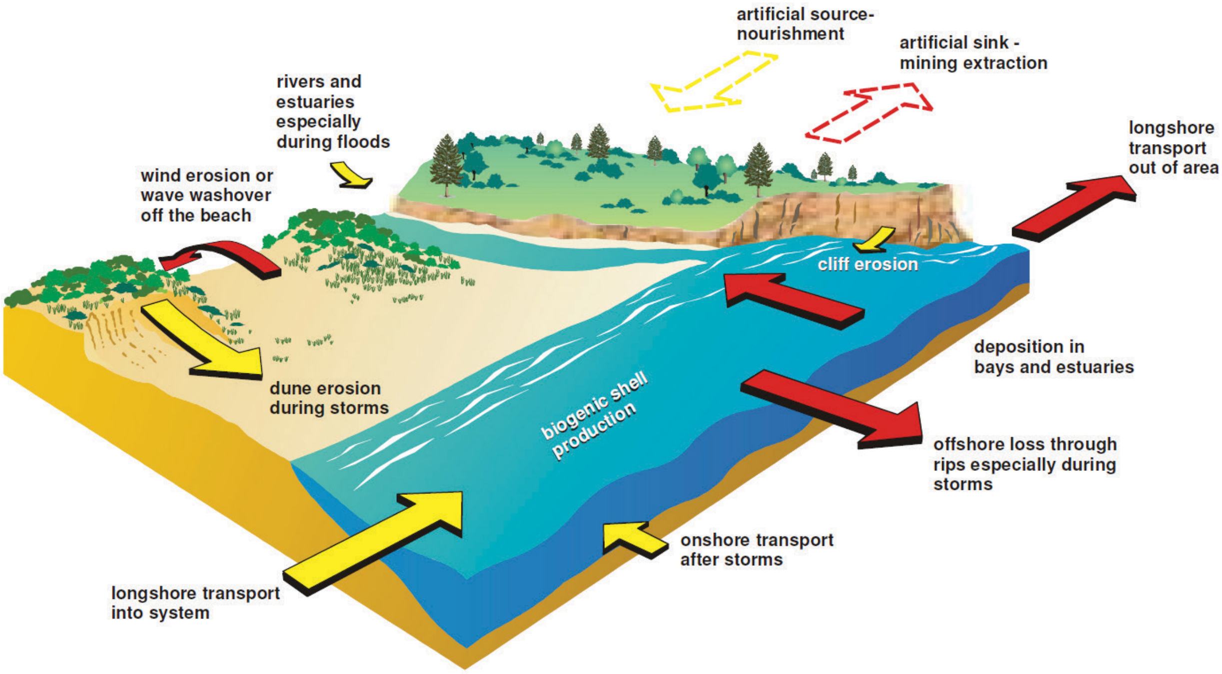



***Figure 17:*** *Some components of a sediment budget, taken from NSW Department of Land and Water Conservation 2001, Coastal Dune Management: A Manual of Coastal Dune Management and Rehabilitation Techniques, Coastal Unit, DLWC, Newcastle*

## 3.3. Natural and anthropogenic causes of erosion.

Coastal erosion is a natural process that occurs due to various geological and environmental factors. However, human activities have significantly accelerated coastal erosion in recent years, causing significant environmental and economic damage. There are both natural and anthropogenic causes of coastal erosion (Figure 18) that need to be addressed in order to mitigate its impacts. In the Caribbean Sea, tidal water level fluctuations are relatively small and sediment transport is usually dominated by wind generated waves. In the following pages we will review some natural and anthropogenic causes of erosion.


***Figure 18** Factors affecting coastal erosion and sediment transport, from Splinter and Coco (2021). See* https://www.frontiersin.org/articles/10.3389/fmars.2021.788657/full.html

### 3.3.1. Natural drivers of erosion.

Natural causes of coastal erosion include the long-term migration of sediment, extreme weather events like hurricanes, and long-term variability in wave climate. These natural factors can lead to fluctuations in the amount of sediment deposited or removed from beaches, resulting in erosion in certain areas.

Waves and currents are significant natural causes of coastal erosion in the Caribbean. Wave action continuously shapes the shoreline by transporting sand and sediment along the coast, a process known as longshore drift. Strong currents can remove large volumes of sediment from beaches, leading to erosion. Caribbean beaches exposed to the Atlantic Ocean experience higher wave energy, which can increase the rate of erosion.

The Caribbean is prone to hurricanes and tropical storms, which bring intense wind, heavy rainfall, and storm surges. Storm surges result from the combination of low atmospheric pressure and strong winds, causing a rise in sea level that can inundate coastal areas, erode beaches, and destabilize coastal landforms. Hurricanes can also generate large waves contributing to significant erosion and sediment transport along the shoreline.

Over longer timescales, coastal landform dynamics also affect natural coastal erosion processes. The geological and geomorphological characteristics of a coastline influence its susceptibility to erosion. For instance, soft sediments, such as sand and mud, are more vulnerable to erosion compared to rocky coastlines. In the Caribbean, the diversity of coastal landforms, ranging from sandy beaches and dunes to cliffs and mangrove forests, results in variable erosion rates across the region.

### 3.3.2. Anthropogenic causes of erosion.

Man-made structures can be a major cause of beach erosion if designed incorrectly or if they have unintended consequences. Man-made structures such as groins, breakwaters, seawalls, and revetments that are built perpendicular or parallel to the shore, as shown in Figure 19, can interrupt natural sediment transport and cause erosion in certain areas (Silva et al., 2018).

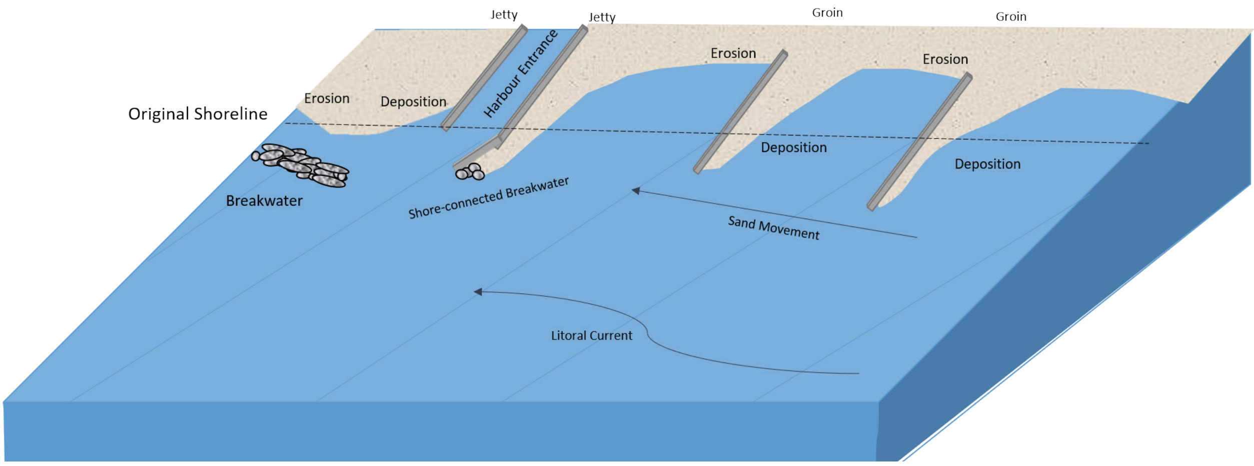



***Figure 19**: Interruption of longshore sediment transport caused by coastal structures, from https://anserosion.weebly.com/coastal-processes.html*

Seawalls and other shore-parallel structures can cause excessive wave reflection, hindering natural beach growth and leading to erosion (Figure 20). Additionally, they can disrupt the natural sediment exchange between the beach and dune system. Other shoreline hardening structures like revetments can also prevent natural beach migration and disrupt natural processes, leading to erosion (Nicholls et al., 2018).

Large-scale interruption of sediment sources due to human activities is also a major concern. Mining and construction activities can destroy sand dunes, removing a crucial source of sediment and compromising the natural buffer that protects the shoreline from erosion. River channelization and dam construction can decrease the sediment load carried by rivers to the coast, leading to sediment deficits and exacerbating coastal erosion. In addition, dredging activities can destabilize the seabed, disrupt sediment transport, and increase turbidity, leading to beach erosion and the degradation of coastal habitats.

One of the most common and avoidable causes of erosion is the man-made destruction of coastal barriers. Human activities like deforestation and filling of wetlands can destroy mangrove forests, while overfishing, destructive fishing practices, and pollution can damage coral reefs. These natural barriers provide protection against waves and storms, but when destroyed, they leave coastlines more vulnerable to erosion (Mumby et al., 2018). There are specific examples in the Caribbean Sea of degraded coral reef areas leading to more severe erosion (Reguero et al., 2018). There are also quantitative

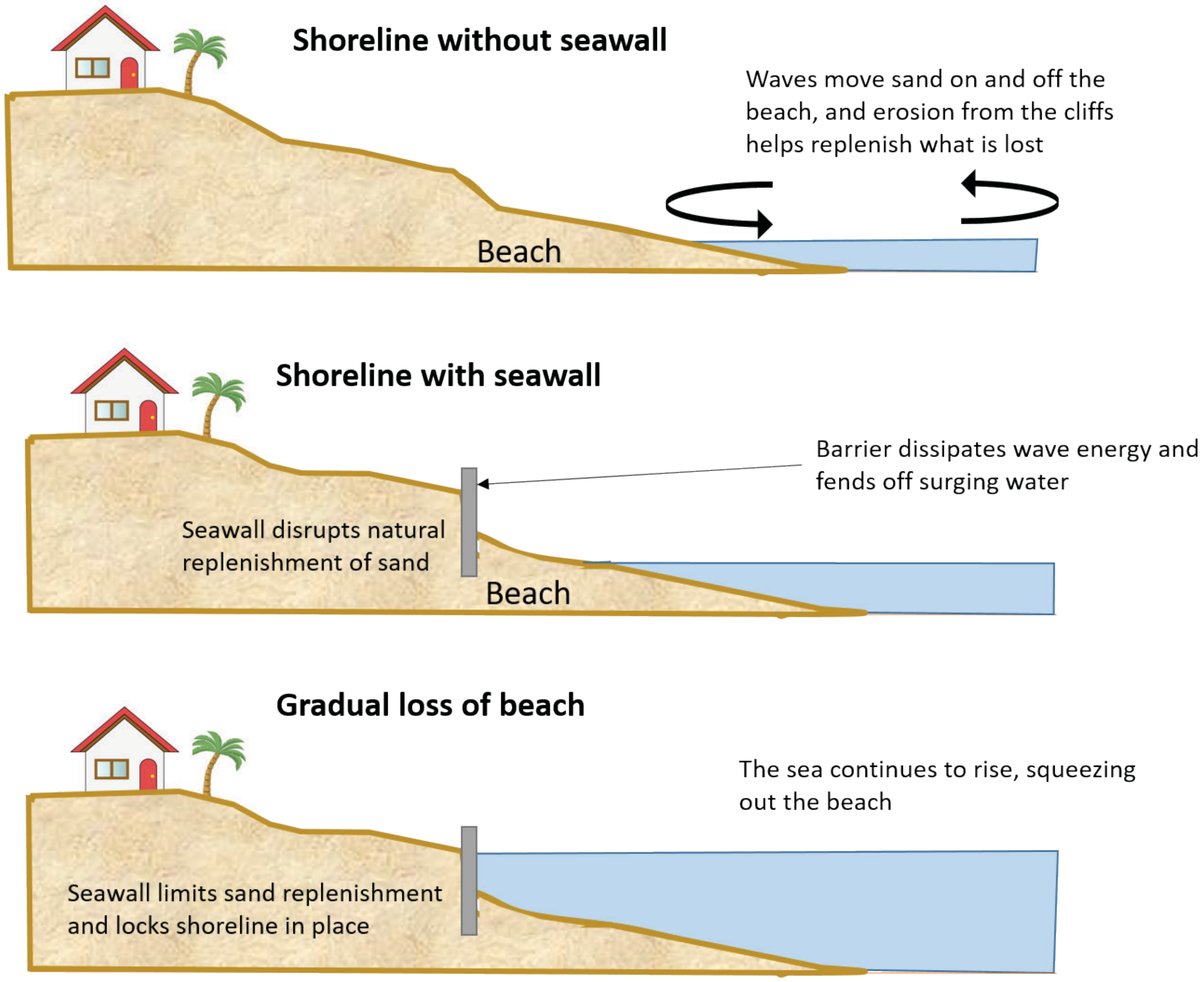



***Figure 20*** *The relationship between seawalls and Beach Loss . From https://www.surfrider.org/coastal-blog/entry/seawalls-are-stealing-our-sandy-beaches*

studies that show the economic importance of reefs for protecting coastal properties and the coastal economy (Storlazzi et al., 2021).

Climate change is exacerbating coastal erosion by increasing the frequency and intensity of storms, contributing to sea level rise, and altering weather patterns. These factors can accelerate erosion rates in the Caribbean and other coastal regions, amplifying the impacts of both natural and anthropogenic causes of erosion. Global sea level rise, primarily driven by climate change, is another factor contributing to coastal erosion in the Caribbean. As sea levels rise, the shoreline retreats landward, resulting in the inundation and erosion of coastal areas. Low-lying islands and coastal plains in the Caribbean are particularly vulnerable to the impacts of sea level rise. Climate change-driven erosion is a growing concern as well. With sea level rise and more frequent extreme weather events, coastal erosion is likely to become an even more significant problem in the future (Reguero et al., 2015). Coastal communities will need to develop adaptive strategies to address the impacts of climate change on coastal areas.

### 3.4. Identifying erosion cycles and events

Beach erosion and accretion occur on various timescales, reflecting the complexity of coastal systems and their interactions with oceanographic phenomena. These timescales can be broadly categorized as episodic, seasonal/annual, and long-term/chronic.

**Episodic – extreme events:**

- Hurricanes: Tropical cyclones can lead to rapid and severe beach erosion through storm surges, heavy rainfall, and strong wave action. The impacts of hurricanes on beaches can be both short-lived and long-lasting, depending on the intensity of the storm and the resilience of the coastal system (Figure 21 and Figure 22).

- Winter swells: In some regions, winter storms generate powerful swells that can cause episodic beach erosion. These events can lead to temporary changes in beach morphology, such as the formation of scarps or the removal of sand from the upper beach.

**Seasonal / Annual response to annual wave climate:**

- Seasonal wave climate: Beaches can experience seasonal changes in response to variations in wave energy and direction throughout the year. For example, increased wave energy during the winter months can cause erosion, while calmer wave conditions during the summer can promote accretion and beach recovery. In some regions, seasonal wind patterns can influence the movement of sediment along the coastline. These seasonal changes in sediment transport can lead to alternating periods of erosion and accretion.

**Long-term / Chronic – response to long-term sediment supply, tectonics, etc.:**

- Long-term sediment supply: Beaches can experience long-term erosion or accretion depending on the balance between sediment inputs (e.g., river discharge, cliff erosion) and outputs (e.g., sediment transport, offshore loss). Changes in sediment supply due to natural processes or human activities can lead to chronic erosion or accretion over years to decades.

- Tectonics: Tectonic activity can influence beach erosion and accretion over long timescales by causing changes in land elevation or altering the regional sediment budget. For example, tectonic uplift can cause a coastline to become more resistant to erosion, while subsidence can make it more vulnerable to sea level rise and erosion.

- Sea level rise: Long-term sea level rise, driven by climate change, can lead to chronic coastal erosion as the shoreline retreats landward. This process can be especially pronounced in low-lying coastal areas and on small islands.

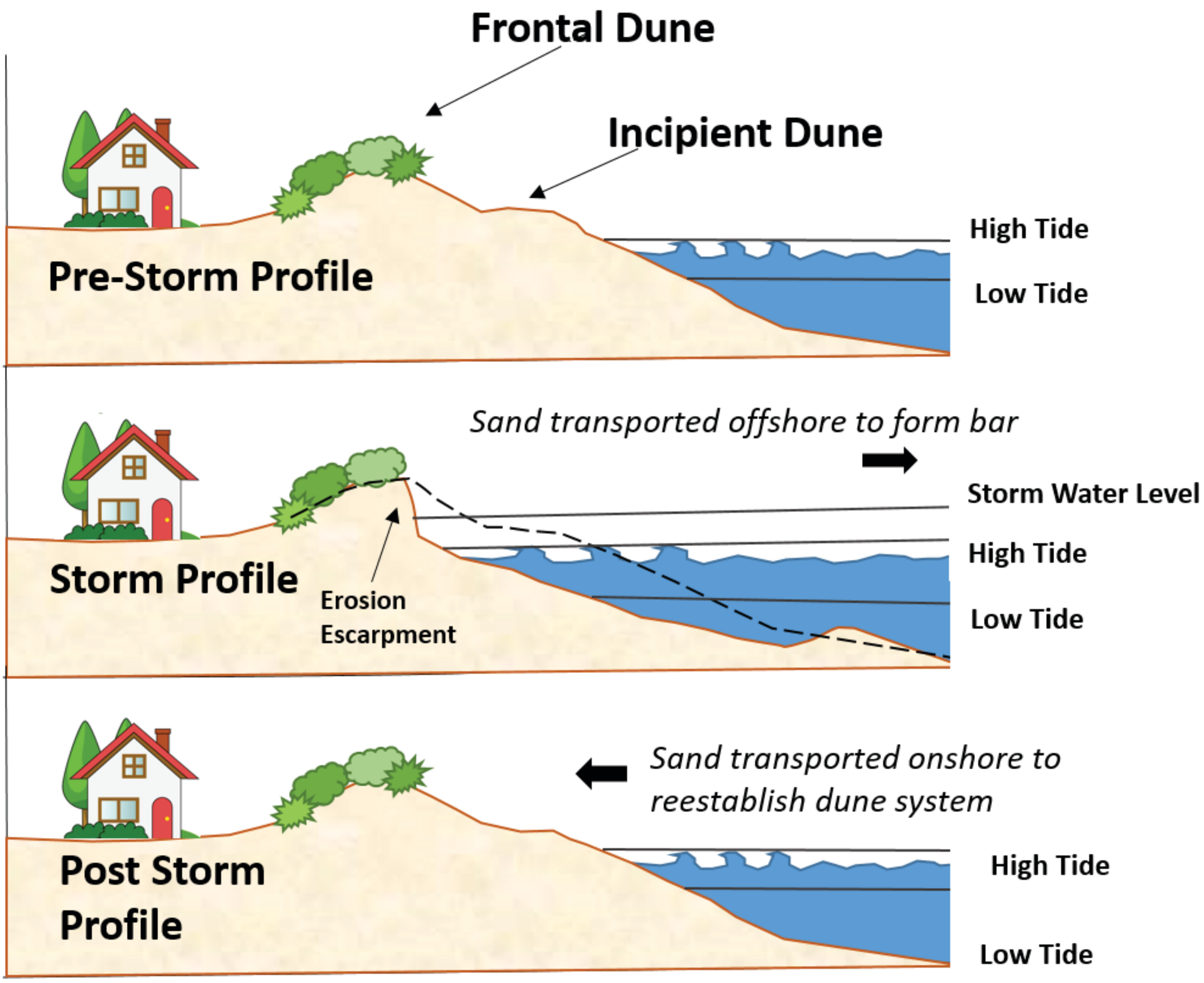



***Figure 21*** *Typical beach erosion and accretion cycle in a case with no permanent loss of sand. From© State of New South Wales and Office of Environment and Heritage 2018*

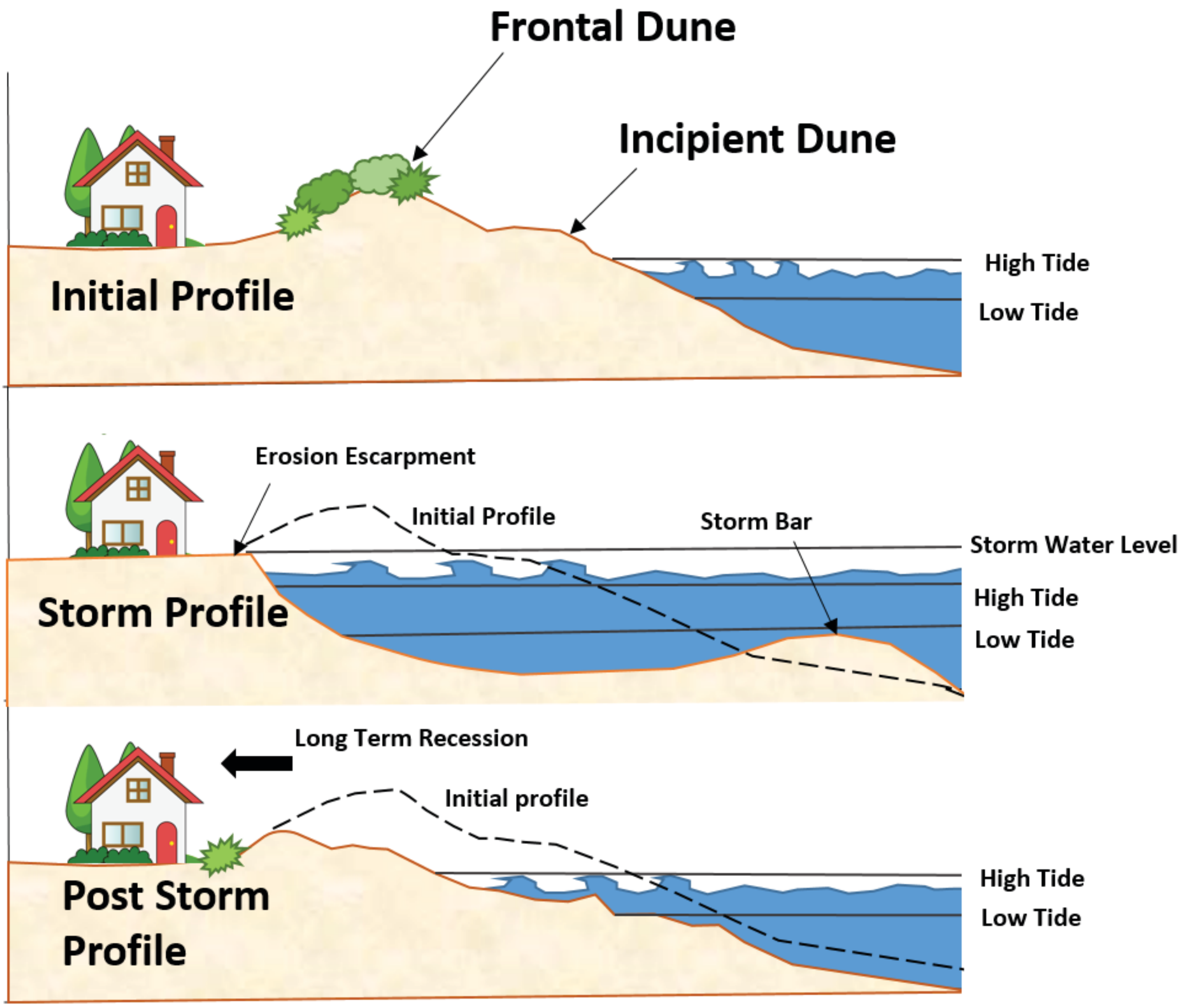



***Figure 22*** *Typical beach erosion pattern where there is a long-term erosion trend. © State of New South Wales and Office of Environment and Heritage 2018*

Understanding the different timescales of beach erosion and accretion is essential for effective coastal management and the development of adaptation strategies to protect coastal communities and ecosystems from the impacts of coastal erosion. In Chapter 4, monitoring techniques that allow for the quantification of these changes in beach width are discussed in detail.

