POSSIBLE STORM SURGE IMPACT ON CODRINGTON AND BREACHING OF SAND DUNES

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EXECUTIVE SUMMARY

To mitigate the impact of storm surges on Codrington, we present eight options and their costs. Options are listed from least to highest cost, not in order of preference. The best option for Codrington should be selected not on cost, but on the overall difference the option will make on the island.

The cost of solving the problems discussed in this report will increase by a factor of two or three if not addressed soon.

The deterioration of coral reefs is believed to be a continual contributing factor to beach erosion along the coast, as are the continued sand mining and quarry operations on the north end of the island.

SECTION I. INTRODUCTION

Acknowledgements

Many have shared experiences, ideas, and information for this report, in particular:

- John Mussington, headmaster, Sir McChessney George Secondary School in Barbuda School, and marine biologist.
- Chad Knight Alexander, director, Planning and Public Works, Barbuda Town Council.
- John Webber, secretary, Barbuda Fishing Council.
- Lewis, Environment Office, Ministry of Works, Transport and Environment, St. John's, Antigua.
- Philmore Mullin, head, National Office of Disaster Services, Antigua and Barbuda.
- Kelvin Punter, chairman, Fisheries Council Barbuda, and member, Barbuda Town Council.
- Randolph Beazer, Barbuda Council chairman.

Synopsis

This brief preliminary engineering report identifies the major issues and concerns as outlined the Caribbean Open Trade Support (COTS) Scope of Work (SOW) document, Item 3, "Objectives and Tasks," Project Code US0112.001 for Chemonics International Inc. The prime contract is AFP-I-00-04-0002-01-PA.

This document contains a preliminary engineering study; more detailed engineering and design work is required prior to approvals, acquisitions, or construction. This is intended as a guideline and should not be used in any other capacity.

Overall Project Objective

To mitigate possible storm surge impact on Codrington through a combination of soft and hard engineering techniques.

Educational Component

We have developed and incorporated an educational component into the project, involving the teachers and students of the Sir McChessney George Secondary School in Barbuda with the help of its headmaster, John Mussington. The educational component includes three main sections:

1. Fund and construct a nursery at the secondary school. The main purpose of the nursery will be to:

— Supply indigenous plants, trees, and scrubs for revegetating breached sections of sand dunes.
— Grow and supply mangroves and seagrape seedlings to reestablish wetlands along the coast.
— Teach Barbudan children techniques to graft, grow, and care for indigenous plants, trees, and shrubs, and how to grow ornamental plants, trees, and shrubs to sell at local and regional hotels and resorts. The nursery could also supply planting material for restoration and enhancement work associated with the management of Lagoon National Park.

2. Design and construct a sand-trapping fence in line with best management practices and teach children that sand dunes cannot be viewed in isolation from other components of the coastal system. Sand dunes and beaches are interdependent and must be managed together. Sand dune management, furthermore, should be viewed within the overall context of integrated coastal area management through links with the physical, economic, and social components of coastal systems.

3. Teach bioengineering and bioremediation to children by:

— Teaching how to use vetiver grasses to stabilize and protect infrastructure in Barbuda, including roads, wetland areas, and construction and home sites.
— Teaching how to use vetiver grasses to rehabilitate areas from which sand has been taken and stabilize the slopes of the remaining sand dunes in the mining area.

Integrated Management Plan for Codrington Lagoon

The Organization of American States approved $78,925[1] to fund the 2007 execution plan. John Mussington has been selected as park manager to guide the project through to a fully functioning national park. Implementation of an integrated management plan for the park is a key objective. These conservation measures will ensure the sustainability of the various resources on which a significant number of Barbudans depend. These resources are also the basis for other nontraditional livelihoods. The physical components of the lagoon that form the basis for its natural resources are vulnerable to global warming and the resultant rises in sea level and tropical storm activity. This USAID intervention is intended to provide technical and financial assistance and to install measures that will mitigate negative impacts on the lagoon. Such interventions are considered critical to the successful implementation the management plan.

The proposed measures to protect Codrington from storm surges, as outlined in this report, are in accord with all of the components and activities in the integrated management plan for Codrington Lagoon.