## Summary

In conclusion, coastal erosion is a complex process that can have significant environmental and economic impacts. While natural causes of erosion cannot be fully prevented, anthropogenic causes can and must be mitigated. Strategies to address anthropogenic causes of erosion should prioritize the protection of natural barriers, reducing the interruption of sediment sources, and limiting the use of shoreline-hardening structures. Additionally, communities need to develop adaptive strategies to address the impacts of climate change on coastal areas. By taking action to mitigate anthropogenic causes of coastal erosion, we can help protect our coastlines and preserve our natural resources.

# Chapter 4

## COASTAL EROSION MONITORING

Regular monitoring of erosion is an essential prerequisite for the management and prevention of this phenomenon because it enables a better understanding of the dynamics at work at different scales of time and space, guiding the implementation of mitigation measures.

It is crucial to distinguish seasonal, annual, or even multi-annual cycles from event impacts and long-term trends (climate change) as described in Chapter 3. Additionally, observations must differentiate the effects on the different compartments of the beach (Chapter 2) to provide an integrated view of the beach system.

A typical example is the partial or total disappearance of a beach following a storm or cyclone. Without monitoring or observation, a manager may be tempted to implement coastal engineering works to halt the phenomenon. However, observations may indicate that the sand has been partly stored in the form of bars in the submerged part of the beach and that it may return, thanks to less energetic swells. This information allows decision-makers to avoid 1) unnecessary expensive investments, 2) blocking hydro-sedimentary dynamics, and preventing the natural return of sand, and 3) favouring, when possible, gentle protection solutions based on nature (e.g., revegetation of the top of the beach).

This chapter thus seeks to detail the different methods of observation and measurements to implement a monitoring network or an observatory of coastal erosion. Chapter 6 will focus on the monitoring network set up in the Greater Caribbean as part of the Sandy Shorelines project while this chapter addresses the following aspects of coastal erosion monitoring:

1. Morphological indicators that reflect the current dynamics.

2. Hydro-meteorological forcings to be followed to understand cause-and-effect relationships

3. The criteria for selecting the beaches to be included in the monitoring network

4. Methods and tools for field measurement and sampling

5. Digital tools for processing measurement and observation data

6. Methods of analysis and interpretation of the information obtained

A summary for decision-makers will synthesize the information essential for the implementation of a monitoring network.

## 4.1. Indicators of erosion processes.

Indicators observable in the landscape are discussed here, as well as markers to be measured and monitored over time to translate the current dynamics (the observation methods are detailed in 4.3).

### 4.1.1. Indicators to be observed.

This section presents the typical morpho-indicators of the tropical beaches of the Greater Caribbean (Figure 23). This includes those of the beaches themselves and the associated compartments in the back-beaches (dunes) or in the front-beaches (underwater beaches).

**Beaches:**

First, the slope indicates the reflective or dissipative character of the beach (Wright and Short, 1984). If the beach is exposed to energetic conditions, meaning significant agitation (waves), its slope will be steeper and referred to as reflective. The slope may steepen after a given event or have a permanently steep profile, depending on its one-time or chronic exposure to waves. Beaches with a gentle slope are considered dissipative because they are less exposed to waves (typically bay bottom).

In the Greater Caribbean, the most reflective beaches will tend to be on the facade exposed to the Atlantic Ocean rather than the Caribbean Sea, where conditions are calmer (western facade of the islands, in particular). Depending on the width of the beach, the steepest part may be found only in the shore jet area where the waves die

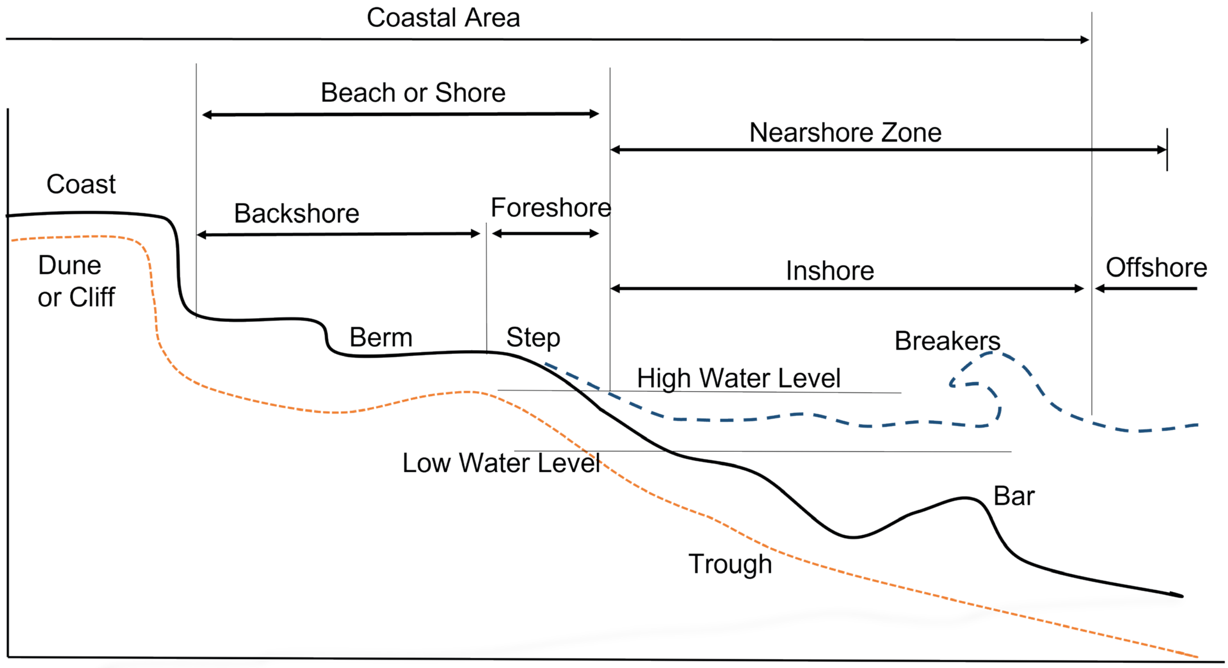



***Figure 23.*** *Beach profile and morphological characteristics (adapted from Kraus, 2005)*

with a flatter beach top. On narrow beaches, wave action can affect most of the slope of the beach.

On reflective beaches, ripples called beach crescents may appear in the shore jet zone. They are another marker for identifying exposure to high-energy levels of hydrodynamic forcings (waves). Crescents can also appear and disappear thanks to the passage of swells.

Several storm-specific markers should also be considered. Indeed, after the passage of a storm or cyclone, a top beach berm is often present due to the erosion created by the waves and the transport of sand from the aerial beach to the underwater beach. At the foot of this escarpment or further down the beach when the storm is less strong, there is most often a storm leash, which is the deposit of vegetation, algae, or other waste left by the waves. The presence of several levels of deposits (several leashes) makes it possible to distinguish the chronology of the storm or the sequence of several wave episodes.

Finally, the appearance of beach sandstone at the level of the bank jet zone indicates a loss of sediment thickness that can be punctual in time or more often tendential. Indeed, these indurated sand formations form naturally at about 1m depth under the chemical effect of heat and humidity (Vousdoukas et al., 2007). This type of formation is more frequently found in tropical contexts.

At the top of the beach, the vegetation-sand boundary, where it exists, is finally a marker for monitoring the longer-term dynamics of the site. In the Caribbean and more widely in the tropics, it is often composed of creeping plants of the ipomea type (Ipomea *pes-caprae*). Vegetation plays a role in fixing sand, and its disappearance or removal may partly explain the observed erosion phenomena.

### Back-beach:

Some beaches of the Greater Caribbean may be bordered on the land side, by a more or less developed dune system as discussed in Chapter 2.

The foot of the dune is then the most interesting marker to follow in order to observe the potential retreat. The dune front can also be cut by waves during a storm and form a micro-cliff whose escarpment will depend on the height of the edge dune.

The dune vegetation line on the beach side, like that of beaches, can also provide information on the trend of evolution.

### Foreshore:

The slope on the underwater part of the beach is generally gentler than on the aerial part but typical morphologies are to be observed.

This is particularly the case for front-rib bars. These bars can be permanent or temporary, move relative to the coast, split or cut depending on wave conditions. They can also be created after the passage of a storm that has caused sand to be transported from the aerial beach.

For the so-called coral beaches, the foreshore is marked by the presence of a fringing reef, sometimes doubled by a barrier reef. If these reefs are not mobile like sandbars, it may be interesting to observe their silting or potential degradation. Indeed, even if the sand stocks are partly fossil (inherited from geological periods of lower sea level), coral reefs are still today the providers of bioclastic sand of the beach and their degradation jeopardizes sand production (Perry and Hepburn, 2008; Perry et al., 2011). Reef degradation can be natural (mechanical shock of waves or consumption by living organisms such as parrotfish) but in the Caribbean, it is too often due to poor water quality in connection with insufficient or non-existent treatment of wastewater from human origin (Rosado-Torres et al., 2019).

The presence of a pass is also important to take into account because it can “drain” the sand during a storm but make it more difficult to bring it back to the land beach because of the blocking presence of the reef.

### 4.1.2. Indicators to be measured.

To study the evolution of the range considered, it is therefore possible to use the morphologies observed as indicators of its state and changes. The measurement tools for these indicators are presented in Section 4.4.

The longitudinal indicators make up what is called the coastline. At the bottom of the beach, it is often the limit of shore jet that is raised or that of the crescents of beach or the sea leash. At the top of the beach, the vegetation line or the foot of the dune are used. This longitudinal monitoring can make it possible to observe the transport related to coastal drift (Chapter 3) and seasonal cycles, or even the phenomena of “rotations” typical of pocket beaches (Chapters 2 and 3).

However, the retreat of the coastline does not necessarily indicate erosion because the amount of sand can remain the same and it is important to follow the transverse dynamics of the beach through the beach profiles. This cross-sectional indicator consists of recording the slope of the beach, potentially from the dune to the underwater part. At least 3 beach profiles need to be established on a beach to observe the tilts and reproduce the surveys consistently along the same axis.

Finally, the most comprehensive indicator is the one that accounts for the morphology of the beach in three dimensions. For this, point clouds can be raised to constitute grids of Digital Terrain Models. The crossing of the grids at different dates makes it possible to precisely identify the areas of loss and deposit. As for the profiles, different techniques are possible to cover the aerial and underwater parts.

## 4.2. Marine weather parameter.

To interpret and explain the observed trends, it is necessary to take into account the marine weather forcings (Figure 24) that are at the origin of them (Chapter 2).

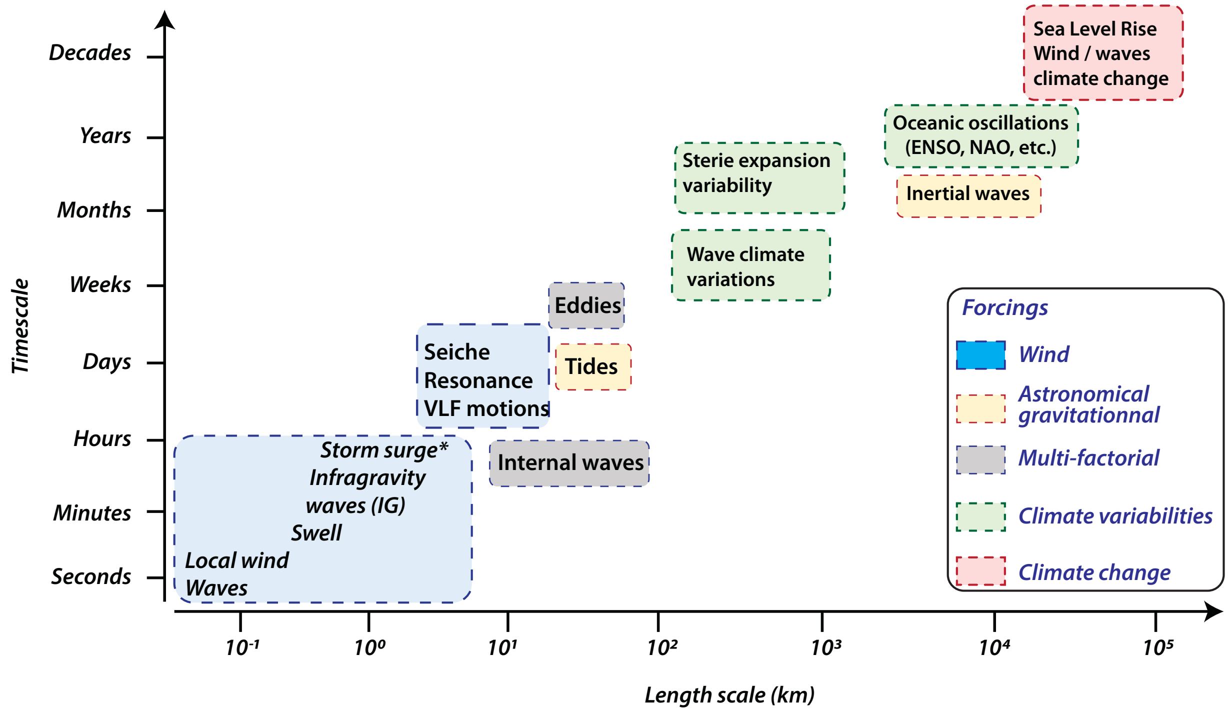



***Figure 24*** *Meteo-marine forcings regarding their timescale (BRGM)*

## Waves

As such, it is important to measure or collect information on wave conditions over the period considered.

The wave data are broken down into three main parameters: height H (meters), period Tp (seconds) and direction Dir (degrees) and which can be broken down into so-called "significant" values (Hs or H 1/3 corresponding to the average of the third of the strongest waves) or max or peak values (Hmax or Hp). The height and period of the waves tell us about the associated energy. The orientation indicates the incidence of the swell relative to the range under consideration and the direction of sediment transport by the coastal drift (Chapter 3).

The frequency spectrum (in Hertz) of the wave can also be an interesting parameter for further analysis of the different wavelengths and their respective roles (infragravity waves in lagoon areas, for example).

## Water levels

Water levels or sea levels are also a potential parameter to monitor, especially if the waves do not explain the observed changes.

The level is expressed in meters relative to a reference, called hydrographic 0, different from the terrestrial vertical reference. It is therefore necessary to specify the reference system in which it is considered.

Sea level is a function of astronomical tides, seasonal cycles linked, for example, to major ocean currents or variations in temperature and salinity of water bodies (Figure 25) Storm surge can also influence water levels. It is related to the drop in barometric pressure, the action of the sea wind or the breaking of waves (Chapter 3).

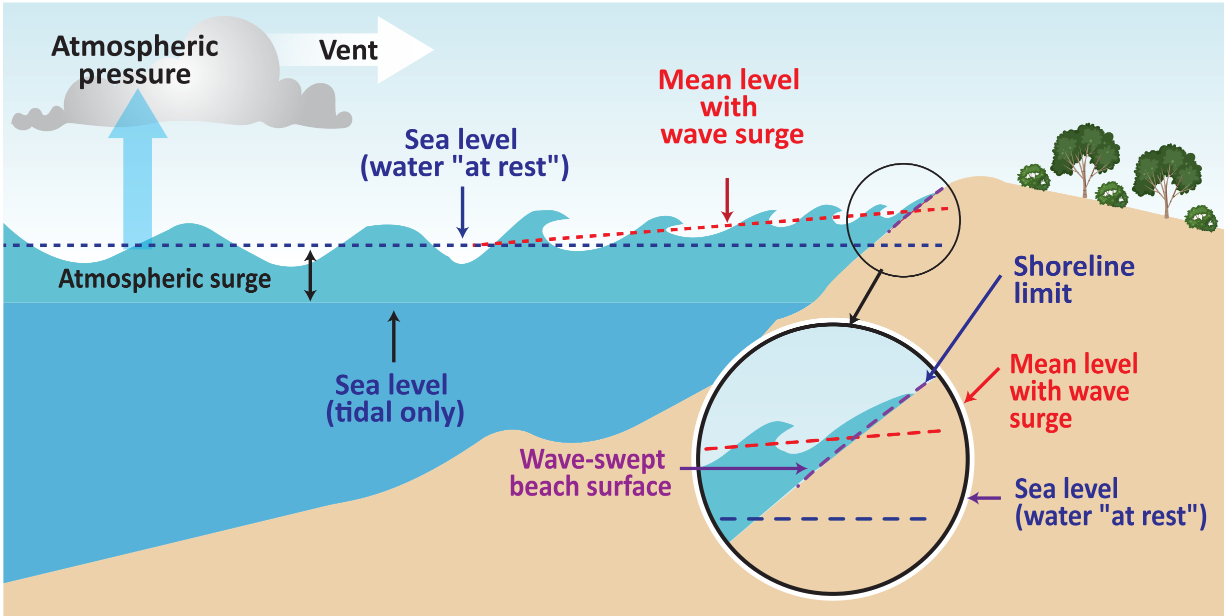



***Figure 25*** *Different sea levels considering atmospheric and marine forcings (BRGM)*

### Currents

The currents can be measured (speed in m/s and direction in degrees) if we try to specify the hydro-sedimentary transport in the submerged area of the beach, especially in bays or lagoons where passing effects can complicate circulations.

### Wind

Weather parameters are generally less used. The action of the wind is morphogenous on the top of the beach and the dune formations by the phenomenon of deflation, i.e. the transport of sand by the wind (Chapter 3).

Like currents, wind is considered in speed (m/s) and direction (degree) and measured on average over an hour or day and instantaneous (including gusts).

### 4.3. Anthropogenic actions.

In order to understand the morphological changes observed on the ground, it is finally necessary to integrate any anthropogenic actions on the beach in order to distinguish them from natural dynamics.

Indeed, artificial reloading works, the installation of structures or significant traffic can directly influence sand volumes, sediment transport; or indirectly as vegetation trampling on sand mobility (Pilkey & Cooper, 2014, Hesp et al., 2010).

This information (volumes, plans, dates, etc.) is to be collected from the local community.

### 4.4. Procedure for selecting monitoring network ranges.

Several representativeness criteria make it possible to select the beaches to be integrated into a regional or national monitoring network.

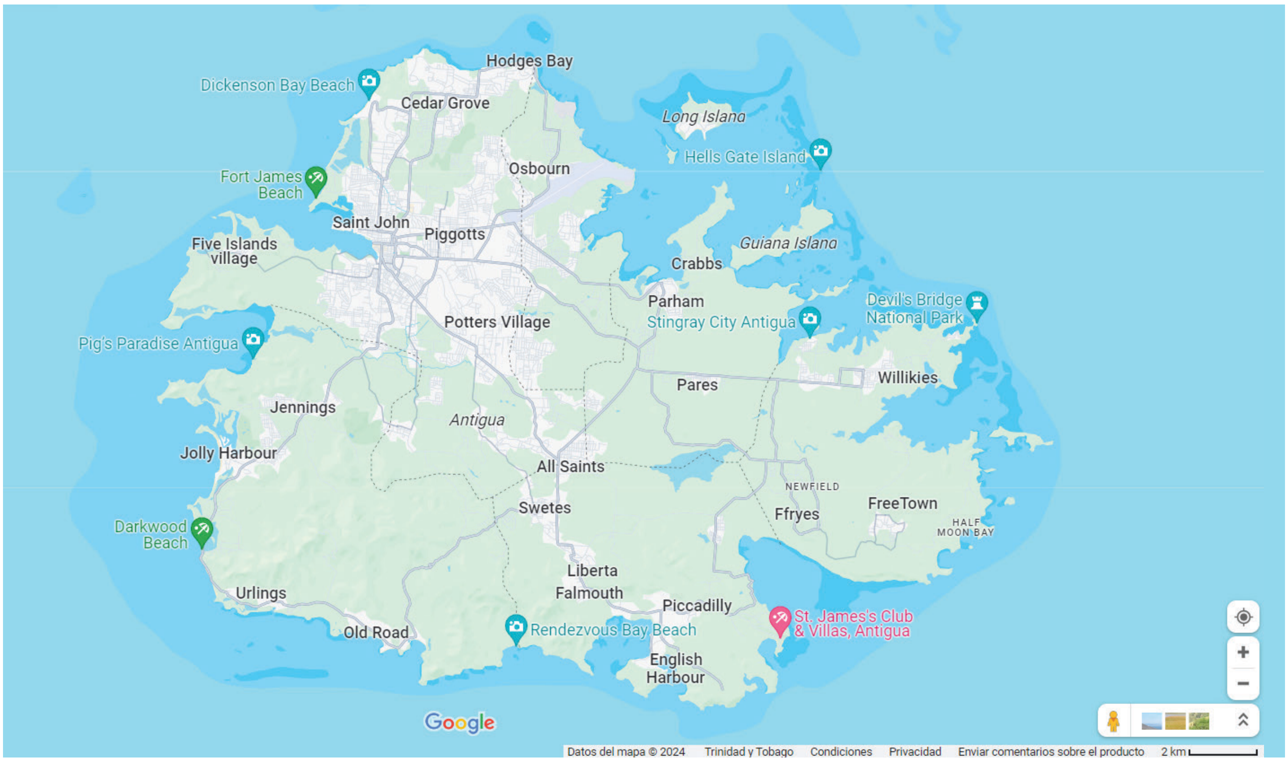
First of all, it may be considered necessary to take into account a geographical criterion in order to cover the different regions or sectors of a territory. For a Caribbean island, different facades can be considered. For an archipelago, it can be on different islands.

In addition, it will be interesting to integrate a morphological criterion in order to distinguish different types of beaches (with or without coral reefs, dunes; pocket beaches, open beaches, bays; composed of volcanic sand, biodetrital; bordered by cliffs, urban beach, etc.).

Exposure or not to waves, the presence of a lagoon sensitive to variations in water levels and currents can also constitute hydrodynamic criteria.