[1] All dollar figures are in U.S. dollars unless otherwise noted.

Proposed Japanese Fishing Complex in Barbuda

Japan is considering the construction of a fishing complex in Barbuda, similar to those in Antigua but on a smaller scale. The proposed location of the complex is 300 meters south of the Barbuda Fisheries Council Office.

We intend to ask the Japanese for financial help in implementing all stages of the proposed storm surge mitigation proposal:

- Rehabilitation of and creating new wetlands areas.
- Construction of a beam to protect critical interstructure (including part of the proposed area).
- Construction and deployment of barrier reef units along the shore.

These measures would help protect Japanese interests in a fishing complex. Additionally we plan to ask the Japanese for financial help in placing 100 artificial reef units in the lagoon; these reefs provide habitat for fish and lobster.

Coastal Wetlands

Coastal wetlands play an important role in reducing the height of storm surges when major storms make landfall.

SECTION II. MITIGATION PROPOSAL

MULTI-PRONGED APPROACH TO REDUCING AND ELIMINATING STORM SURGES FROM CODRINGTON

After considerable study, we suggest a four-pronged approach to eliminating or severely reducing the possibility of storm surges inundating Codrington. This approach recommends soft and hard engineering techniques with a holistic approach:

- Creation of new wetland areas and rehabilitation of the damaged areas.
- Construction of a sand-trapping fence and revegetation of two breached sections of sand beam.
- Construction of a beam to protect critical interstructure.
- Construction and deployment of 1,300 barrier reef units to protect 1,000 meters of shoreline from storm surge.

Figure 1. Google satellite image showing fishing complex to the west of the power station.

Figure 2. Google satellite image showing fishing complex to the east of the airport. Heavy cloud cover prevents a clear image of the airport.

Seven options are given below, in descending order by cost. However, the consultant strongly recommends serious consideration of Options 5, 6, and 7 as they are soft engineering, relatively low cost, and can be implemented immediately.

Option 1

- Protect the entire landward side of the lagoon from storm surge by constructing a 1,000-meter barrier reef system as described in detail in Section IV.
- Construct a berm to protect critical interstructure areas, including the infant school, power plant, airport runway, and government buildings, with specially designed 20-metric ton barrier reef units.
- Revegetate and construct a sand fence in breached areas of the sand dunes.
- Reestablish wetlands in front of critical interstructure and establish a nursery at the middle school to provide plants, trees, and trailing vines for all phases of the project.

The total cost for Option 1 is estimated at $3,250,000.

Option 2

This option is similar to Option 1, except the berm protecting critical interstructure areas will be made of local material — rocks, earth, and sand.

The total cost for this option is estimated at $2,995,000.

Option 3

This option is similar to Option 1, except the berm would be constructed from large geotextile sand-filled tubes, as shown in Figures 98 and 99.

The cost for a MacTube is $31,027.35, as seen in Appendix A, Figure 123.

The total cost for Option 3 is estimated at $2,650.000.

Option 4

This option is similar to Option 1, except that barrier reef units would only be used to protect critical interstructure, and the berm would be made of rock, sand, gravel, and earth.

The total cost for this option is estimated at $1,250,000.

Option 5

This option includes construction of a berm from large geotextile sand filled tubes, revegetation of breached sections of sand dunes, reestablishment of damaged wetland areas along the coastline, and construction of barrier reef units to protect the critical interstructure of Codrington.

The total cost for Option 5 is $31,027.35.

Option 6

This option is similar to Option 6, except it would only require construction of a sand fence and revegetation of breached sections of the northern sand dune (know as Louis Beach). This option represents the *absolute minimum* that should be done to protect Codrington from storm surges.

The total cost for Option 6 is $3,800.00.

If Option 6 is used, we should also create a berm to protect critical interstructure ($31,027.35), bringing the total cost to $34,827.35.

Option 7

This alternative would cover both breached sections of dune with a wire mesh mattress made of 6x8 double-twisted wire mesh, 2.20 mm diameter wire mesh, and galvanized and PVC coating (or Galfan and PVC coating). The mattresses will protect the slope from superficial erosion, hold sediments in place, and allow for the planting and growth of further vegetation (see Figure 97). The mats could be filled with a mix of rocks and soil so vegetation can grow rapidly, or plants could be placed inside the mat pockets, with checkered patterns for example.

It is our strong recommendation that if this option is considered, we use the Galfan and PVC Reno mattresses, as Galfan's design life is 50 to 70 percent stronger and longer than galvanized.

Total cost for Option 7 is $196,308 for Galfan and PVC Reno mattresses, and $187,308 for galvanized and PVC Reno mattresses.

Preliminary Costs

Allowances for engineering (construction supervision based on 30 person-days) and 10 percent contingencies are included in estimates.

Nursery Costs

We have secured two bids from local contractors in Barbuda for nursery construction at the Sir McChessney George School. Copies of the bids can be found in Figures 121, 122 and 123.

Design specifications for the nursery are 30” by 20’ for a shade house on a 6” reinforced concrete pad, with a termite-treated stained wooden frame and covered with green nursery netting and a 36” door.

State of the Art Development Ltd.’s estimate for the nursery is $20,095.02 (EC$54,000.00 at 2.6875 EC to the dollar).

Everett Thomas’s estimate is $22,790.69 (EC$61,250).

Nursery supplies (trays, fertilizer, pots, irrigation, equipment) are estimated at $5,000. John Mussington will prepare a complete list and order the supplies.

SECTION III. ABSTRACT OVERVIEW

This report assesses the morphological characteristics of Barbuda's western coastline and Codrington Lagoon. It also defines possible measures to protect Codrington from storm surges.

The project has developed several components, including:

- Construction of sand-trapping fences along breached sections of the dunes.
- Revegetation of the breached sections.
- Reestablishment of destroyed wetlands along the lagoon.
- Construction of a berm to protect critical interstructure.
- Design and construction of barrier reef units near the landward side of the lagoon to break up or attenuate wave energy and stop the effects of erosion along the shoreline.
- Barrier reef units provide biomass and habitat substrata for lobster, fish, and a variety of marine creatures measuring .48 metric tons per square meter annually.
- Educational aspects include the construction of a nursery at the Sir McChessney George Secondary School in Barbuda. The nursery will be managed and maintained by students and teachers, who will grow the plants, trees, and shrubs to revegetate the sand dunes and reestablishment wetlands along the coast.

Scope of Work

- To determine the level of threat posed to the lagoon and the town from future storm surges and elevated flood levels in Codrington Lagoon.
- To investigate possible breaching of the dune during hurricanes, identify and potentially demarcate the high-impact area, and estimate potential flood levels within the town and surrounding environment.
- Assess the lagoon to identify weak points where breaching from storm surges is possible.

Environmental Values

Codrington Lagoon is an area of great natural beauty. It contains a wealth of environmental values and intrinsic qualities to service a variety of functions. The principal function of this project is to enhance those values.

Existing Conditions

Project location. Barbuda is located 28 miles north of Antigua. The island is 160.5 km^2, with a lagoon system at its northeastern end.

Codrington Lagoon is six to seven miles long and two to three miles wide. Much of it is covered with thick stands of *Rhizophora mangle* (red mangroves) and *Avicennia germinans* (black mangroves). The other lagoon is Goat Island Flash, which is smaller and shallower. Together, the lagoons and their associated flashers and mangrove forests support endangered bird species. These include one of the largest breeding populations (around 7,000 breeding pairs) of the Magnificent Frigate (*Fregata magnificens*, or Man O War) in the Caribbean (Schrieber 1996).

Codrington Lagoon is a particularly important nursery for the Caribbean spiny lobster (*Pamularis argus*). During the underwater reconnaissance survey, snappers, grunts, jacks, and goatfish were seen along with spiny lobsters.

The western side of the lagoon is separated from the Caribbean Sea by a thin sand beam (44 meters at its narrowest point). The beam has been broken through in several hurricanes (Hurricanes Luis in 1995 and Donna in 1960).