Last but not least, the conjunction between known erosion phenomena and the presence of human (buildings, tourist or fishing activities) or heritage issues (worship area, historic site, protected natural area) makes it possible to identify sensitive and vulnerable sites to be monitored as a priority.

Below is an example of a national monitoring network in Antigua and Barbuda (Figure 26).



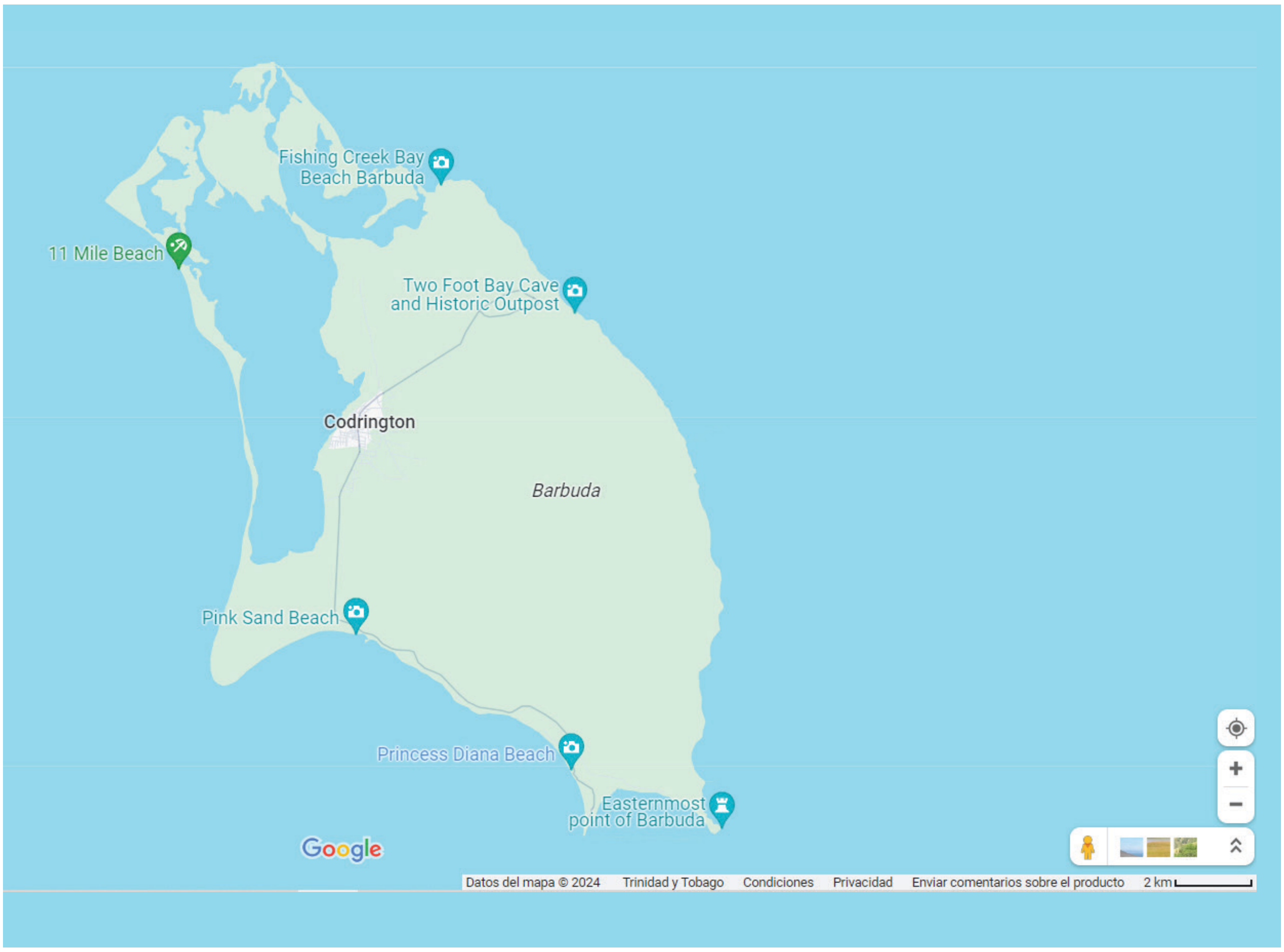




***Figure 26.*** *Antigua and Barbuda Monitored Sites (Sandy Shorelines)*

There are more monitored sites in Antigua where population and issues are concentrated. This network, particularly dense for the size of the territory, covers the two main islands and the different facades. Several types of beach are followed, some natural, others with tourist complexes and others in urban environments.

## 4.5. Field measurement and sampling methods.

This chapter presents the methods to be implemented in the field and the frequency of follow-ups to be carried out in order to develop an observation protocol.

### 4.5.1 Topography.

The main method is to monitor the above indicators by recording their morphological variations from one date to another using topographical methods.

**Basic follow-ups**

The easiest way is to make so-called "landscape" photographs. That is to say, always from the same point of view and with the same influence. To interpret changes (less or more sand typically), it is useful to have an invariant landmark such as a tree, low wall, etc. In the absence of an existing marker, it is possible to install a pile that will ideally be graduated in order to be able to interpret the variations in front or behind the pile but also in altitude (height of the sand on the pile).

This method is used in particular in the participatory science project *CoastSnap* (https://www.coastsnap.com/) which allows anyone to take a photo on a medium and upload it via an application

The disadvantage of this method is that it does not make it possible to quantify precisely and directly the evolutions.

It is therefore important to be able to complement this landscape approach by measuring beach profiles. A do-it-yourself or "DIY" method is to use a graduated frame. This material can be made from 2 vertical and graduated PVC tubes to which is connected 1 horizontal tube (perpendicular) and sliding. The horizontal tube can be replaced by a rope but as it is flexible, it is then more difficult to guarantee its horizontality. The difference in height between the two vertical tubes can thus be measured and then plotted on a graph. It is customary to start from the top of the beach, for example from an existing landmark or a pile implanted for this purpose, and to descend towards the sea at the perpendicular side of the beach.


***Figure 27*** *Basic equipment for profile monitoring: Handheld GPS*

A handheld GPS makes it possible to record the position of the coastline at the bottom of the beach or the limit of the top of the beach Figure 27). These devices, commonly used for hiking or guiding, have sufficient accuracy in plane (X, Y coordinates of the order of one meter) for this type of indicator, but insufficient in altitude (Z coordinate) to make beach profiles.

It is essential to note what is the marker recorded for the coastline (water-sand line, crescents, berm, vegetation line, dune foot, etc.) in order to be able to record the same from one date to another and have a comparable set of data.

**Advanced follow-ups**

To carry out more precise monitoring, it is recommended to use surveying instruments such as those used on construction sites: construction site scope, tacheometer, theodolite and especially differential GPS (or GNSS system). The principle is each time to install a reference station on a point whose X, Y, and Z coordinates are known and to raise the surrounding points from this reference. The known point can be an elevation point referenced by a surveyor or a national body. If it is remote, it is necessary to implant a reference point on the range from the known point.

Construction glasses, tacheometers and other theodolites use a local measurement. Indeed, the station measures the position of a target from a magnifying telescope or a laser beam. GNSS systems, on the other hand, use the position sent by satellites. It is used in "differential" mode because it calculates the difference in position of the mobile station compared to the reference station (Figure 28). This differential mode allows for an accuracy of around 10 cm in altitude and approximately a centimetre in the horizontal plane. Modern GNSS systems now enable the reception of corrections sent via 3G/4G from antennas positioned within the area. Utilizing this method eliminates the need for installing a reference station to achieve decimetre accuracy. However, the subscription cost for the fixed station system can be substantial.

***Figure 28*** *Images of Beach profiling with GNSS systems: fixed and mobile stations*

These instruments therefore make it possible to collect beach profiles but also point clouds over the entire land surface to create a 3D model.

Nevertheless, the most effective way to create a 3D model is to perform a photogrammetric survey using a drone equipped with a camera (Figure 29). By placing timing targets on the ground and having an on-board or ground-based GNSS system (differential mode: fixed station on the ground and mobile sensor on the drone) for georeferencing images, it is indeed possible to grid the range according to a flight plan and a determined altitude in order to then create an ortho-mosaic and a digital surface model. The use of a drone can, however, be limited to making photographs without corrections in the same logic as landscape monitoring. A drone may require, according to the national regulations in force, a pilot's permit or license and may be subject to flight authorizations.

*Figure 29, Topographic survey using drone photogrammetry:*

Fixed camera systems located on the beach also allow images to be taken and straightened so that they are comparable and measurable (Figure 30). The advantage of this technique is to be able to increase the frequency of acquisition, for example every hour, and to send the images via the internet or mobile network to a server. Low-cost autonomous systems are developed from a mobile phone protected by a waterproof case, and powered by a small solar panel (Valentini & Balouin, 2020). More elaborate arrangements include the construction of a tower or mast, such as the one installed on the beach of Hellshire in Jamaica, as part of the Sandy Shorelines project (Chapter 6). This allows the coastline to be extracted automatically from a large image set. Other morphological, vegetation or hydrodynamic indicators can also be monitored from ad hoc treatments (averaged images, image profiles, etc.). This type of treatment can also be carried out from photographs from participatory science (cf. Coastsnap device).

***Figure 30***
*Fixed camera monitoring: Jamaica ( Sandy Shorelines)*

**Lidar** (*light detection and ranging*) data is very useful for having an elevation reference. Most often operated from an airplane or helicopter, these data are very expensive and can hardly be reproduced every year. Miniaturized systems for drones are now available on the market. There are also fixed (on tripod) or mobile (on foot or by car) land equivalents. It is a rangefinder measurement, that is, a measurement of the distance between the sensor and the ground point from a beam of light. A point cloud is thus directly acquired for a 3D representation of the terrain.

Finally, the use of ortho-photographs or ortho-images of aerial or satellite origin may be necessary, especially for sites that are difficult to access. Some sensors offer very high-resolution images, such as the Pléiades satellite (0.5m pixel) that make it possible to visually follow and record the coastline or vegetation line. On the other hand, it is more complicated to extract sufficiently precise information on altitude.

### 4.5.2. Bathymetry.

Bathymetry is the science of measuring the depth of water and underwater relief; it is in a way “the topography of the sea floor”.

Like the terrestrial part, specific methods make it possible to follow the evolution of the morphology of the underwater beach.

#### Basic follow-ups

Taking photographs of underwater landscapes can first of all provide information on the nature of the seabed (rocky, sandy, etc.) as well as on the loss or gain of sand in certain areas (presence/absence of foreshore bars, silting or deterioration of the fringing reef following a storm, etc.). The easiest way is to use a waterproof device to do this. Following an area with an invariant reference frame (for example a pass) makes it possible to better observe the evolutions.

In terms of bathymetric measurements, the simplest way is to use a hand-held echosounder to perform a point depth measurement along a profile from a boat. The principle of the echosounder is to calculate the time of emission and reception of a sound wave reflecting on the bottom. The location coordinates X, and Y can be taken by a handheld GPS and the Z by the sounder simultaneously. Compliance with the axis of the bathymetric profile by the pilot must be made by means of a nautical guidance system (traced on the hand-held GPS or the GPS of the vessel), or at least from a double bitter on land (two land-based marks on the same axis). If the piloting is in sight, it is therefore necessary to make the profile from the sea to the land. Finally, the hand sounder must be held vertically to take the measurement so as not to distort the value. Two or three values can be averaged as needed (if agitated by the water body). In order to be able to compare the data over time, it will be necessary to recalibrate the measurement in relation to the water level and the tide.

#### Advanced follow-ups

More elaborate echosounders allow for more accurate monitoring. These are single-beam (one wave) or multibeam (one wave swath) systems. Lined with a centimeter GNSS system, or even an inertial unit (correction of movements due to roll and pitch), these sounders are fixed vertically on the side or under the boat. They are controlled by software that manages navigation, synchronized and continuous acquisition of X, Y, and Z data, directly ignoring the tide.

Single-beam systems are used along profiles, which can intersect if you want to grid an area and generate a point cloud for 3D modeling. Multibeam systems proceed in the same way but have a swath that becomes wider as water depth increases. It is possible to provide a grid to fully cover a sector according to the mowing.

These devices can be installed on ships of different sizes, as well as on light boats (zodiacs or kayaks, for example) (Figure 31). Solutions on nautical drones are now available, but preferred for protected areas from waves.

A nautical drone, simply equipped with a camera and a centimetre GNSS system, can also be used to carry out a photogrammetric survey of the bottom, ultimately generating a point cloud, an ortho-image, and a digital surface model. Photographs can also be taken by a diver from the surface. As with aerial photogrammetry, targets are needed to calibrate the georeferencing of images.

The bathymetry of a site can, in addition, be observed from video imaging fixed stations on the land (Holman et al., 2013), aerial drone (Brodie et al., 2019), satellite by treatments based on the wave breaking line (to identify the foreshore bars), or marine optics principles (so-called bathymetric inversion method) (Jagalingam et al., 2015). However, these methods are less precise than direct measurement of bathymetry using a sounder.

Finally, various marine geophysical equipment make it possible to acquire information on the nature of the bottom, its morphology, sediment thickness, and even the structure of the seabed. These include lateral sonar, sediment sounder, seismic reflection, etc. (Figure 31).

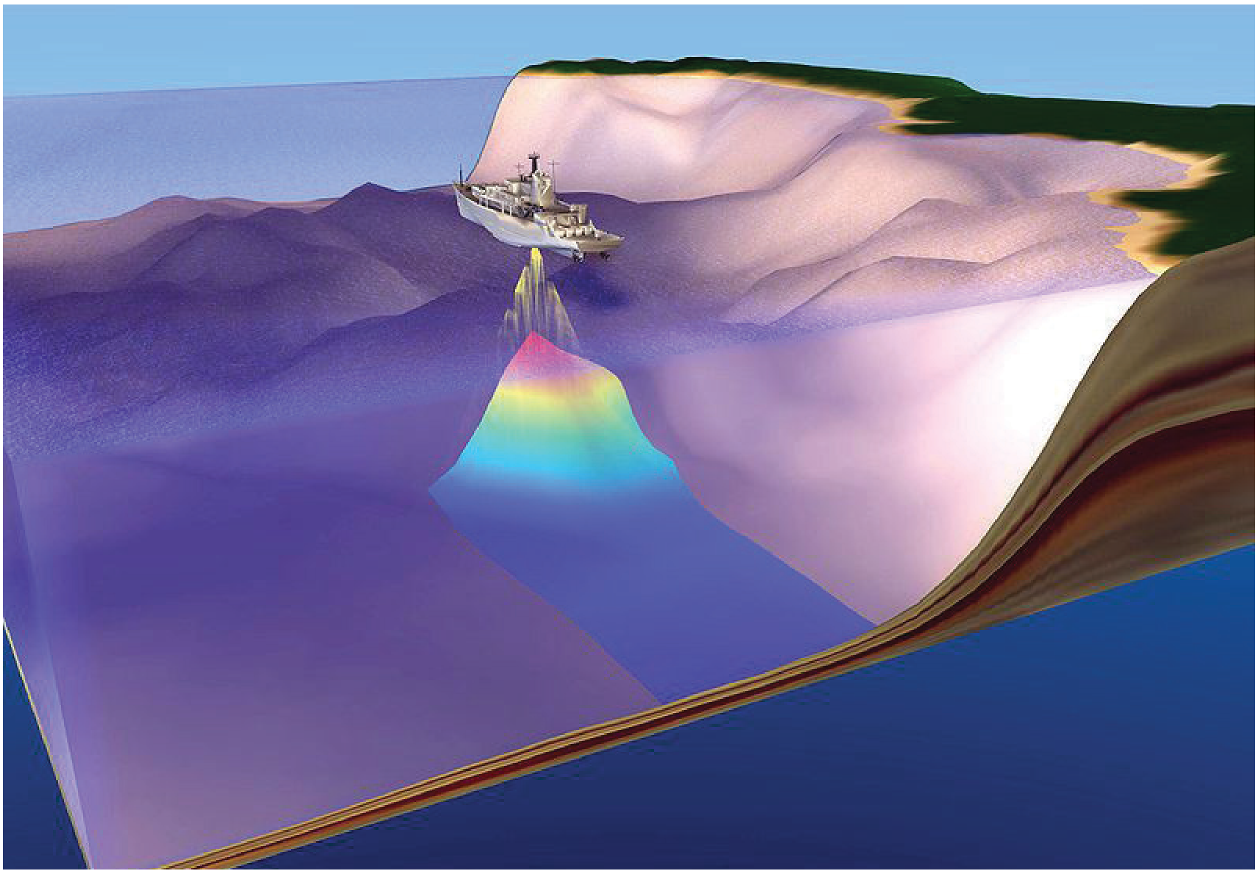


***Figure 31****:Advanced Bathymetry on ship*

### 4.5.3. Sedimentology.

Particle size and sediment nature are also indicators of beach dynamics.

#### Particle size

Particle size is the measurement of sediment size. Different classes are referenced according to the diameter of the grain: clays, silts, sands, sands, pebbles, and blocks.

A particle size gradient is observed as a function of the slope. The steeper the slope, the coarser the diameter will be. The sand transport agent also conditions a particle size sort, as waves can carry grains heavier than the wind. It is therefore important to know the particle size of the different compartments of the beach.

Sampling methods are done, simply using a manual shovel by taking the sand from the first centimeter and storing it in a numbered bag. Most often, the sampling plan is done along the beach profiles. In the underwater part, the use of a sediment dumpster is required from a boat. The *Van Veen* and *Shipeck* models are the most used.

The samples will then have to be dried in an oven before being sorted and weighed by diameter using a particle size column (sieve) or laser particle size meter to obtain a particle size curve

For some specific monitoring, sediment traps can also be used to quantify particle size at different heights depending on wave or wind transport.

**Other sedimentological analyses**

The nature of the sediments is important to consider with sands of bio-detrital origin (from coral or shells), volcanic, alluvial origin, etc. (Figure 32).

***Figure 32*** *Different types of sand: biodetrital, volcanic, alluvial (L-R)*

The composition can also be mixed. In the Caribbean, it can be useful to determine the amount of biodetrital material to estimate the contribution of the coral reef. For this purpose, a calcimetric analysis based on hydrochloric acid is employed to dissolve the carbonate fraction (coral, shells) and quantify its proportion by weighing before and after.

Finally, a binocular magnifying glass examination assesses the blunt index of a grain to estimate the time it has spent in water (morphoscopic analysis). The rounder the grain, the longer it has stayed in the water.

### 4.5.4. Hydro-meteorology.

The means of measuring marine meteorological parameters may be local or regional.

#### Waves and turmoil conditions

This information can first be collected from wave **buoys** when they exist on the facade in question (Figure 33). These buoys, continuously powered by a solar panel, acquire and transmit data in real time (Hs, Tp, Dir), which can be consulted or even downloaded, most often online.

In the absence of a regional system, the use of a local installation can be considered at a lower cost by the installation of a **pressure sensor** that measures the parameters Hs and Tp but also the frequency spectrum of the waves. The disadvantage is that these sensors are not self-contained and must be raised to charge the data and change the battery.

***Figure 33*** *Wave monitoring: fixed buoy*

Finally, if no measurement equipment is available, it is still possible to consult the wave forecast sites (Figure 34) and download their data (references in Chapter 3). In this case, it is necessary to consider that it is only a question of forecasting and not of observation and that a margin of error related to the simulations is present. Nevertheless, the major trends will be well represented.

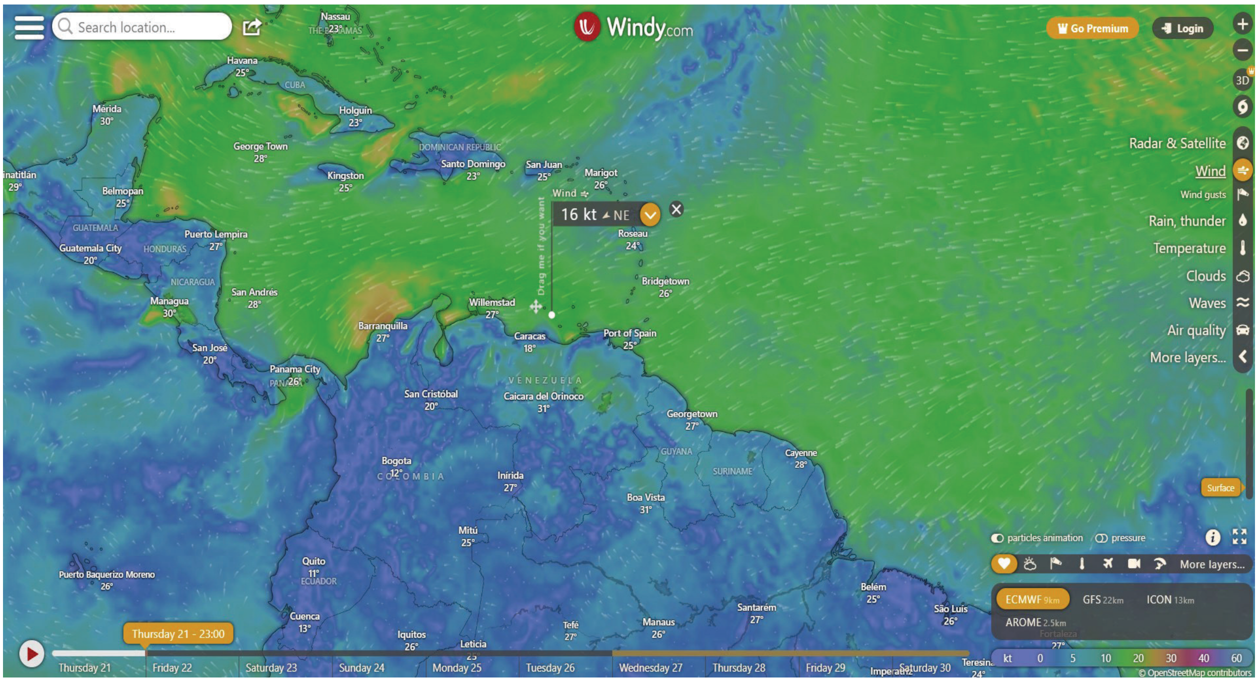



***Figure 34*** *Example of public wave forecast platform (screenshot from* [www.windy.com](http://www.windy.com) *taken on March 21 2024)*

## Water levels

Like wave gauges, regional tide gauges can measure the water level (Figure 35) Located inside the ports, they take into account the tide and seasonal cycles but only the atmospheric component of the storm surge because their location is protected from waves. Their values will therefore be reduced for exposed areas.