Geological information. Barbuda is a low-lying limestone island 174 km^2 in area, located 40 km north of Antigua. Barbuda and Antigua crop out at either end of the shallow, hourglass-shaped Barbuda Bank, some 3600 km^2 and consisting of a tilted oligocene succession of volcanics overlaid by fossiliferous tuffs and capped by marine limestone (Martin-Kaye 1959). However, unlike most other limestone Caraibes, Barbuda lies 50 km east of the island arc axis. It differs by lying on the northeast margin of its bank rather than in the center.

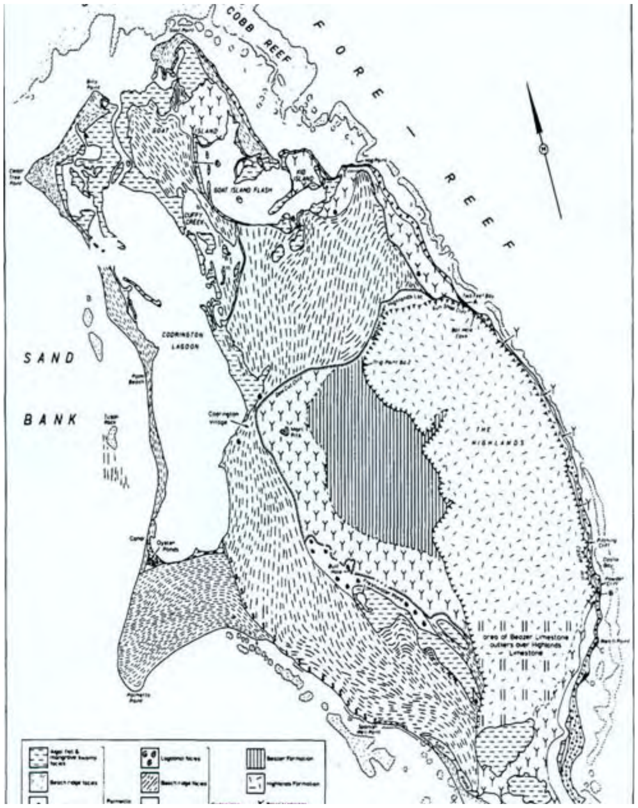


Figure 3. Geological map of Barbuda.

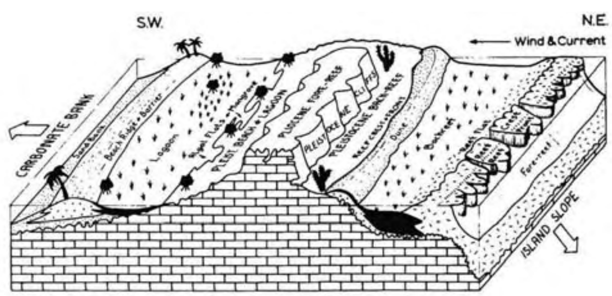


Figure 4. Simplified model of the Holocene carbonate environments adjacent to Pilo-Pleistocene limestone.

Temperature (air and water). Temperatures vary little throughout the year. The temperature fall is usually within the range of 25-29 degrees C and generally drops six degrees at night.

Figure 5. Monthly Average Temperatures in Barbuda

January	22.3	28.2	56.9	10.0
February	22.1	28.3	37.6	8.0
March	22.5	28.6	46.7	8.0
April	23.3	29.2	67.6	9.0
May	24.3	29.8	112.5	10.0
June	25.3	30.5	49.5	8.0
July	25.4	30.7	86.6	11.0
August	25.4	30.9	100.6	13.0
September	24.8	30.7	140.5	11.0
October	24.3	30.4	130.8	13.0
November	23.7	29.5	134.9	13.0
December	22.8	28.6	87.4	13.0

Precipitation and rainfall. The average annual rainfall as recorded by the Met Office in Antigua is 34.74 inches. By comparison, average annual rainfall for Barbuda is 40.98 inches. Barbuda has experienced periods of drought in 1971, 1983, 1990, 1991, 1994, and 1996 to 1998.

There is no sharply defined wet or dry season, but the wet season is generally from August to December and the dry season between January and April.