***Figure 35.*** *Tide monitoring: tide gauge*

Locally, pressure sensors can also be utilized to measure water levels (see 'Waves'). Tidal harmonics can be easily evaluated several years in advance. Additionally, there are water level prediction models based on historical tide gauge data (Figure 40). The latter takes into account not only the tide but also seasonal variations and sea level rise. However, the effects of event-driven surges are not predictable by these models (Codiga, 2011).

### Currents

There are few regional devices or forecasting models and most often, currents are measured locally and temporarily by means of current meters over the entire water column or by cutting the water column into slices.

It is also possible to use dinghies. These devices are similar to buoys on which a GPS is attached. They inform about the intensity and the main pattern of the currents. They can be useful at the sediment cell scale to determine current and sediment fluxes, or at the regional scale to assess major surface currents.

#### Winds

Stations used by meteorological services most often collect this data, although it is possible to implement one locally or to make instantaneous manual measurements. Online forecasting models are also common.

### 4.5.5. Frequency of observations.

The frequency of observations depends on the cycles to be followed and the means available. First of all, it is important to be able to record monitoring over several years in order to be able to compare and dissociate cyclicities (monthly, annual or even multi-annual) from long-term trends.

In the Caribbean context, within the same year, it is necessary to be able to qualify seasonal variability with a field campaign on each selected beach before and after the hurricane season. A complementary campaign must also be able to be triggered at the passage of a significant event (cyclone, storm) in order to measure the maximum recoil before rebalancing the system. Some fairly comprehensive protocols provide for monthly surveys.

Finally, permanently installed sensors allow “continuous” monitoring (hourly, for example), either during an intensive campaign (one month on a lunar tidal cycle, for example) or permanently and in real time for autonomous stations with remote data transmission.

### 4.5.6. Summary of field methods and example protocol.

There is a wide variety of methods and tools to monitor beach dynamics. If the basic follow-ups are relatively simple and inexpensive, the most advanced methods all require a dedicated training and a consequent budgetary investment.

The table below summarizes the different methods, the estimated associated investment (cost, training), their performance (reliability ratio, efficiency) and the recommended monitoring frequency (Table 2).

Table 2: Synthesis of monitoring methods and tools

| Method | Instrument | Indicator | Cost | External training | Perfomance | Frequency of acquisition |
|---|---|---|---|---|---|---|
| **Topography** | Camera | Landscape tracking, fixed landmarks | $300 max | No | Weak | Bi-annual if travel is necessary; random if there is a framework for public participation |
| | Handheld GPS | coastline, surveys X, Y | $300 max | Self | Weak | Monthly to bi-annual |
| | DIY graduated frame | Beach profiles | $50 max | Self | Weak | Monthly to bi-annual |
| | site level, theodolite, tachometer | Beach profiles | $300 - 10 000 | From several days to several years | Very good | Monthly to bi-annual |
| | Differential GNSS system | beach profiles, point cloud | $6000 - 20 000 | From several days to several years | Very good | monthly to bi-annual |
| | oblique photo drone | Landscape tracking, fixed landmarks | $1000 max | From several days | Weak | monthly to bi-annual |
| | Photo-grammetric drone | Scatterplot | $10 000 | From several days to several years | Good | continue |
| | Fixed video camera | Scatterplot, coast line | $300 to 5000 | No ad hoc training, companion-ship | Good | continue |
| | lidar on land or in the air | Point cloud | $5000 min | From several days to several years | Very good | Bi-annual to interannual |
| | Aerial and satellite images | Coastline, surveys X, Y | Google Earth Pro (free) | From several days to several years | Good | Bi-annual to interannual |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Bathymetry** | Camera | Landscape tracking, fixed landmarks | $300 Max | No | Weak | Bi-annual |
| | Handheld echosounder | Beach profiles | $300 Max | Self | Weak | Monthly to bi-annual |
| | Single and multibeam sonars | Beach profiles, point cloud | $1000 Min | From several days to several years | Good to very good | Monthly to bi-annual |
| | Nautical drone | Point cloud | $2000 Min | From several days to several years | Good | Monthly to bi-annual |
| | Video imagery, drone, satellite | Point cloud | $0 – 10 000 | From several days to several years | Good | Bi-annual to interannual |
| | Seismic, sediment sounder, lateral sonar | Beach profiles | $10 000 Min | From several days to several years | Good to very good | A reference Lift |
| **Sedi-mentology** | Shovel, skip | Beach profiles | $10 - 1000 | Self | Weak | Bi-annual to interannual |
| | DIY trap | Beach profiles | $300 Max | Self | Weak | Intensive campaign |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Hydromete-orology** | pressure sensor | 1-point measurement | $300 - 1000 | from several days to several years | good to very good | Intensive campaign |
| | Wave | 1-point measurement | $50 000 | from several days to several years | good to very good | continue |
| | tide gauge | 1-point measurement | $1000 min | from several days to several years | good to very good | continue continue |
| | point current meter or ADCP | 1-point measurement | $15000 - 35 000 | from several days to several years | good to very good | Intensive campaign |
| | Weather station, anemometer | 1-point measurement | $300 min | from several days to several years | good to very good | one-time to continuous |

These estimates remain very variable because for the same type of equipment, there are entry-level and professional ranges with considerable differences. The training, performance and recommended frequency are also to be adapted to the use and the desired objective.

For example, below is the monitoring protocol implemented in Guadeloupe by BRGM:

1. Seasonal surveys of 2 topo-bathymetric campaigns per year, before/after the hurricane season from a GNSS system coupled to a single-beam sounder (light boat) on a dozen beaches (profiles, coastline, vegetation line);

2. Annual photogrammetric survey by terrestrial drone on the most sensitive sites (ortho-mosaic, grid);

3. Continuous survey (hourly) by autonomous video camera "low cost" on sites prone to strandings of Sargassum (coastline);

In the event of a cyclone post-event campaign, inventory of impacts on the entire linear (landscape photo and drone on major impact sites).

## 4.6. Digital tools for information processing

Once the raw data has been collected, processing is necessary to make it interpretable.

### Processing of planar coastline data (2D)

Coastline data (or other indicators of this type such as the foot limit of dune, berm, vegetation, etc.) are obtained either from field surveys (GPS/GNSS points) or from images (fixed cameras, drones, aircraft, satellites). In both cases, the use of a Geographic Information System (GIS type ArcGIS, QGIS, etc.) or a programming interface (Python, Matlab, etc.) is necessary to represent the position of the coastline on a plan map (2 dimensions).

For GPS data, you need to import the points (X, Y coordinates) and automatically generate a line by connecting them. In the case of an image, the line is directly generated point by point through photo-interpretation and digitization (the operator "draws" on the image).

The analysis of the temporal evolution of the coastline is conducted by superimposing several dates of coastlines and calculating indices of evolution (distance, annual rates) along transects intersecting the coastlines. The DSAS tool developed by the USGS from ArcGIS automates these tasks (Figure 36 ).

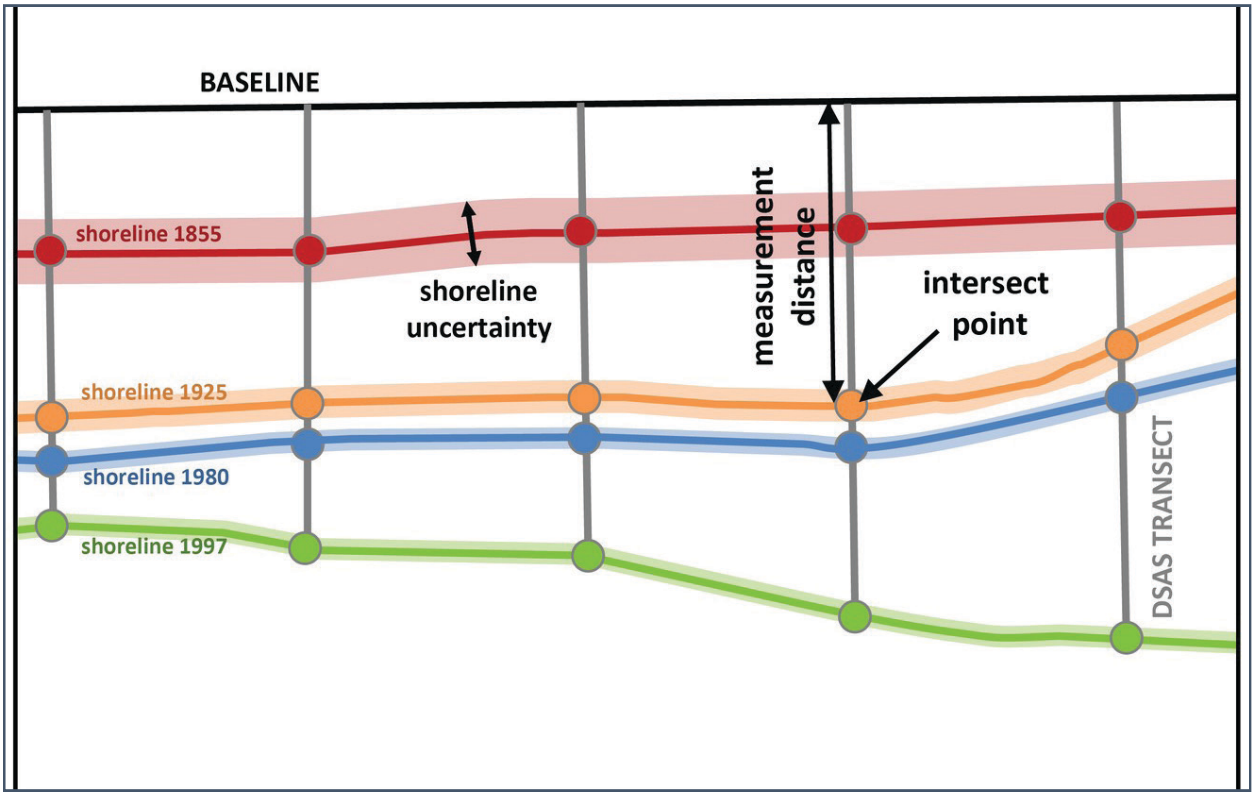



***Figure 36*** *DSAS generates transects that are cast perpendicular to the reference baseline at a user-specified spacing alongshore. DSAS measures the distance between the baseline and each shoreline intersection along a transect, and combines date information, and positional uncertainty for each shoreline*

## Processing cross-sectional range profile data (2D)

Beach profiles are extracted from field campaigns or altimeter grids (photogrammetry, lidar).

For topo-bathymetric data, the X,Y, Z coordinates of each point should be imported into a spreadsheet or programming interface and a graph representing the slope of the cross-sectional range (2 dimensions) with the distance in meters from the profile head on the abscissa, and the altitude in meters on the ordinate (Figure 37). Different tools allow you to automatically generate profiles from the coordinates of GPS points. Profiles can also be extracted from existing elevation grids via the grid module of a GIS or grid-specific software (e.g. *Surfer*) using the dedicated profile tool (Figure 37).

The superposition of the same profile at different dates makes it possible to estimate transverse evolutions (loss or gain of sand thickness in meters, transit along the profile). In addition, the comparison of several profiles of a range makes it possible to apprehend longitudinal variations (transit of sand from one sector to another). The location of profiles on a map can also be done by importing the X,Y coordinates under GIS.

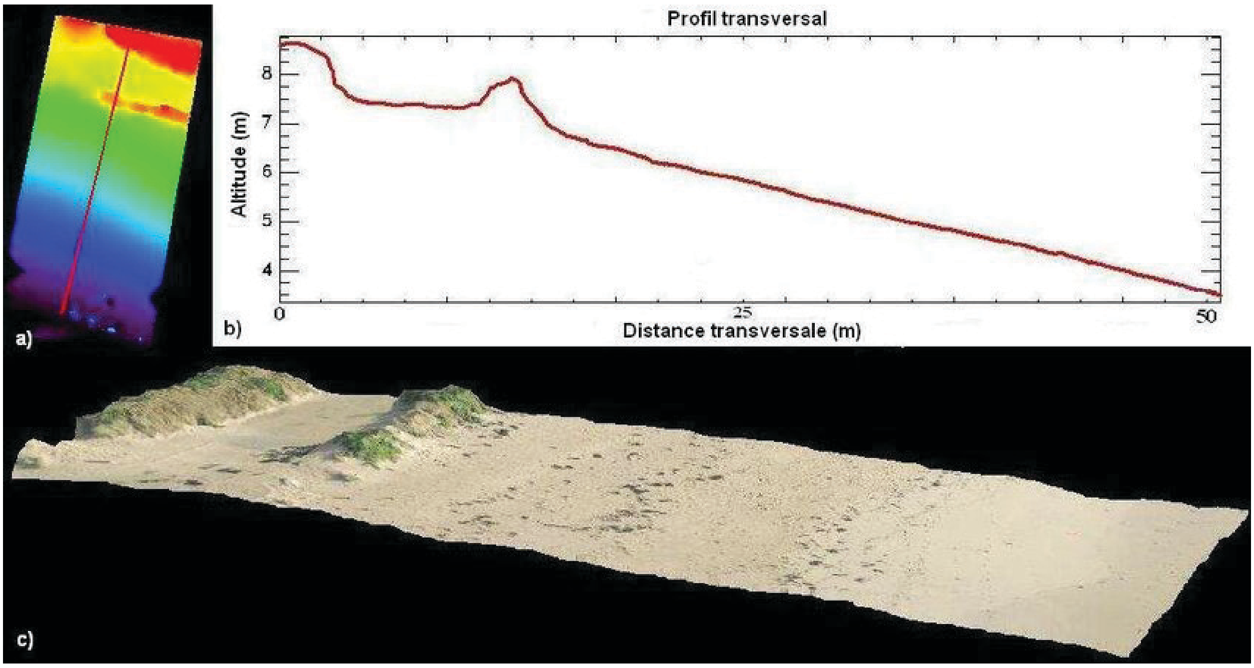



***Figure 37*** *Beach profiles data processing: from field survey (left) or from DEM extraction (right)*

## Point cloud and grid processing (3D)

The principle is to mesh a scatterplot to create a 3-dimensional representation of the range. Point clouds are created from *in situ* data (GNSS, lidar) or images (photogrammetry). Direct measurement of ground altitude generates a Digital Elevation Model (DEM), while extraction from an image mosaic is limited to a Digital Surface Model (DSM) whose value may be that of a building's canopy or roof rather than the ground.

It is possible to create a grid by importing the points X, Y, Z under GIS or a specific software (Surfer, Cloudcompare, etc.). For photogrammetry, the creation of an ortho-mosaic, a point cloud and a grid is done using dedicated software such as *Agisoft Metashape*.

The temporal analysis is carried out by crossing the grids in order to calculate the gains or losses of volumes (in m3) and identify the corresponding transits (Figure 38).

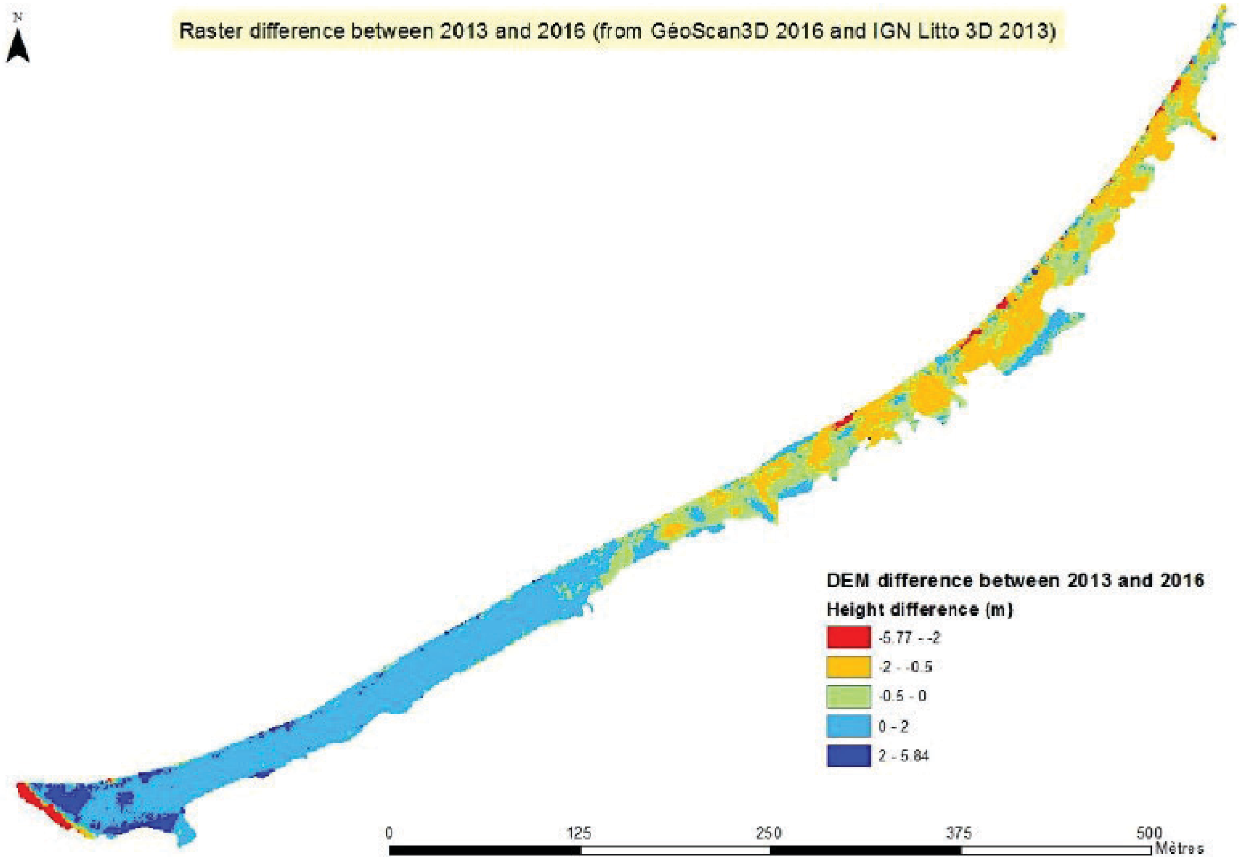



***Figure 38*** *Topographic Grid time analysis: subtraction of the elevation from one date to another to obtain erosion and accumulation for each pixel (BRGM)*

## Processing of meteo-marine data

Marine weather data is mostly imported via scripts and packages that can be automated. These make it possible to extract specific parameters from the integrated data (average, maximum, significant, direction, etc.). For wave data processing, the Wafo (https://github.com/wafo-project/wafo) package, for example, is very widespread and functional on Matlab and Python. It is of course possible to use a spreadsheet for quick data visualization.

A time series of wave height (for example) makes it possible to identify morphogenic storm periods and to relate them to the morpho-indicators recorded (profiles, coastlines, DTMs (Figure 39). Swell roses also make it possible to contextually represent the (average) swell climate.

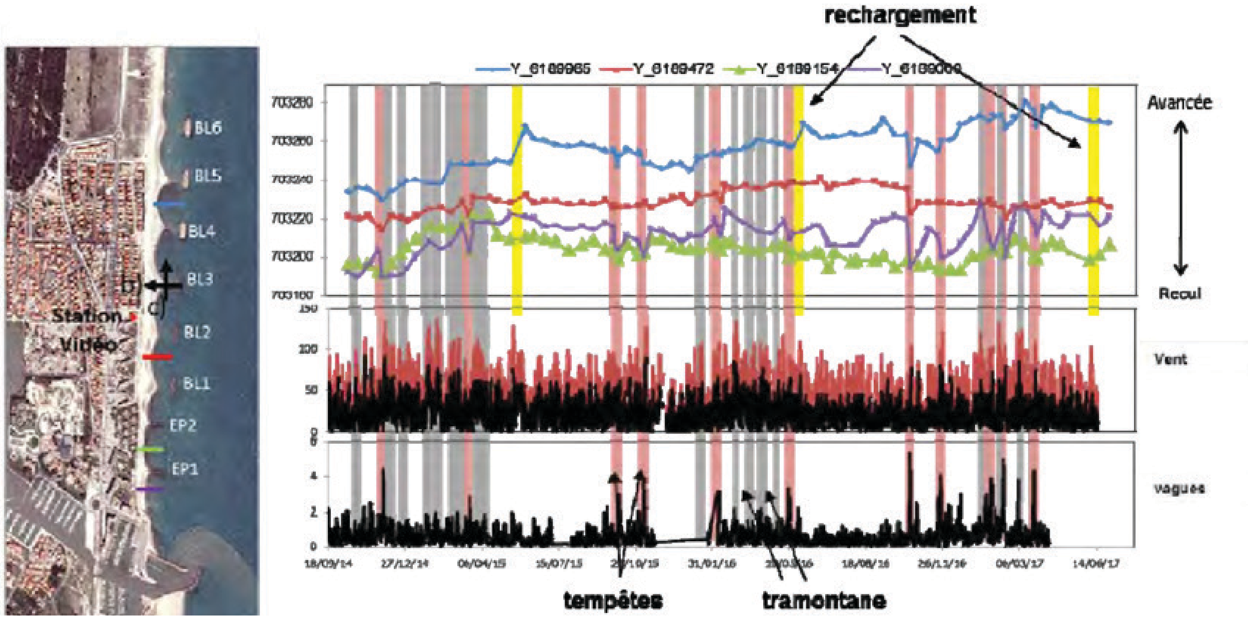



*Figure 39* *Time series with superposition of coastline positions (colors related to profiles), wind and waves (top to bottom)*

### Sedimentological data processing

Particle size data is the most widely used. The simplest treatment method is the representation in the form of a particle size curve (referred to as S) with the diameter of the grains on the abscissa and the cumulative frequency of the weights on the ordinate. This curve allows the evaluation of the proportion of particle size classes in a sample according to different statistical indices (median, quantiles, sorts, etc.).

Spatially, it is useful to report the median in different ways along profiles or, better yet, in the form of a grid if you have a sufficiently tight mesh. This information is particularly crucial in the context of artificial sand reloading operations where the brought-in sand must be most similar to the local sand.

## 4.7. Key points for decision-makers

1. A national or regional monitoring network is essential to understand the dynamics of beaches in their complexity and cyclicity.

2. There are a multitude of tools and methods and the investment must be proportional to the economic and heritage issues of the beaches.

3. The training of dedicated staff is necessary.

4. The sustainability of an observatory is envisaged in the long term.

5. Follow-ups help guide recommendations in terms of management and adaptation on the site.

# Chapter 5

## AN OVERVIEW OF NUMERICAL MODELS AND THEIR ROLE IN UNDERSTANDING AND MITIGATING COASTAL EROSION.

### 5.1. Introduction

Oceanographic numerical models are an essential tool for understanding the dynamics of coastal systems, erosion processes, and designing beach protection projects. These models use computers and algorithms to solve mathematical equations, simulate oceanographic processes, and provide predictions of wave heights, currents, sediment transport, and coastal erosion. By simulating different scenarios, the models allow oceanographers and coastal engineers to assess the potential impacts and causes of coastal erosion and develop strategies for mitigating its effects.

In this chapter, we briefly describe some of the most popular models used by oceanographers and coastal engineers, including numerical wave models, coastal circulation models, coupled wave/current/sediment transport models, and beach erosion and dune breaching models. For educational purposes, we will also highlight some of the numerical modelling work undertaken in the executive projects funded by the Association of Caribbean States (ACS) and carried out by Inversiones GAMMA SA of the Cuban Ministry of Science, Technology, and Environment. These projects focused on the beach rehabilitation at Viento Frío, Colón, Republic of Panama; Runaway Bay, Antigua and Barbuda; and Bonasse, Cedros Bay, Republic of Trinidad and Tobago. Since numerical modelling is a very advanced field, it is worth emphasizing that the goal of this chapter is not to teach readers to use a model but to understand how they work and what can be expected from modelling efforts.

### 5.2. How numerical models work.

Numerical oceanographic models are essential tools in coastal engineering, used to simulate and predict various coastal processes. These models helps engineers and oceanographers understand physical processes occurring in the ocean and coastal areas, such as wave generation and propagation, currents induced by winds, waves and tides, sea levels and storm surges, sediment transport, and coastal erosion.

There are different types of numerical models used in coastal engineering, including hydrodynamic models, which simulate the movement of water in the coastal zone; wave models, which simulate the generation, propagation, and transformation of waves; and sediment transport models, which simulate the movement of sediment in the coastal environment. These models often work together, as the processes they simulate are interrelated and affect one another. For example, wave models can provide input to sediment transport models, as waves are a key driver of sediment movement. This is especially true in the Caribbean, where tides are small and waves are usually the main driver of sediment transport and shoreline change.

Numerical models can be one-dimensional, two-dimensional or three-dimensional, and each may be more adequate depending on the complexity of the issue being analysed. In the context of nearshore hydrodynamics and beach erosion, 1D, 2D, and 3D models each offer different advantages. A 1D model considers variations along a single horizontal dimension, typically the cross-shore profile. This is optimal for simulating scenarios where variations in the alongshore direction are minimal or can be ignored, and the focus is on changes in beach profile, sediment transport, or wave transformation along a single transect. A 2D model considers variations in both the horizontal dimensions, cross-shore and alongshore, and is ideal for simulating phenomena like longshore currents, rip currents, or sediment transport patterns that have significant variations in both horizontal directions but where vertical variations can be averaged or ignored. Finally, a 3D model considers variations in all three spatial dimensions and is necessary for simulating complex scenarios where both horizontal and vertical variations in the hydrodynamic parameters are significant, such as the detailed interaction between waves, currents, and the seabed, or the transport of sediments and pollutants in the water column. The choice of model dimensionality ultimately depends on the nature of the problem, the available computational resources, and the required level of detail in the simulation results.

Numerical modelling has many advantages, such as the ability to simulate complex processes in a controlled environment, predict future changes, and design effective coastal erosion mitigation measures. However, there are also limitations, such as the need for accurate input data, the computational resources required, and the simplifications and assumptions that are made to represent complex natural processes in a mathematical model. Sometimes these assumptions can lead to large errors, and it is important to always keep in mind that models are not perfect. This is why model calibration and validation with actual measured oceanographic and sediment data is important. Despite these limitations, numerical modelling is an indispensable tool in coastal engineering, helping to better understand coastal processes and design effective measures to protect our coastlines.

To implement and run a numerical model to simulate waves, currents and/or sediment transport for a coastal area, a series of crucial steps must be executed. Each step is outlined in general terms below:

1. **Determine the model domain:** First, the geographical scope of the study area must be defined, as well as the model's grid resolution. For nearshore models the grid should encompass the area of interest, spanning from relatively deep waters where appropriate data is available to force the model, and should extend to the nearshore region where the desired beach or study area is located. This is a very important step as defining an inadequate domain can lead to incorrect and misleading results due to boundary effects. The shape of the domain can vary depending of the type of model and whether it uses a structured grid usually requiring rectangular domains, or an unstructured mesh which allows more flexibility in defining the domain and can conform to depth contours (Figure 40).

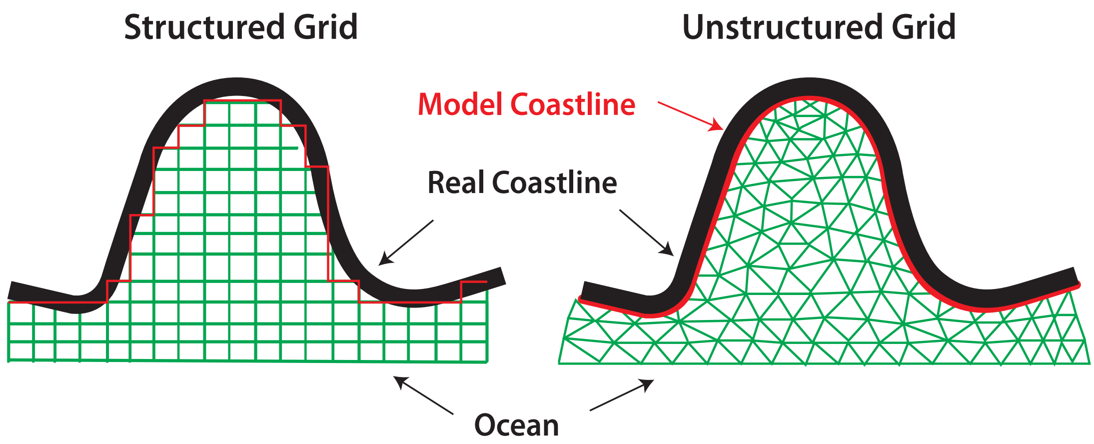



***Figure 40*** *Differences between structured and unstructured grids, © 2001-2024 FVCOM @ MEDML. Designed by Dr. Chen*

2. **Collect input data**: Oceanographic models need various input datasets, such as bathymetry data, wind data, tide data and offshore wave conditions. The bathymetric data used for the model grid or mesh must be of high quality, ideally obtained from LIDAR data, and should resolve the most important bathymetric features affecting waves and currents in the area. The vertical datum should be adjusted carefully

to coincide with other datasets, especially water level forcing conditions. Offshore wave conditions for use as boundary conditions for the model are also extremely important. These can be obtained from oceanographic buoy data or regional wave models such as Wavewatch III (https://polar.ncep.noaa.gov/waves). These time-dependent wave conditions are usually applied at the seaward boundary of the model. Wind speed and direction are also usually applied as surface boundary conditions, and can be obtained from land-based or buoy-based meteorological sensors or from regional numerical models such as GFS, among others. For sediment transport models, input data such as sediment grain size composition and distribution and the spatial distribution of benthic habitats is needed.

3. **Pre-process data:** All data pre-processing, including coordinate system transformations, data interpolation onto the model grid, and data consistency checks, must be performed before running the model. These data should be carefully visualized to ensure there is no spurious input data that can negatively affect the model results.

4. **Set up the model:** This stage involves selecting model parameters such as the physics parameterizations, numerical schemes, computational time step, and frequency range. The length of the simulation is also important and must be carefully determined based on the type of model, model resolution, and available computational resources.

5. **Execute the model:** After configuring the model and preparing the input data, the simulation is run. Most modern models are running using a parallel computing architecture and can be run in Linux, Mac or Windows operating systems. The most advanced and computationally expensive models usually run in Linux based systems. Nowadays, it is not necessary to own an expensive computer cluster, as cloud based computing services such as Amazon Elastic Compute (https://aws.amazon.com/ec2/) provide the ability to run large models without any local computational infrastructure.

6. **Post-processing and result analysis:** Once the model run is completed, output data post-processing occurs. Software such as Python, MATLAB and others are used to generate visualizations of the results such as figures displaying the spatial distribution of wave height contours and nearshore currents for various simulation time steps and at different zoom levels.

## 5.3. Numerical Modelling of Waves.

Numerical wave models simulate wave generation, propagation, and transformation using mathematical equations that describe wave physics. The models utilize input data on wind speed, atmospheric pressure, ocean currents, and bathymetry to predict wave height, direction, and period. These models are essential for understanding wave climate and assessing its potential impact on coastal morphology. There are two types of wave models: phase-averaged or spectral wave models, and phase-resolving models.

Phase-averaged wave models simulate the evolution of wave energy across a range of frequencies and directions, providing statistical information about the wave field but not resolving individual waveforms or phases. On the other hand, phase-resolving models simulate the complete waveform of each wave, capturing the phase relationships between waves and accurately representing wave-wave interactions, wave breaking, and other nonlinear effects.

Two of the most popular wave models are the WaveWatch III and the SWAN model. WaveWatch III is a global wave model that provides wave forecasts up to ten days in advance. The model uses input data on wind speed and atmospheric pressure to predict wave height, period, and direction. Developed by the US National Oceanic and Atmospheric Administration (NOAA), it is used by organizations such as the US Navy and the European Centre for Medium-Range Weather Forecasts. The Caribbean WaveWatch 3 wave model, available at http://ww3.cimh.edu.bb , is a regional implementation of the global WaveWatch 3 wave model specifically designed for the Caribbean Sea.

The SWAN (Simulating WAves Nearshore) model from the Netherlands is a spectral wave model that simulates wave transformation from deep water to the nearshore zone. Widely used for coastal engineering applications, including wave energy assessments, coastal erosion studies, and harbour design, the SWAN model can be found at https://swanmodel.sourceforge.io Figure 41 shows an example of numerical wave modelling conducted by Inversiones Gamma in its execution of the executive beach restoration project at Bonasse Beach in Cedros Bay, as presented in the report by Izquierdo Alvarez et al. (2022).

Phase-resolving wave models, such as SWASH (Simulating WAves till SHore) and XBEACH, are advanced phase-resolving numerical models designed to simulate nearshore wave processes with high accuracy. SWASH is a model that simulates wave transformation, wave breaking, and wave-induced currents in the surf zone, while

XBEACH is specifically designed to model coastal erosion and sediment transport under extreme storm conditions. Both models are important for understanding nearshore hydrodynamics that affect coastal erosion because they provide detailed insights into the wave behaviour and sediment transport processes occurring in the nearshore zone. The paper by Escudero et al. (2012) is a great example of how wave modelling can be used to understand the physics related to how the Mesoamerican Reef in Mexico protects sandy shorelines in North Quintana Roo from erosion.

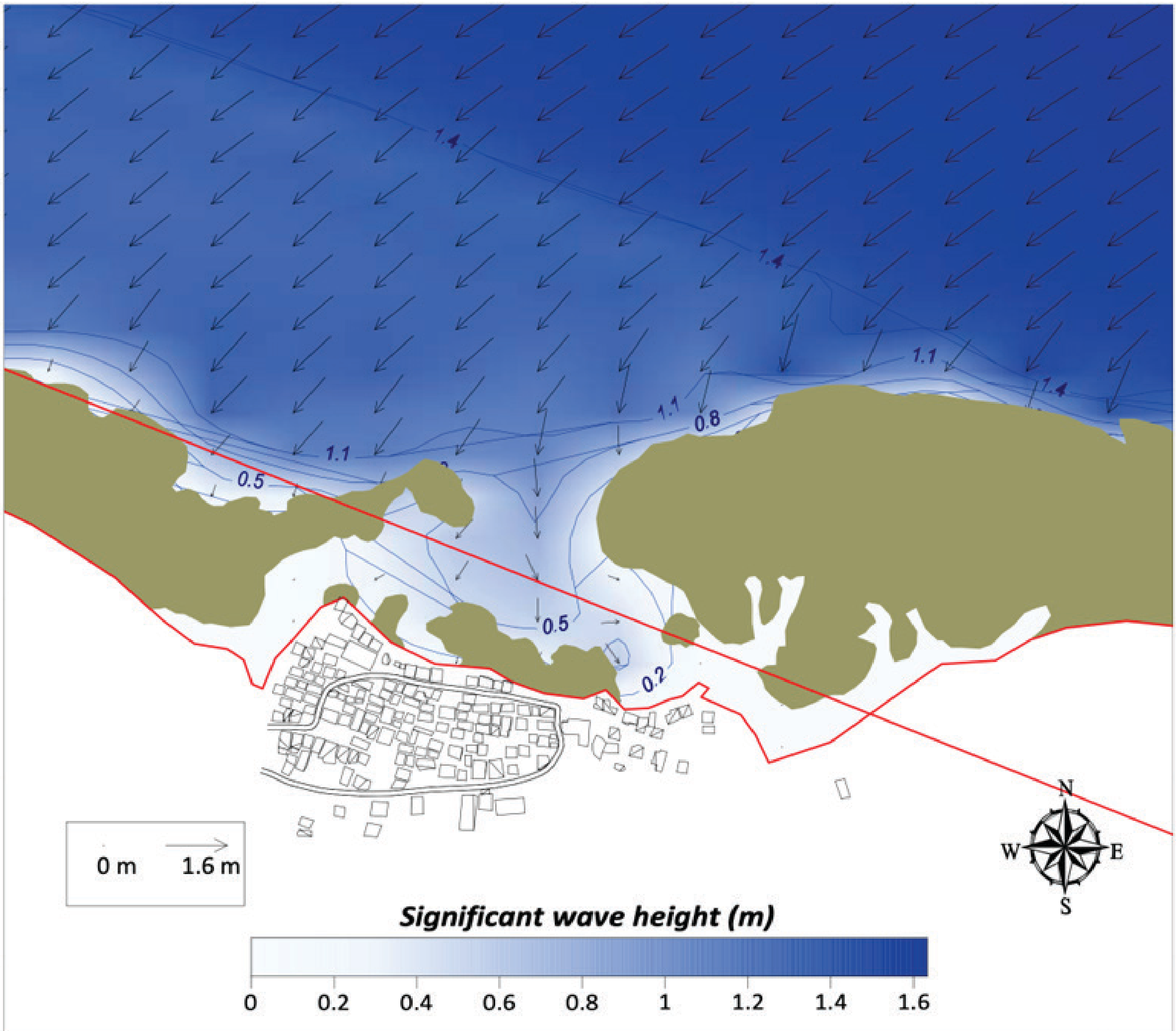



***Figure 41** Example of numerical wave modeling conducted by Inversiones Gamma in its execution of the executive beach restoration project at Bonasse Beach in Cedros Bay, Trinidad and Tobago. Shown are wave heights (shades of blue) and wave direction.*

### 5.4. Numerical Modelling of Currents.

Coastal circulation models simulate the flow of water in the coastal and nearshore zone, incorporating the effects of tides, waves, winds, and buoyancy forces. These models are essential for understanding coastal currents, water level fluctuations, and the transport of sediment and pollutants. Three of the most popular models are the ROMS model, the ADCIRC model, and the FVCOM, among others.

- The 'Regional Ocean Modeling System' (ROMS) is a state-of-the-art numerical model that simulates ocean circulation and wave propagation in the coastal zone. It predicts water level changes, tidal currents, and sediment transport, making it widely used for coastal research and management. ROMS plays a crucial role in studies of coastal flooding, sediment transport, and ocean acidification.

- The Advanced Circulation (ADCIRC) model, a finite-element model, simulates the effects of tides, waves, and storm surges on coastal hydrodynamics. In the Caribbean, it finds extensive use in storm surge prediction and hazard assessment, especially for hurricanes and extreme weather events.

- The Finite Volume Community Ocean Model (FVCOM) is a three-dimensional, unstructured grid, finite volume coastal ocean circulation model, simulating ocean currents, tides, and temperature and salinity distributions in coastal and estuarine waters. Particularly valuable for the Caribbean, FVCOM is employed to simulate water flow in mangrove areas, estuaries, and inlets.

Additionally, phase-resolving models like SWASH and XBEACH can simulate wave-induced currents in the coastal zone. Due to the more straightforward physics of waves and their easier measurability, wave models are generally more accurate than circulation models. Rigorous validation of circulation models is crucial, especially when considering processes like buoyancy, large-scale ocean currents, and wind-induced currents. Figure 42 illustrates the output of a coastal circulation model used by Inversiones Gamma in its execution of the executive beach restoration project at Bonasse Beach in Cedros Bay, Trinidad and Tobago (Izquierdo Alvarez et al., 2022).

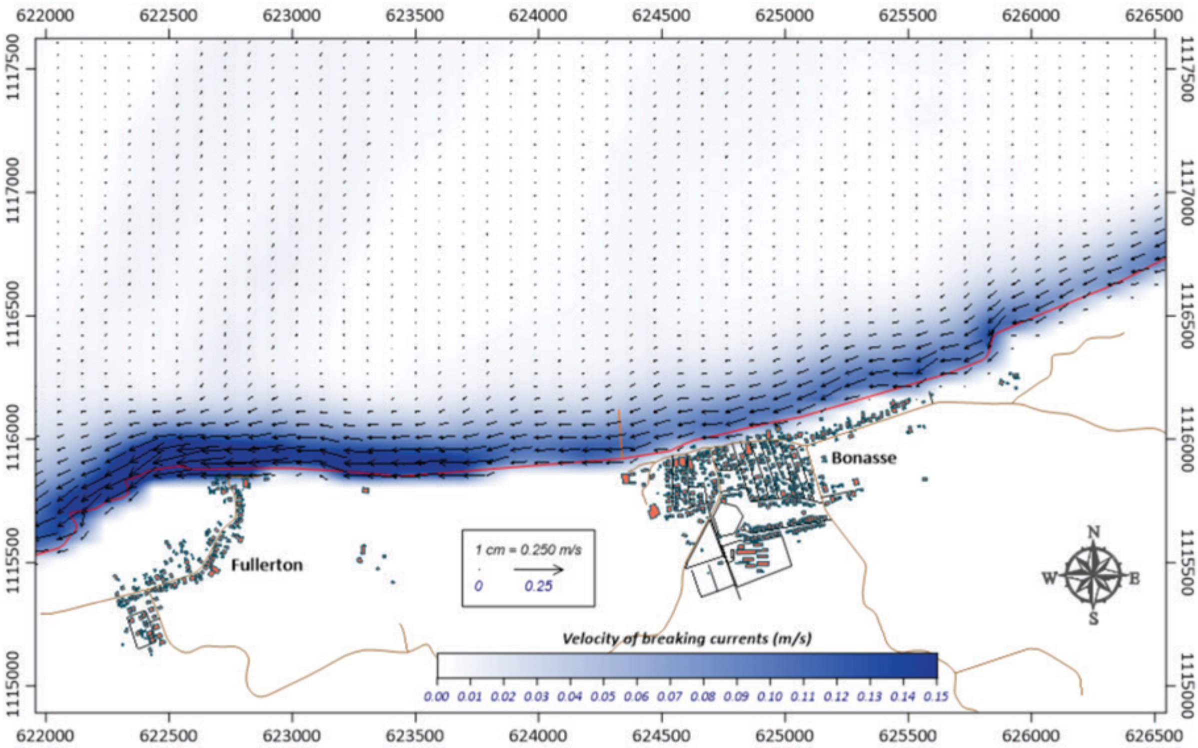



***Figure 42** Example of the output of a coastal circulation model used by Inversiones Gamma in its execution of the executive beach restoration project at Bonasse Beach in Cedros Bay, Trinidad and Tobago.*

## 5.5. Numerical Modelling of Sediment Transport and Coastal Erosion.

Coupled wave/current/sediment transport models simulate the interaction between waves, currents, and sediment transport in the coastal zone. These models are essential for understanding the processes that shape coastal morphology and the impact of coastal erosion. These models are also essential to estimate the potential success of a coastal restoration project and how it may impact beach dynamics. Some of the most popular models are listed below:

The Delft3D model (https://oss.deltares.nl/web/delft3d) is a 3D numerical model that simulates waves, currents, and sediment transport in the coastal zone. The model can be used to predict beach erosion, dune breaching, and shoreline changes, among other variables. Delft3D is widely used for coastal management, including for the design of coastal protection measures and the assessment of coastal hazards.

The XBeach model (https://oss.deltares.nl/web/xbeach/) is a numerical model that simulates the hydrodynamic and morphodynamic processes in the nearshore zone. The model can be used to predict the impact of coastal erosion on beaches and dunes, including dune breaching and overwash. XBeach is widely used for coastal research and management, including for understanding the impacts of storms on beach nourishment projects.

CSHORE (Cross-Shore): CSHORE is a one-dimensional, process-based model for predicting cross-shore sediment transport and beach profile changes (Johnson et al., 2012). It includes formulations for wave transformation, sediment transport, and erosion/deposition processes, and was developed by the US Army Corps of Engineers.

GENESIS (Generalized Model for Simulating Shoreline Change): GENESIS is a one-dimensional numerical model for simulating longshore sediment transport and shoreline change. It combines wave transformation, sediment transport, and shoreline evolution in a single framework.

CMS (USACE 'Coastal Modeling System'): CMS which is an integrated model suite for the calculation of circulation, waves, sediment transport, pollutant mixing and morphology change (Buttolph et al. 2006). It was also produced and is maintained by the USACE. It is more advanced than GENESIS and CSHORE in that it allows for 2D simulations, but lacks the ability to explicitly resolve the erosion of the upper beach profile.

The models listed above are only a partial list and there are many other models that simulate sediment transport and erosion. Model selection for a specific study will depend on the experience of the oceanographer and or coastal engineer, available computational resources, and the complexity of the site. Figure 43 shows an example of sediment transport and morphology change modelling carried out by Inversiones Gamma for the executive beach restoration project at Runaway Bay Beach in Antigua and Barbuda. The illustration was extracted from the report by Morales Diaz et al. (2022).

### 5.6. Numerical Modelling in Support of Projects Design.

Very high-resolution numerical modelling is sometimes the only available tool to oceanographers and engineers as they try to estimate the potential performance of a coastal erosion mitigation project. In general, models are usually applied to examine actual and with-project wave and circulation patterns as well as evaluate different project alternatives.

For example, when placing wave dissipation structures near a beach, the effects of

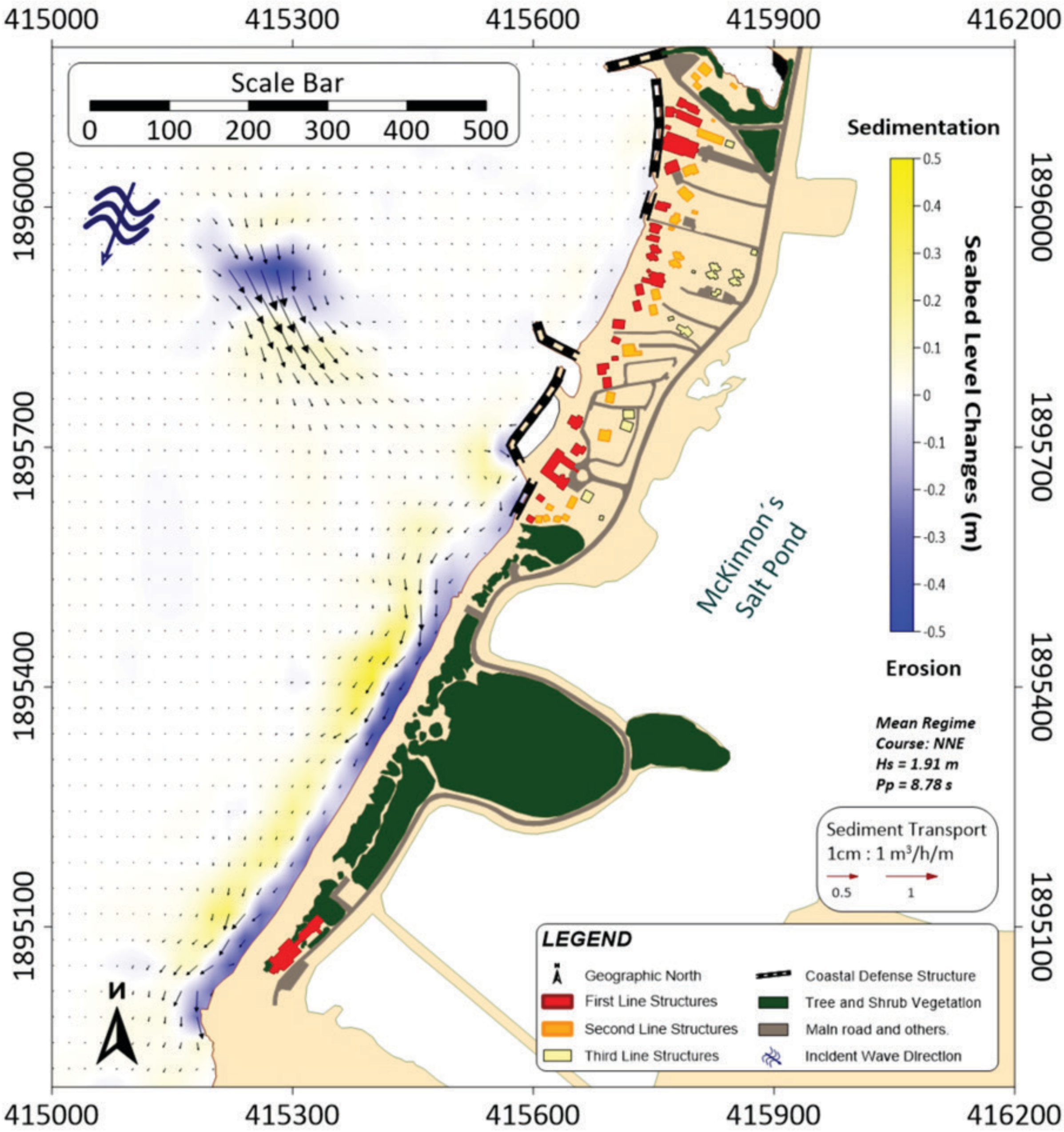



***Figure 43*** *Example of sediment transport and morphology change modelling carried out by Inversiones Gamma for the executive beach restoration project at Runaway Bay Beach in Antiagua and Barbuda. Taken from the report by Morales Diaz et al. (2022).*

these structures on the wave and circulation dynamics must be analysed under operational conditions as well as during extreme events. This is important to ensure that the structures accomplish their goal while making sure that there are no unintended consequences for nearby beaches. The impacts of any wave attenuation structures in the overall circulation dynamics of the study area should be studied closely given the importance of adequate water quality for the health of the biological organisms such as corals and seagrasses.

Numerical models are also used to estimate the expected lifetime of beach nourishment projects and the frequency of maintenance nourishment that would be required to maintain a certain beach width. When numerical models are coupled to economic models, these models can also help with the determination of the cost vs benefit ratio and whether a specific shoreline stabilization or erosion mitigation project is economically feasible.

Recent papers have also shown the use of numerical modelling to assess Nature Based Solution efficacy such as upper beach vegetation restoration to mitigate coastal erosion (Laigre et al., 2023).

For examples of project specific numerical modelling in the Caribbean and how modelling can help inform the design of beach restoration projects, the reader is referred to the aforementioned reports by Morales Diaz et al. (2022) and Izquierdo Alvarez et al. (2022).

### Summary

The selection of an appropriate numerical model for understanding coastal and beach erosion depends on the specific coastal environment and the objectives of the study. Each model has its advantages and limitations, and it is crucial to consider the complexity, data availability, and computational resources when choosing a suitable model. In some cases, it may be beneficial to combine multiple models to better capture the different processes and scales involved in coastal erosion and sediment transport.

# Chapter 6

## MEASURES FOR THE PROTECTION AND REHABILITATION OF CARIBBEAN BEACHES

The issue of coastal erosion, not just in the Greater Caribbean but globally, primarily linked to sea level rise caused by climate change, and the economic significance of beaches for many coastal nations, has underscored the necessity to explore a wide array of mitigation strategies. These strategies span from soft to hard approaches, encompassing intermediate solutions and hybrids.

### 6.1. Procedure for assessing the causes of erosion and proposals for solutions.

For the analysis of alternatives, a comprehensive evaluation of the specific site is initially required, identifying the causes of coastal erosion, the natural and artificial elements present in the area, and ensuring, as far as possible, the recovery and preservation of its natural values. According to the Manual on Artificial Beach Nourishment (CUR, 1987), the coastal processes operating in the area and specific economic interests must also be taken into account.

The methodological proposal for the rehabilitation and protection of beaches by Torres-Hugues & Córdova-López (2010) presents a scheme of how a coastal erosion solution project can be approached (Figure 44). The methodology proposed by these authors responds to a broader point of view on the design of solutions, as it contemplates a wider range of options and establishes a more detailed environmental observation process to prevent or timely respond in case coastal erosion reappears.

Similarly, the assessment of the environmental impact that the proposed solution can generate is required, considering the potential positive and negative impacts of environmental, socio-cultural, and economic types (GAMMA - ICIMAR, 2022).

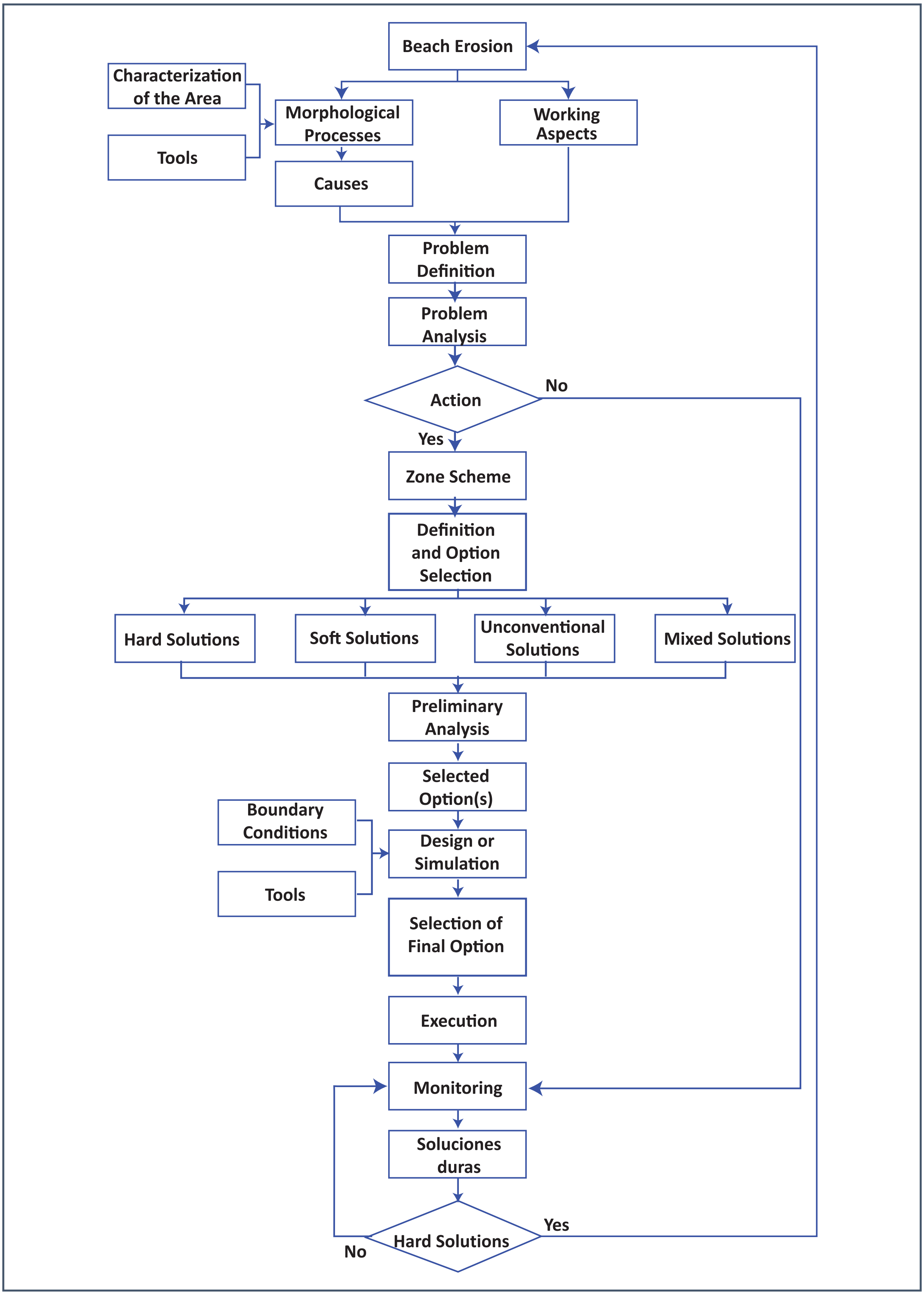



*Figure 44 Methodology for the rehabilitation and protection of beaches (taken from Torres-Hugues & Córdova-López (2010)*

### 6.2. Legal considerations.

The legal considerations that must be taken into account to carry out coastal erosion mitigation projects, depend on the legislation enforced in each country for this type of works. In general, many countries do not have clear rules in this regard that serve to clearly direct actions in this area.

For example, according to the report of GAMMA - ICIMAR (2022), there is no legislation in the Republic of Panama, based on the operation of coastal systems that limits the extension of properties on the dynamic profile of the beach. For its part, in Antigua and Barbuda there is no institutional and legal framework that promotes and guarantees the implementation of strategies and actions, aimed at the gradual restitution of the natural conditions of the beach (GAMMA, 2022). While other countries have advanced in the generation of this institutional and legal framework, moving towards erosion mitigation programs. For example, Barbados has created a Coastal Zone Management Unit (https://www.coastal.gov.bb) whose work includes the design and execution of hard and soft engineering measures for the protection, stability and improvement of beaches (Wong, 2018). The report also highlights the implementation of the Integrated Coastal Management Program of Varadero Beach in Cuba, as well as its National Investment Program for the Recovery of Beaches, as part of a State Plan for Confronting Climate Change, which was preceded by the implementation of Decree Law 212, on the Management of the Coastal Zone (GAMMA, 2022).

### 6.3. Solutions to mitigate coastal erosion.

In general, solutions against coastal erosion are divided into two large groups, hard (grey infrastructure) and soft (nature-based solutions or green infrastructure), although in recent years hybrid solutions have also become widespread, which combine aspects of both groups. Solutions based on the ecosystem, are increasingly taking more prominence. However, their main disadvantage is the slowness with which practical results are obtained for the restoration of the beach, although in the long term they can be decisive. (Wong, 2018)

**Table 3** Coastal erosion Solutions by category

| Hard solutions | Hybrid solutions | Soft solutions |
|---|---|---|
| Dikes<br>Spurs<br>Breakwater<br>Artificial breakwaters | Living Shorelines | Nature-based engineering<br>Ecosystem restoration<br>Ecosystem-based management |

### 6.3.1 Hard solutions or grey infrastructure

The hard options also called grey infrastructure, correspond to engineering with hard structures built on the beach (dikes, spurs, breakwaters or artificial breakwaters). These options influence coastal processes to halt or slow the rate of coastal erosion.

**Spurs**

A spur is a coastal structure constructed perpendicular to the shoreline from shore to sea, to trap littoral sediment transport or control littoral currents (Figure 45). This type of structure is easy to build with various materials such as wood, rock or bamboo and is normally used on sandy shores. The disadvantages are that it produces local undermining at the feet of the structures, causes erosion downstream, requires regular maintenance and usually requires more than one structure (Prasetya, 2007).

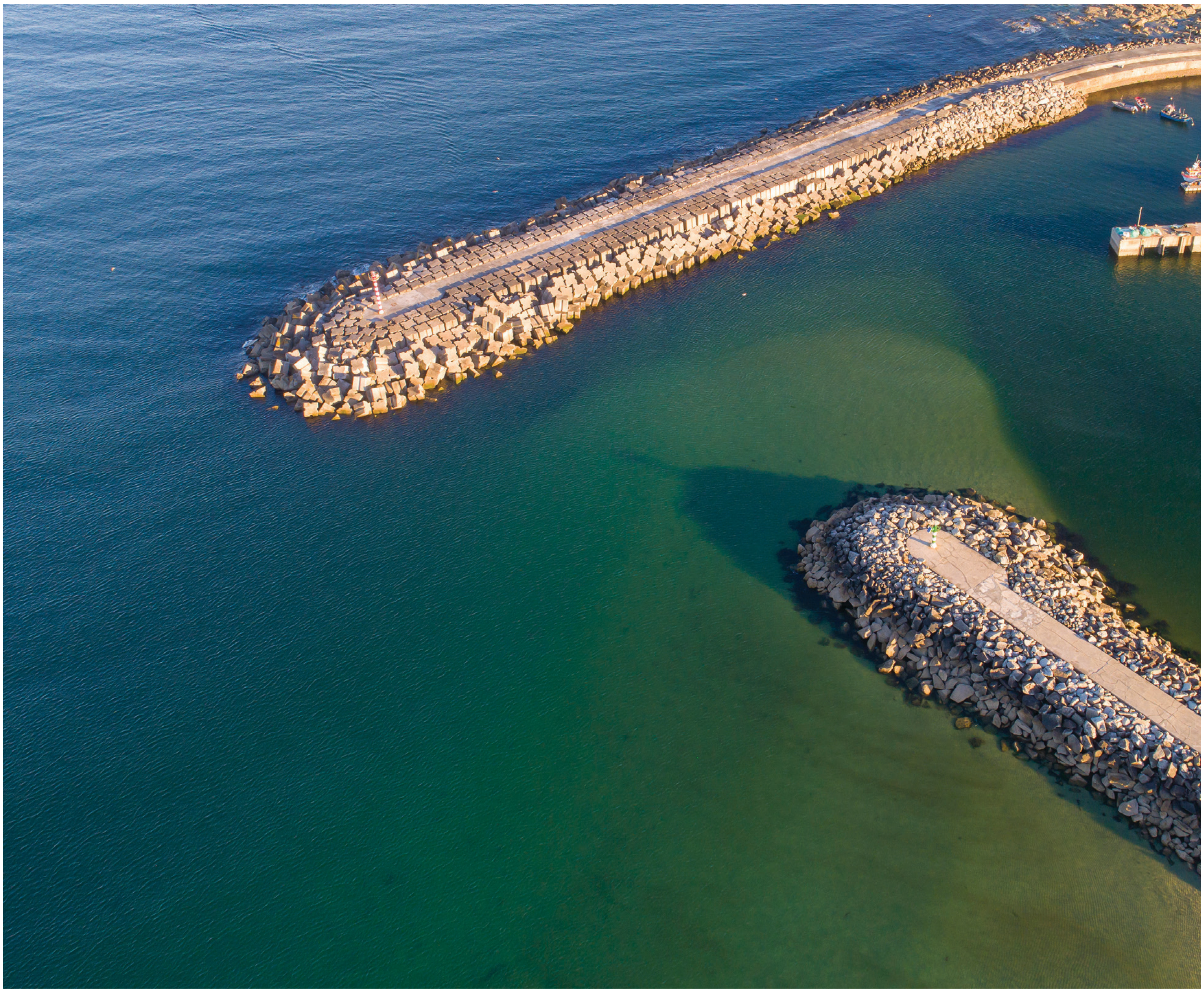


***Figure 45*** *Example of Coastal spurs*

This type of solution, which has been widely implemented in many Caribbean beaches, especially in the continental Caribbean, has multiple examples in which the expected results are not very successful compared to the real ones, generating erosion downstream. For example, the spur built on the main beach of the city of Riohacha (Colombian Caribbean) caused the restoration of the beach in about 100 m, but caused two major damages, on the one hand, the accumulation of sediments between the spur and the mouth of the Ranchería river (which provides the sand of the sector), generating a blockage in times of low water; additionally the lack of sediments downstream, due to these structures, generated a high erosion in the sectors of Jose Antonio Galán and Marbella (Ricaurte-Villota et al., 2018).

**Dike**

A dike is a structure built parallel to the shoreline that protects the shore from wave action (Figure 46). This structure has many different designs; it can be used to protect a cliff from wave attack and improve slope stability and can also dissipate wave energy on sandy shores. The disadvantages are that it creates reflections of the waves and favours the transport of sediments offshore; undermining occurs at the foot of the eroded beaches, does not favour the stability of the beach and must be built along the entire coast. Otherwise, erosion will occur on the adjacent coast (Prasetya, 2007).

***Figure 46.*** *Curved face retaining dike*

The construction of these structures includes materials such as rubble mounds, granite masonry or reinforced concrete. Depending on their arrangement, the dikes are classified into: Curved face dike, Stepped Malecon and Breakwater dike.

### Submerged breakwater

A submerged breakwater is a structure parallel to the coast (in the area near the coast) that serves to absorb waves. It reduces wave energy to its leeward and creates a ledge or tombolo behind the structure that influences sediment transport along the coast (Figure 47). More recently, most submerged breakwaters become multipurpose artificial reefs in which fish habitats develop and improve the break for water sports activities. These structures are suitable for all coasts. Their disadvantages are that they are large and relatively difficult to build, they need a special design and the structures are vulnerable to the action of strong waves (Prasetya, 2007).

*Figure 47 Submerged breakwaters)*

### Artificial breakwater

This structure is built to promote natural beaches because it acts as an artificial promontory (Figure 48). It is relatively easy to build and requires little maintenance. The disadvantages are that it is also a relatively large structure, can cause erosion downstream of the protected coastline length, and has little stability against large waves (Prasetya, 2007).

***Figure 48*** *Artificial breakwater*

### 6.3.2 Soft solutions or nature-based solutions

Some solutions that have gained ground in the field of coastal erosion mitigation are nature-based solutions. The approach of Small Island Developing States (SIDS) strategies to confront climate change is essentially adaptive. For many countries, adaptation essentially involves the design of strategies for a gradual withdrawal from the most vulnerable areas, adjusted to the foreseeable pace of sea-level rise and the monitoring of the retreat of the coastline. Although it is recognized that withdrawal, as an adaptation strategy, is not possible in many Small Island Developing States (SIDS) due to their small size, limited land and low-lying nature (Wong, 2018).

### 6.3.3. Nature-based engineering

#### Artificial beach nourishment

Artificial beach nourishment is one of the most widely applied beach restoration techniques today, owing to its environmental and landscape advantages over other alternatives based on the use of rigid structures. It is also considered one of the most successful and effective techniques. This method involves providing new volumes of sand from a nearby loan area, contributing sediment lost due to erosion back into the system. It supplies the beach profile with the necessary volume of sand and space for dynamic operation, functioning as a coastal defense (GAMMA Inversiones, 2022).

Beach nourishment solutions have been successfully implemented in Varadero beach

(Cuba) and proposed in executive beach rehabilitation projects in Runaway (Antigua and Barbuda), Bonasse Bay (Trinidad and Tobago), and Viento Frío (Panama). Some project details can be found in Chapter 6 of this handbook.

The main disadvantage of this alternative is that, although it quickly restores the sand lost over several years and revitalizes the profile's functionality, it does not directly address the causes that generated the erosion processes. Consequently, it requires periodic maintenance over the years. Despite this drawback, the rapid restoration of the profile and the avoidance of new structures in the coastal area are among its most significant advantages, making it an environmentally friendly and aesthetically pleasing solution compared to the construction of breakwaters, seawalls, or piers. Its application does not hinder the implementation of other measures in the future, if necessary, as it does not alter the basic morphology of the coastal sector or introduce costly elements that are difficult to eliminate (GAMMA Inversiones, 2022).

This type of solution comprises three main components: the definition of loan areas, the suitability of the sand to be used, and the calculation of the filling volume.

**Loan area:** This consists of the location of a loan area, marine or adjacent continental, with the volume and quality necessary to be introduced on the beach and at a distance from the area of action that is economically viable (GAMMA Inversiones, 2022).

**Suitability of the sand to be used:** Through the sedimentological characterization, both of the beach and the loan area, the granulometric composition and genesis of the sand are established, whose results allow the delimitation of areas with better possibilities for its use in restoration work (GAMMA Inversiones, 2022).

**Calculation of the volume of filling:** International experience shows that various criteria are used to estimate the volume of filling, although there is agreement that the density of discharges should not be less than 60 $m^3$ per linear meter of beach (Juanes, 1996). For the design of the beaches, a formula is used that determines the equilibrium profile from the conditions of waves and given sediment. When artificial feeding is performed, the injected sand is distributed along the entire profile within the break zone to a depth known as the active profile closure depth (h*) (GAMMA Inversiones, 2022a). The quantitative assessment of the volume of additional fill that is required to obtain the real dimensions of the project is carried out, taking into account the losses of sand that can be produced by natural selection, sediment transport and redistribution by grain sizes (GAMMA Inversiones, 2022a), using the calculation of the overfill factor RA according to the methodology proposed in the *Shore Protection Manual* (Army Coastal Engineering Research Center, 1984) and in the *Manual on Artificial Beach Nourishment* (CUR, 1987).

***Figure 49*** *Feeding a beach with dredge*

## Sandbags and Geotubes

Sandbags are a common solution against coastal erosion, often stacked along the coast to provide protection against waves and sea-level rise. The advantages include their typically economical and accessible nature as a solution against coastal erosion. However, the disadvantages arise from their synthetic material composition, despite their natural appearance. Additionally, as they are usually filled in situ, any perforation in the sandbags can severely compromise their resistance.

Geotubes, which are high-strength sandbags made from various geotextile fabrics (Figure 50), offer an alternative. The chosen fabric determines the strength and porosity of the solution against coastal erosion, and they are filled with various materials, stacked in place, and covered with sand and vegetation. Geotubes provide the benefits of offering structure and stability to the coast, increasing the surface resistance of the sand, and dissipating wave energy. They can be integrated with native plants, reinforcing the coastline and creating a more natural environment. However, a potential disadvantage is their exposure over time or after a storm. While this does not necessarily compromise the product's functionality, it may be less attractive for coastal communities aiming for a natural coastline (Colonial Construction Materials, 2022).

***Figure 50:*** *Geotubes in beach area (Taken from Geosolutions)*

### 6.3.4. Ecosystem restoration methods.

These methods aim to work with the physical environment and complement it, using natural coastal defense methods. They use ecological principles and practices that have a lower negative impact on the natural environment and generally a lower cost.

#### Restoration of coastal dunes and their vegetation

Coastal sand dunes are renowned for their ecological functions and aesthetic qualities, constituting a unique habitat with high biodiversity value for flora and fauna. Moreover, they are recognized for their protective abilities, acting as a natural barrier against floods caused by storm surges and waves (D'Alessandro et al., 2020). The dune vegetation restoration strategy takes into account the natural zoning in plant species that reflects their tolerance to different salinity levels of the substrate, with herbaceous plants being those that tolerate the highest levels of saline aerosol (GAMMA, 2022).

Similar to other coastal erosion mitigation alternatives, it is crucial to understand the dynamics of the coast and determine the availability of a sand source for dune construction before initiating any restoration phases (Lithgow et al., 2014).

The restoration of dune systems (Figure 51) involves six basic steps: the elimination or control of sources of degradation, topographic recovery, recovery of vegetation (when necessary), site protection, disclosure, and long-term monitoring (Ley-Vega et al., 2007).

***Figure 51*** *Dune Restoration Activity*

This type of measure has been successfully implemented in various parts of the Caribbean, such as Cuba and Mexico, for example, on the beaches of the Riviera Maya in Mexico, the project "Adaptation to climate change based on ecosystems with the tourism sector" (ADAPTUR) has been successfully developed, in which the restoration of dunes was implemented with various types of strategies, including reforestation with varied and stratified species1.

## Restoration of coral reefs and seagrass beds

Using the coastal protection service provided by submerged coastal ecosystems such as coral reefs and seagrasses, which is based on the principle that these ecosystems dissipate wave energy by breaking waves or friction through reef structures and thus protect coastal areas (van Zanten et al., 2014). Coral reefs also produce fine sand that feeds coastlines and retains sediment (Bellwood, 1995; Reguero et al., 2018), while seagrass meadows further stabilize sediment through their dense layer of rhizomes and roots, even in extreme wave events (James et al. 2021).

This type of initiative is being carried out successfully in several Caribbean countries, such as Cuba, Mexico, Costa Rica, Dominican Republic, Colombia, among others. Although it is true that there are still no conclusive results on their effectiveness in reducing coastal erosion, the exercises carried out so far involve various local actors in the regions, such as tourism operators and fishermen, which generates strategies to reduce the vulnerability of coastal inhabitants, as in the case of the Colombian project "A million corals for Colombia"[2].

***Figure 52**:A marine scientist conducting a coral restoration project in a damaged reef ecosystem*

1 https://adaptur.mx/
2 https://cop26.minambiente.gov.co/un-millon-de-corales-por-colombia/

### 6.3.5. Coastal management strategies.

Part of the problem of coastal erosion is due to anthropic causes such as sand extraction, disorderly growth of coastal areas, poor construction of coastal protection infrastructure, destruction of coastal ecosystems such as dunes, coral reefs, seagrass meadows, among others; which in addition to losing their ecosystem service of sediment provision and retention, diminishes their ability to protect coastlines from coastal threats such as hurricanes, levy seas, tsunamis and other extreme events. Some of the alternatives for the protection and rehabilitation of beaches are related to coastal zone management strategies, which guarantee that their resources are used rationally while preserving their beauty and natural processes.

#### Coastal planning and public policy tools for coastal erosion

Planning for the future development of the coastal zone, at a safe distance behind the beach, will reduce the need for costly defensive measures in the future (Cambers, 1998).

A practical approach to managing both compatibilities and incompatibilities in the marine environment in view of development pressure and growing interest in nature conservation is Marine Spatial Planning (MSP), which is a management tool for the allocation of the spatial and temporal distribution of human activities in maritime spaces in order to achieve ecological, economic and social goals that have been specified through a political process (Ehler and Douvere, 2013). It determines how, when and where the activities will be developed, to meet the objectives proposed for a given area, respecting the uses of marine space and integrating the demands of development with the need to conserve the environment. MSP can be implemented in an area through a sequence of ten steps, which are described in Figure 53.

#### Integrated Coastal Zone Management (ICZM)

Integrated Coastal Zone Management (ICZM) is a concept that has been around for more than 30 years since its inception. However, it was not until the Earth Summit in Rio de Janeiro (Brazil) in 1992 that it was globally embraced as the central concept for the management of coasts and oceans (Steer et al., 1997). In many ways, it is similar to Marine Spatial Planning (MSP); for example, both are comprehensive, strategic, and participatory, aiming to maximize compatibility between human activities and reduce conflicts between human uses and nature (Ehler and Douvere, 2013).

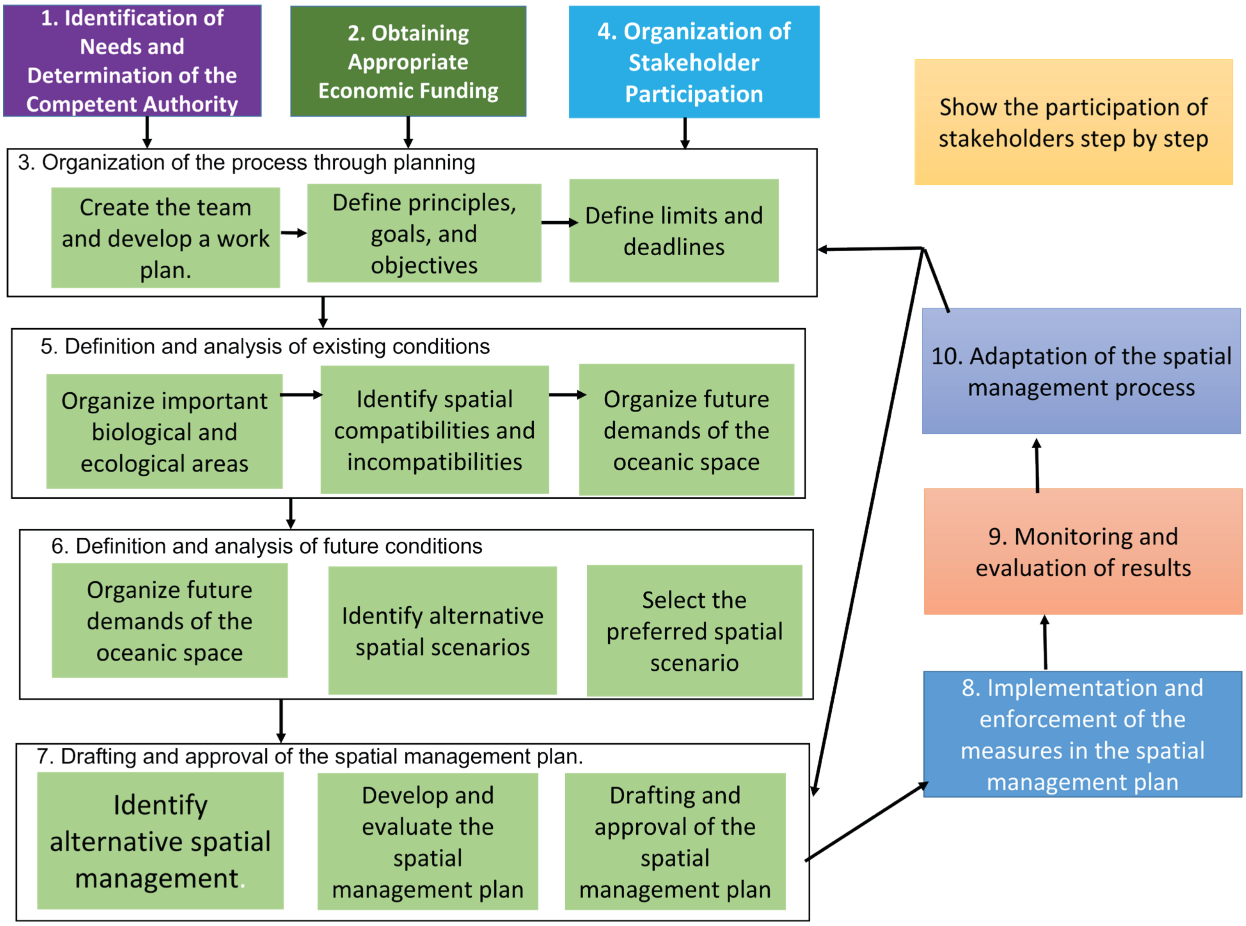



*Figure 53. Step-by-Step Guide to the Marine Spatial Planning Process (Adapted from Ehler and Douvere, 2013).*

ICZM aims to guide the development of coastal areas in an ecologically sustainable way. ICZM programs must be guided by the Rio Principles, with an emphasis on equality between generations, the precautionary principle, and the "polluter pays" principle. ICZM must have an interdisciplinary and holistic nature, particularly concerning Science and Policy. The primary goal of ICZM is sectoral and intergovernmental integration, and for this, institutional mechanisms for effective coordination between the multiple levels of government operating in the coastal zone are fundamental. These mechanisms must be tailored to fit perfectly within the specific and unique context of each national government (Steer et al., 1997).

## Environmental education

Finally, environmental education constitutes, together with scientific research, a primary tool for achieving environmental awareness, which is necessary for the sustainable management of coastal and marine affairs and spaces (González-Ruiz et al., 2003).

In the same way, it arises as a need of humans to face the environmental crisis. It is required that society understands the complex nature of the environment, as a result of the interaction of social, biological, physical and cultural aspects, so that education represents the fundamental basis of long-term development (Bautista-Zúñiga, 2013), with communities actively participating in the care and preservation of their coastal and marine areas.

### 6.3.6 Hybrid solutions

#### Living Shorelines

Living Shorelines refer to a number of “soft armour” techniques used to stabilize coastlines and protect or enhance natural features. These techniques seek to control erosion and flooding by recreating or enhancing natural coastlines through vegetation and other natural or organic materials. Hybrid techniques combine vegetation, such as marsh plants and submerged aquatic vegetation, with harder materials to add structure and stability, such as oyster shells, biological (erosion control products made from biodegradable natural materials) material or rocks. Benefits include erosion control and flood protection, while increasing tidal connectivity with minimal disruption to normal coastal processes (Massachusetts Wildlife, 2017).

### 6.3.7. Cost vs. benefit analysis

The choice of which sites should be defended and how it is done is based on a cost-benefit analysis, especially if one takes into account the widespread problem of coastal erosion along the coasts of the countries; which is why the prioritization of the sites to intervene is required.

To evaluate the different management alternatives, economic, environmental, and recreational protection against extreme events and resource impacts must be taken into account (Figure 54). In terms of economic impacts, direct and indirect costs are evaluated. Direct costs are the estimated construction costs to implement a strategy, whether public, private or mixed, while indirect costs are the economic repercussions of each strategy: loss or gain of land or property, economic activity, etc. Additionally, consideration of impacts on the environment, recreational activities, storm protection and the resources needed for their implementation provides a more comprehensive comparison between strategies (Porro et al., 2020).

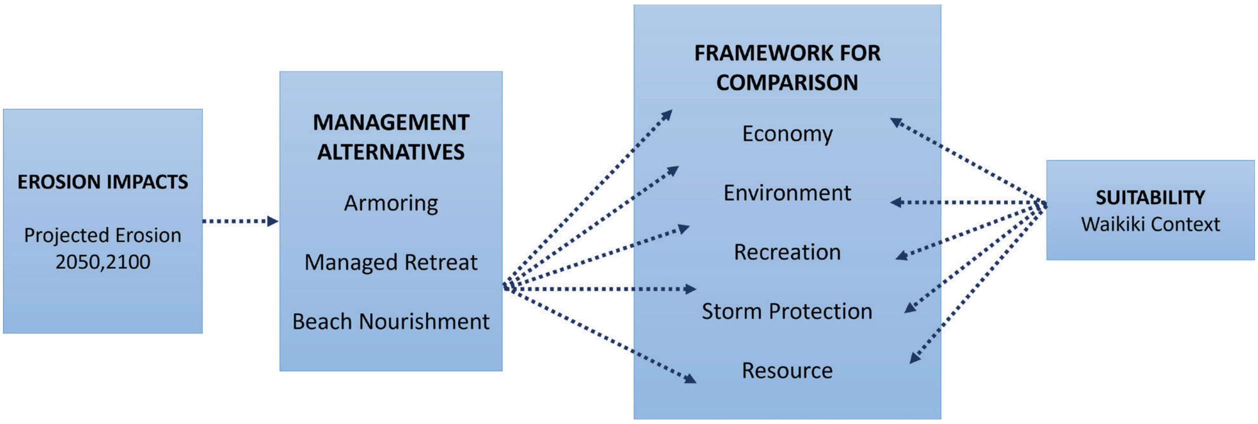



*Figure 54 Framework for assessing the impacts of erosion management alternatives (Taken from Porro et al., 2020).*

# Chapter 7

## LESSONS LEARNED IN THE DEVELOPMENT OF THE SANDY SHORELINES PROJECT

In this chapter of the guidebook, a review of the execution of the actions of each component of the project is conducted with the aim of drawing lessons in organizational, conceptual, methodological, and logistical aspects. These lessons enable a better elaboration of tasks for future national and regional projects, ensuring the continuity of investigations into the effects of climate change on the sandy beaches of the Greater Caribbean and the adoption of the best measures for their confrontation.

### 7.1. Component 1. Establishment of focal points for participating countries.

The activities conceived in Component 1 had an organizational-methodological character. In each participating country, the institution that would assume the responsibility of coordinating activities at the national level and sustaining the required exchange of work with the ACS was defined, and the network of Focal Points of the project was established.

In the third face-to-face meeting of Focal Points held in Panama in August 2018, the "Project Profile for the Elaboration of the National Plan for the Coastal Erosion Process" was analysed and approved, which reflects the organizational procedure for the conduct of tasks at the national level.

The subsequent progress of the project work showed that the National Plan was methodologically well conceived and became the reference document to evaluate the progress of the tasks to be carried out by the Focal Points in each country. In this regard, the following lessons learned can be noted:

**COMPONENT 1**

- The National Plan should better define the commitment and responsibility of the institutions that collaborate with the Focal Point in the execution of the project and in particular, in the areas of training and field work of the monitoring network.

- The annual schedule should define more precisely the tasks of the project and the institution responsible for its implementation.

- The quarterly check of compliance with the National Plan should be the main tool to control the progress of the project by the project management.

## 7.2. Component 2. Institutional capacity building and human resources.

The project's training program included the participation of specialists from the Focal Points in 3 internationally renowned events on coastal issues, as well as a working visit to the Korea Institute of Ocean Science & Technology (KIOST). The participation in these events served to update the most advanced topics of research on coastal erosion processes and the impact of sea level rise, as well as the engineering alternatives that are currently applied to confront them.

In 2018, a training activity was developed in Panama with the participation of some 30 specialists from the region, which included the teaching of the postgraduate course "Coastal Processes and Methodological Criteria for Beach Recovery," a sedimentology seminar by Cuban specialists, and three conferences given by experts from Colombia, Barbados and Korea. Both the postgraduate course and the sedimentology seminar were taught in the three countries where the beach rehabilitation projects were developed.

While all activities developed under Project Component 2 were successfully assessed, the following lessons learned can be noted:

**COMPONENT 2**

- Training activities are more effective when they are developed in each country because a greater number of participants is achieved and practical tasks are carried out with case studies of national interest.

- Training should meet the needs of each country and include training in the use of equipment acquired for field and laboratory work.

- Training should include training in interpreting the results of monitoring work.

- Training activities should be part of the National Plan of each country and involve universities.

- Expand and systematize the exchange and technical consultations between the specialists of the Focal Points, the technical coordinator and the specialists of the Technical Advisory Group (TAG).

### 7.3. Component 3. Establishment of the regional erosion monitoring network.

One of the objectives proposed by the "Sandy shorelines" project was the updated evaluation of the intensity, extent and causes of erosion on Caribbean beaches; for which it was considered necessary to establish a regional monitoring network that would ensure long-term measurements and allow evaluating the effect of sea level rise.

In order to standardize the criteria for the establishment of the monitoring network, the methodological documents were prepared and analysed with the Focal Points: "Procedure to follow for the selection of the beaches of the monitoring network," "Worksheet to form the inventory of the beaches," and "Guide for the preparation of the beach inventory sheet" that would serve as a reference for the realization of the fieldwork and the preparation of the reports of the progress in the work of the network.

From the beginning of the "Sandy shorelines" project, it was always understood that the establishment of the regional network would be a complex task in view of the technical, organizational and logistical difficulties that would have to be overcome. What was unforeseeable is that in the period of execution of the project, a global pandemic would appear that would make it even more difficult to carry out the tasks, especially the acquisition of the equipment requested by each Focal Point.

Despite these drawbacks in the virtual meetings with the Focal Points, the verification of the progress in the establishment of the network was always included in the agenda and with the reports prepared by each country, a comprehensive report was prepared in January 2023, in which the main weaknesses of the national reports were pointed out and the difficulties encountered by each Focal Point in carrying out the work were collected. On the basis of which the following lessons learned can be identified:

**COMPONENT 3**

- The Focal Points have identified a need for an increase in technical personnel and the broadening of collaborative partnerships with other institutions, including universities and specialized centres.

- The acquisition of the new equipment must be entrusted to a company specialized in import services to expedite negotiations with suppliers and the transportation process.

- It is pointed out as a need of the Focal Points, the increase in logistical and financial support for the development of the field work of the network.

- Plan and systematize the supervision of the development of the work of the monitoring network and the interpretation of its results by the technical coordinator and the specialists of the TAG.

### 7.4. Component 4. Elaboration of 3 beach rehabilitation projects as "case studies".

In the conception of the "Sandy shorelines" project, it was considered appropriate to include the preparation of three beach rehabilitation projects in places with different characteristics that would exemplify in some way the diversity of the beaches of the region and the generalized nature of the problem.

For the selection of the sites to develop the "Case Studies," the project management, in consultation with the specialists of the TAG, elaborated a procedure that was subsequently approved by the Focal Points and consisted of the following steps:

1. Elaboration by the project management and the TAG of the criteria and commitments to be followed by the Focal Points to make the proposal of the site to be selected.

2. The criteria to be followed by the TAG to evaluate the proposals of the Focal Points.

3. Visit of TAG specialists to the selected sites for the verification of the information evaluated.

The three steps indicated were satisfactorily completed and the beaches of Viento Frío in Panama, Runaway Bay in Antigua and Barbuda, and Bonasse Bay in Trinidad and Tobago were selected.

The three executive beach restoration projects were in charge of the environmental services company, GAMMA S. A. belonging to the Ministry of Science, Technology and Environment of Cuba, (CITMA) and were conceived under four basic principles:

1. The study of the processes and functioning of the coastal system for the correct identification of the causes of erosion.

2. The evaluation of regulatory and management measures to eliminate or minimize as much as possible, the anthropic causes of erosion.

3. The reduction to the indispensable hard engineering solutions.

4. The evaluation of the feasibility of reconstruction of the natural conditions of the beach with artificial sand feeding and ecosystem-based adaptation.

The application of this practice has been highly satisfactory on Cuban beaches, both for the maintenance of the natural and aesthetic conditions of the beach, and to achieve the protection of the new hotels by the reconstructed and reforested dunes. An example of these results can be seen in Figure 55 which depicts a designed dune aimed at safeguarding the IberoStar Hotel from extreme erosive events and sea level rise at Varadero Beach, Cuba, in July 2015 on the left and on the right, the same scene just a few days after the passage of Hurricane Irma in September 2017, highlighting the protective role of the dune in preserving hotel facilities and maintaining the recreational and aesthetic conditions of the beach.

***Figure 55*** *Restoration project of Varadero beach .*

# Chapter 8

## RECOMMENDATIONS FOR DECISION MAKERS

As stated at the beginning, the purpose of this document, a "Guidebook for the Protection and Rehabilitation of Greater Caribbean Beaches," is to provide a simplified guide to understand a common problem worldwide, with a focus on the Caribbean region. The beach erosion problem affects many islands in the region physically, socially, and economically. The information is intended to be useful to specialists, decision-makers, and the general public. We are aware that there are many specialized and comprehensive well-written manuscripts that consider the beach erosion problem, and the purpose of this document is to be a rather simple guide.

In **Chapter 1**, the introduction recounts how a meeting addressing 'Challenges, Dialogues, and Cooperation for the Sustainability of the Caribbean Sea' served as the catalyst for seeking funding to address these concepts in the Caribbean Region. The project was financed by KOICA, the International Korean Agency, and comprised eight objectives. Notably, one of these objectives was to develop a 'beach rehabilitation manual with scientific and engineering criteria tailored to the unique characteristics of tropical beaches in the Caribbean region.' This objective later materialized as Component 5, titled 'Preparation of the Beach Rehabilitation Guidebook for the Caribbean.' The project involved nine Caribbean countries—Antigua & Barbuda, Costa Rica, Cuba, Dominican Republic, Guatemala, Haiti, Jamaica, Panama, and Trinidad and Tobago—and some of their experiences are shared within this guide.

**Recommendation for policy and decision-makers:** In instances of emerging challenges, it is advisable to seek consultation from experts and conduct a thorough assessment to ascertain whether the issue has local or regional implications. Collaborating with other nations facilitates the exchange of diverse expert opinions and potential solutions, thereby enhancing the likelihood of securing funding for problem resolution. Furthermore, acknowledging the value of sharing experiences, including those that did not yield solutions, is crucial, as these insights contribute significantly to the collective understanding of effective problem-solving strategies.

**Chapter 2**, Definition of beach, states the definition and concepts used in the study of Sandy Beaches and avoids misunderstandings and misconceptions, setting the standard in terminology applied to the Caribbean region. It is important to have a common description of the type and size of the materials found on sandy beaches, as well as the clear identification of the dynamic erosion and accretion process that modify these areas. Several examples are given showing some of the Caribbean beaches. The legal aspects and laws related to shorelines were discussed, stressing the importance of having local, state, or nationwide legislation in this matter. Not all the countries in the Caribbean region have laws that oversee the regulation of shorelines.

**Recommendation for policy and decision-makers:** Identify the specific terminology and concepts related to sandy beaches in the national context. Aim to harmonize these terms and align them with regional concepts and terminology for a unified understanding. Investigate the presence and enforcement of regulations or laws concerning shorelines. If such legislation is absent, consider consulting the regulations in place across various Caribbean countries and actively advocate for their adoption. Understand whether the processes affecting shorelines are natural or anthropogenic, and determine the responsible entities for their remediation

**Chapter 3**, Erosion on Caribbean beaches, deals with the understanding of erosion and accretion processes in sandy beaches. Some geographic variations of coastal erosion in the Caribbean are discussed. Each beach process is different, and all the different factors must be considered when comparing coastal beaches of other regions of the world. As it has been mentioned, many beaches in the Caribbean countries are touristic sites, thus the impact of erosion or accretion phenomena may have a very important economic change that could be temporary or permanent.

**Recommendation for policy and decision-makers:** It is important to understand the processes of erosion and accretion that happened on a beach. By talking to the local population or authorities about the state of the beach years ago or asking for old photographs, one may have an idea of the changes that have occurred in an amount of time. Because we have the impact of severe phenomena such as storms or hurricanes in the Caribbean region and we are subjected to gradual changes due to climate change, thus the remedy actions require different strategies. Determine the economic value of the region and assess the potential repercussions in the event of beach erosion or accretion, considering variations in onset (gradual or sudden) and intensity (light to severe). Quantify the potential impact on individuals, residences, hotels, businesses, infrastructure, and facilities, considering the duration and extent of these effects.

In **Chapter 4**, Coastal erosion monitoring, it is essential to know the components of the beach and its profile, to determine the conditions and how it will behave in case of important or extreme hydrometeorological events. Beaches below the waterline must be monitored in calm conditions, and the part above the waterline, for instance, the sand-vegetation boundary, before and after the passage of an important event. Natural and anthropogenic processes must be considered and analysed to select the adequate and reliable erosion monitoring system. The selection of a beach to be monitored for erosion is based on several criteria: geographical, morphological, hydrodynamic, and the social factors to identify sensitive and vulnerable sites. Field measurement types and sampling methods are presented, in order to have a quantitative measurement of the beach erosion process.

Topography based on photography, a handheld GPS, construction of monuments and site scopes, tacheometer, theodolite, and differential GPS or GNSS system, are all instruments used to monitor the beaches. Some will be done manually, and its frequency of measurement will depend on the availability of personnel and resources. Other systems are automatic and they may be sending information to a monitoring site on a regular basis. Other techniques such as the use of aerial or satellite images or drones can be used. Bathymetric measurements are also very valuable but rather expensive, although now there are nautical drones designed to do this type of analysis. Monitoring the sedimentology, the size and material of the grains that compose the beach is important to understand possible changes. This work has to be done manually and as frequently as possible.

The hydrometeorological events occurring at the monitoring site are now done with stations that measure frequently and transmit their information to a remote centre, where they may be analysed and studied. Change in water level and current measurements are a very important parameter, and depending on the morphology of the site, they will be different. The chapter shows “Table 2: Synthesis of monitoring methods and tools” with the methods and approximated cost of the monitoring. The cost of the instrumentation listed on the table is about US$160,000.

**Recommendation for policy and decision makers:** in order to select the sandy beaches to monitor, it is important to prioritize based on those where most of the mentioned parameters can be measured regularly and to have a centre for concentration and analysis of all the collected signals. Also it should be based on the importance of the social and economic impact that erosion of the beach can present in the short and long term, in order to establish mitigation procedures. Evaluating the possible economic cost of losing a touristic sandy beach will be important, as compared the mentioned monitoring cost, and possible remediation actions. The consideration of a national monitoring network, that includes the instrumentation, plus the interpretation of data, should be considered, as well as the training of staff.

**Chapter 5**. An overview of numerical models and their role in understanding and mitigating coastal erosion.

Numerical models allow us to understand the dynamical behaviour of the costal systems, their erosion processes and to design beach protection plans or projects. In order to use these computational tools, we need to have data to be supplied to the program, and the more information we provide, the better results. The chapter does not intend to teach the use of a particular numerical model, but rather to describe some of the models and their attributes and requirements, such as: a) determination of the model domain, b) collection of input data, c) Pre-processing data, e) set up the model, f) execution of the model, and g) post-processing and result analysis. Several analyses can be conducted using numerical models. Wave modelling, for instance, delves into wave physics, utilizing data like wind speed, atmospheric pressure, ocean currents, and bathymetry to forecast wave characteristics such as height, direction, and period. Other numerical models focus on describing water currents' motion and circulation, aiding in determining water level fluctuations and sediment movement. Additionally, sediment transport and coastal erosion modelling help comprehend the coastal shaping process and evaluate the efficacy of coastal restoration efforts.

The Chapter describes a good number of numerical models, to give an example of their characteristics and requirements. This information will allow decision makers to foresee what type of analysis can be obtained as well as their limitations.

**Recommendations for Policy and decision makers**. Initially, it is essential to identify and comprehend the type of data to be analysed, such as wave behaviour, current circulation, or sediment transport, along with their intended use and benefits for the projects. Subsequently, it's crucial to determine the necessary information for your project to be modelled, considering its availability, cost, format, and compatibility with the required format for numerical simulations. Assessing the adequacy of available data and computer resources is also important. Once the numerical model is executed and results are obtained, interpretation follows, including an evaluation of accuracy and precision.

It is worth noting that there's no one-size-fits-all numerical model; selection depends on the specific problem and available information, with each model presenting its own set of advantages and disadvantages. In many cases, optimal results may necessitate the utilization of multiple numerical models.

**Chapter 6**. 'Measures for the protection and rehabilitation of the Greater Caribbean beaches' notes that, in formulating measures for the protection and rehabilitation of Greater Caribbean beaches, it is crucial to give due consideration to legal aspects pertaining to beach line definition and erosion remediation. This ensures that the proposed actions are not only supported but also guaranteed by the government. It is noteworthy that several Caribbean countries lack specific regulations in this regard; however, Barbados serves as a positive exemplar with its well-established Coastal Zone Management Unit.

Identification of the erosion processes occurring at the beach to propose a remediation method is needed to decide on: hard solutions (grey solutions), soft solutions, hybrid conventional solutions, or mixture of solutions. The type of hard or grey solutions (spurs, containment dams, submerged breakwaters, artificial breakwaters) are remediations that require infrastructure, may be costly and in some cases produce erosion and accretion in specific parts, and have a visual impact.

Soft solutions or nature-based solutions are becoming more appealing such as: artificial sand feeding, sandbags, and geotubes, although they require a loan area, suitability of the material and the required volume. The ecosystem restoration methods, with a lower negative impact on nature and usually with a lower cost, are a very appealing solution. Some of these methods are restoration of coastal dunes and their vegetation, and restoration of coral reef and seagrass beds.

Hybrid restoration solutions combine enhancing natural coastlines using vegetation and other natural components, with harder materials to add structure and stability. The cost vs. benefit analysis must consider economic, environmental, recreational, and protection against stream events, to make the adequate and plausible solution.

**Recommendation for policy and decision makers**: Several critical considerations must be taken into account, including the necessary studies, cost/benefit analysis, and the timeline required for implementing remediation, along with estimating its duration. Achieving a flawless and permanent remediation is often elusive; thus, a judicious combination of various techniques frequently represents the optimal solution. It is imperative to allocate sufficient time and seek expert advice to make informed decisions.

**Chapter 7**, titled “Lessons Learned in the Development of the Sandy Shorelines Project,” delves into the investigation of the impact of climate change on sandy beaches in the Greater Caribbean. This chapter serves as an illustrative example of the actions taken to transition from problem analysis to the establishment of a comprehensive system for studying and monitoring sandy beaches in the region. The six components of the project provide a structured protocol, offering guidance for achieving similar goals.

**Component 1**, the Establishment of Focal Points for Participating Countries, is essential to identify optimal partnerships in each country. This involves assessing interest from research centres, government entities, or a combination of both, depending on local conditions.

In **Component 2**, focusing on Institutional Capacity Building and Human Resources, emphasizes the significance of tailored training for participants in accordance with the unique needs of each country. The goal is to maximize participation and includes on-site visits to selected beaches as part of the project.

**Component 3**, which pertains to the establishment of the Regional Erosion Monitoring Network, requires careful consideration of various factors when selecting sites and forming the erosion monitoring network. These considerations encompass legal aspects, socio-economic impact, training for personnel responsible for equipment and data processing, expected project duration, and operational costs. While difficulties in execution were anticipated, the unforeseen challenge of a pandemic further complicated the process.

**Component 4**, involving the Elaboration of Three Beach Rehabilitation Projects as “Case Studies,” specifically selected Viento Frio in Panama, Runaway Bay in Antigua and Barbuda, and Bonasse Bay in Trinidad and Tobago. These locations met the established requirements set by GAMMA, a Cuban company with extensive experience in the field.

**Recommendation for policy and decision makers:** Establish and sustain capacity-building initiatives, prioritizing investments in training individuals for equipment maintenance and data processing and interpretation. While selecting superior equipment may incur higher initial costs, it proves to be a judicious decision over time. Anticipate financial requirements, encompassing not only equipment procurement but also the ongoing operational needs of the monitoring network.

# Appendices
# Erosion on Caribbean beaches

Appendix A: Oceanographic data sources for conducting metocean studies (Lead author: Miguel Canals)

- Regional models (ECWMF, GFS WAVE, others)
- Operational buoys
- Need for expanding buoy and observational networks

Appendix B: Oceanographic numerical models used to understand erosion processes and design beach protection projects (Lead author: Miguel Canals)

Numerical wave models

- Coastal circulation models
- Coupled wave/current/sediment transport models
- Beach erosion and dune breaching models

## 7.5. Appendix A: Oceanographic data sources for conducting metocean studies

Historic wave model data plays a crucial role in understanding the effects of wave climatology on beach dynamics, sediment transport, and coastal erosion. These data provide information on the patterns and trends of wave activity over time, allowing researchers to identify annual wave cycles as well as multi-annual variability that shapes beaches. This information is important for coastal managers, engineers, and decision-makers, as it can inform the development of strategies to mitigate coastal hazards and reduce the impact of extreme weather events on coastal communities.

Annual wave cycles can significantly impact beach morphology, particularly in regions such as the Caribbean Sea, which is prone to tropical storms and hurricanes as well as long period winter swells. These events generate high-energy waves that can result in significant sediment transport and erosion. Understanding the patterns of wave activity during different seasons can help researchers identify the periods when coastal erosion is most likely to occur and develop appropriate mitigation measures.

Multi-annual variability, such as El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO), can also play a significant role in shaping coastal morphology. These climate phenomena can result in changes in wave activity which can cause significant changes in sediment transport and erosion patterns. By analysing historical wave model data, researchers can identify the impact of these phenomena on coastal morphology and develop strategies to mitigate their effects.

To help researchers and coastal managers better understand the patterns and trends of wave activity in the Caribbean Sea, several wave models are available that provide historical wave model data. These models allow users to access information on wave activity over time and provide insights into how wave climatology shapes coastal morphology. The availability of these data and the insights they provide are essential for developing effective coastal management strategies that reduce the impact of coastal erosion and mitigate the effects of extreme weather events.

Here are some of the most commonly used wave models that can provide historical wave model data in the Caribbean Sea, along with links to the websites where users can download the data:

- WAVEWATCH III: The National Centres for Environmental Prediction (NCEP) provides historical WAVEWATCH III data for the Caribbean Sea region on their website. The data can be accessed at: https://polar.ncep.noaa.gov/waves/download.shtml

- The National Centres for Environmental Prediction (NCEP) have introduced an advanced wave forecasting model known as the GFS WAVE model. This state-of-the-art numerical model incorporates the latest understanding of oceanographic and meteorological processes, leading to more accurate wave predictions and improved understanding of wave dynamics in various marine environments. The GFS WAVE model combines high-resolution wind data from the Global Forecast System (GFS) with sophisticated wave modelling techniques, enabling it to predict wave heights, periods, and directions with greater precision.

- ECMWF-WAM: The European Centre for Medium-Range Weather Forecasts (ECMWF) provides historical ECMWF-WAM wave model data for the Caribbean

Sea region on their website. The data can be accessed through their Climate Data Store at: https://www.ecmwf.int/en/forecasts/datasets/set-ii

- The Caribbean WaveWatch 3 wave model (Figure 56 below) found at http://ww3.cimh.edu.bb is a regional implementation of the global WaveWatch 3 wave model specifically designed for the Caribbean Sea. It simulates wave heights, wave directions, and wave periods using input data on ocean currents, wind speed, and atmospheric pressure. The model provides high-resolution wave forecasts up to three days in advance, making it a valuable tool for marine safety, coastal management, and planning activities such as shipping, tourism, and offshore operations.

There are also several oceanographic buoys in the Atlantic Ocean and in the Caribbean Sea that may be useful for understanding wave activity, especially when combined with model output. The National Data Buoy Center (NDBC; https://www.ndbc.noaa.gov ) maintains a network of buoys in the Atlantic Ocean and Caribbean Sea, providing invaluable data for understanding wave characteristics of Caribbean beaches. These buoys are strategically placed to continuously collect and transmit vital oceanographic and meteorological data, such as wave height, wave period, and wave direction, which are crucial for researchers, coastal managers, and policy makers in assessing beach dynamics and coastal processes. The real-time information gathered by the NDBC buoys contributes to better forecasting of coastal hazards, such as storm surges and erosion, enabling more informed decision-making on coastal protection and mitigation strategies. Additionally, the data collected by these buoys can be used to calibrate and validate numerical models, helping to improve the accuracy of predictions regarding climate change impacts and long-term trends in the region's coastal environments.

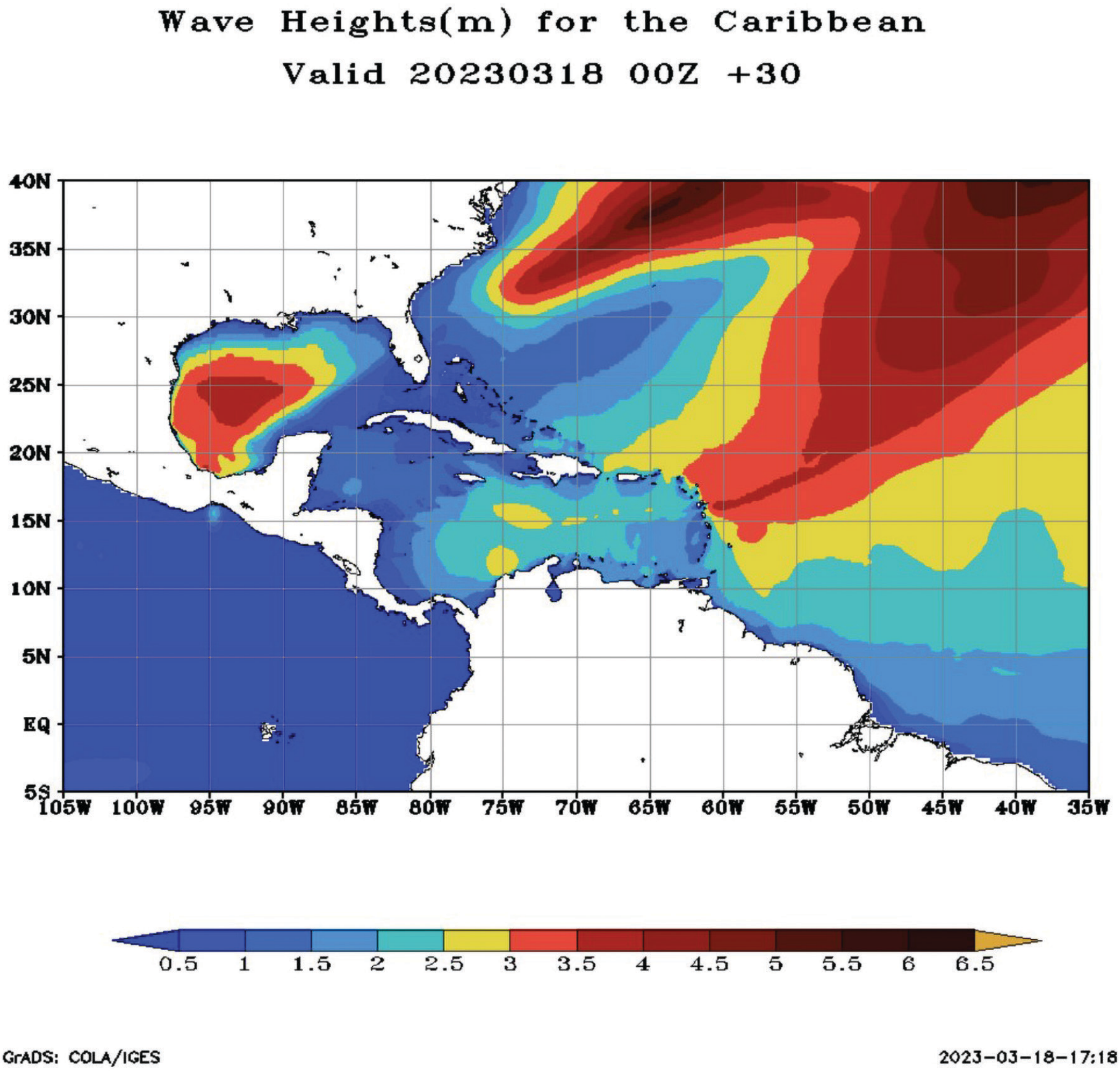



***Figure 56*** *Caribbean WaveWatch 3 wave model © Copyright - Caribbean Institute for Meteorology and Hydrology*

## 7.6. Appendix B: Oceanographic numerical models used to understand erosion processes and design beach protection projects

Oceanographic numerical models are an essential tool for understanding erosion processes and designing beach protection projects. These models use mathematical equations to simulate oceanographic processes and provide predictions of wave heights, currents, sediment transport, and coastal erosion. The models allow oceanographers and coastal engineers to assess the potential impact of coastal erosion and develop strategies for mitigating its effects. In this appendix, we will describe the most popular models used by oceanographers and coastal engineers, including numerical wave models, coastal circulation models, coupled wave/current/sediment transport models, and beach erosion and dune breaching models.

**Regional Numerical Wave Models**

Numerical wave models simulate wave propagation and transformation using mathematical equations that describe wave physics. The models use input data on wind speed, atmospheric pressure, ocean currents, and bathymetry to predict wave height, direction, and period. These models are essential for understanding wave climate and assessing its potential impact on coastal morphology. Two of the most popular wave models are the WaveWatch III and the SWAN model.

- WaveWatch III is a global wave model that provides wave forecasts up to ten days in advance. The model uses input data on wind speed and atmospheric pressure to predict wave height, period, and direction. WaveWatch III is used by a range of organizations, including the National Oceanic and Atmospheric Administration (NOAA), the US Navy, and the European Centre for Medium-Range Weather Forecasts.

- The SWAN (Simulating Waves Nearshore) model is a spectral wave model that simulates wave transformation from deep water to the nearshore zone. The model is widely used for coastal engineering applications, including wave energy assessments, coastal erosion studies, and harbour design.

**Phase-Resolving Wave Models**

Phase-resolving wave models, such as SWASH (Simulating Waves till Shore) and XBEACH, are advanced numerical models designed to simulate nearshore wave processes with high accuracy. Unlike phase-averaged models, which only consider the mean values of wave parameters, phase-resolving models account for the individual phases of each wave, capturing the complex interactions between waves and the nearshore environment more realistically.

SWASH is a model that simulates wave transformation, wave breaking, and wave-induced currents in the surf zone, while XBEACH is specifically designed to model coastal erosion and sediment transport under extreme storm conditions. Both models are important for understanding nearshore hydrodynamics that affect coastal erosion because they provide detailed insights into the wave behaviour and sediment transport processes occurring in the nearshore zone.

**Coastal Circulation Models**

Coastal circulation models simulate the flow of water in the nearshore zone, including the effects of tides, waves, winds, and buoyancy forces. These models are essential for understanding coastal currents, water level fluctuations, and the transport of sediment and pollutants. Two of the most popular models are the ROMS model and the ADCIRC model.

- The Regional Ocean Modeling System (ROMS) is a state-of-the-art numerical model that simulates ocean circulation and wave propagation in the coastal zone. The model can be used to predict water level changes, tidal currents, and sediment transport, among other variables. ROMS is widely used for coastal research and management, including studies of coastal flooding, sediment transport, and ocean acidification.

- The Advanced Circulation (ADCIRC) model is a finite-element model that simulates the effects of tides, waves, and storm surges on coastal hydrodynamics. The model is widely used for storm surge prediction and hazard assessment, including for hurricanes and other extreme weather events.

**Shoreline Change and Sediment Transport Models**

Coupled wave/current/sediment transport models simulate the interaction between waves, currents, and sediment transport in the coastal zone. These models are essential for understanding the processes that shape coastal morphology and the impact of coastal erosion. Some of the most popular models are listed below:

- The Delft3D model is a 3D numerical model that simulates waves, currents, and sediment transport in the coastal zone. The model can be used to predict beach erosion, dune breaching, and shoreline changes, among other variables. Delft3D is widely used for coastal management, including for the design of coastal protection measures and the assessment of coastal hazards.

- The XBeach model is a numerical model that simulates the hydrodynamic and morphodynamic processes in the nearshore zone. The model can be used to predict the impact of coastal erosion on beaches and dunes, including dune breaching and overwash. XBeach is widely used for coastal research and management, including for

- SBEACH (Storm-induced Beach Change): SBEACH is a widely used empirical model for predicting beach profile changes due to storm-induced erosion. It accounts for wave transformation, sediment transport, and beach profile evolution.

- CSHORE (Cross-Shore): CSHORE is a one-dimensional, process-based model for predicting cross-shore sediment transport and beach profile changes. It includes formulations for wave transformation, sediment transport, and erosion/deposition processes.

- GENESIS (Generalized Model for Simulating Shoreline Change): GENESIS is a one-dimensional numerical model for simulating longshore sediment transport and shoreline change. It combines wave transformation, sediment transport, and shoreline evolution in a single framework.

The selection of an appropriate numerical model for coastal and beach erosion depends on the specific coastal environment and the objectives of the study. Each model has its advantages and limitations, and it is crucial to consider the complexity, data availability, and computational resources when choosing a suitable model. In some cases, it may be beneficial to combine multiple models to better capture the different processes and scales involved in coastal erosion and sediment transport.

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