Beach classification. Beaches in Barbuda can be sorted into four basic types:

- Seasonally unstable (from Cedar Tree Point to the Canal/Oyster point)
- Depositional (Coco Point to Spanish Point)
- Relatively stable (Billy Point to Hog Point)
- Unstable and erosional (Several hundred meters south of the canal, Palmetto Point, and the area from the boat harbor to the Coco Point airstrip)

Soils. The only information we could obtain on soils in Barbuda was from a 1992 study by the Organization of American States, which classified soils into six series:

1. Codrington clay, found mainly around Codrington and to its south and southeast extending to the coast, in flat areas.
2. Barbuda clay loam, found in the Highlands in 5 to 20 degree slopes.
3. Blackmere clay loam, found in approximately 1/3 of Barbuda, in areas east, southeast, and northwest of Codrington, at the southeastern tip of Barbuda, at Goat, Rabbit, and Kid Islands, and at the narrow sand bar separating the western shoreline (Low Bay) and Codrington Lagoon. Land in this series slopes 10° and is characterized by varying limitations of shallowness, stoniness, salinity, and compaction.
4. Beach sand, found on beaches and overlaying the critical aquifer at Palmetto Point.
5. Mangrove swamp, found in mangroves in Codrington Lagoon and in the swamps in southern Barbuda.
6. Salina, found fringing sections of Codrington Lagoon and in major swamps south of Barbuda.

Current studies. No current studies were made during the two site visits; however, it is recommended that a surface current study be made using dyes and drogues of the lagoon and ocean area directly in front of the sand beams. A current study would help us better understand the longshore currents and movement of sand along the coastline.

Climate and weather. The temperature varies little throughout the year in Barbuda. Daytime temperatures fall within the range of 25º-29ºC and usually drop to 6ºC at night.

During the winter months (October to April), Barbuda is occasionally influenced by frontal systems moving eastward across the southern part of the United States. The trailing edge of these fronts sometimes results in winds blowing from the northwest and northeast for short periods of time — usually no more than one to two days. (More detail on wind patterns is provided in Section III).

Hurricanes generate high winds and waves, storm surges, heavy rainfall and flooding. Barbuda lies within the hurricane belt. These intense storms occur between June and November, with most tropical storms/hurricanes occurring in September. Within recent years, several hurricanes have passed sufficiently close enough to Barbuda to cause significant damage, including Hugo (September 1989), Luis and Marilyn (September 1995), Bertha (July 1996), Georges (September 1998), Jose (October 1999), and Lenny (November 1999).

Oceanography

Winds. Consistent with its location in the North-East Trade Winds belt, Barbuda experiences predominantly easterly winds, with seasonal shifts from the east-northeast to the southeast. Figure 6 depicts a hindcast wave rose for the area south of Barbuda from 1990-1999. The U.S. Army Corps of Engineers prepared a wave information study for the waters surrounding Puerto Rico (USACE, 2003, http://frf.usace.army.mil/wis/). The study includes hourly hindcast predictions of wave and wind fields at 12 locations spaced one degree apart in latitude and longitude. The hindcast is a numerical prediction of wave heights, periods, and direction, and wind speeds and directions generated from measured weather records across the region.

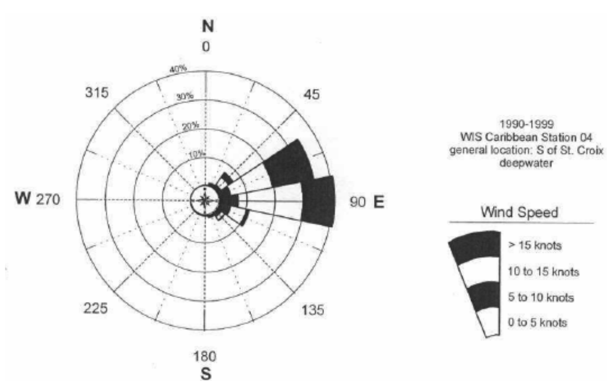


Figure 6. Annual distribution of wind directions and speed based on hindcast wave data from the U.S, Army Corps of Engineers' wave information studies.

The hindcast presents data from 1990-1999 and predicts conditions during hurricanes and tropical storms. For Barbuda, stations lie to the south on the south side of St. Croix and to the east in the Anegada Passage. Comparing the exposure of these stations to that of the proposed beach improvement sites, Station L1-04 south of St. Croix was chosen for analysis. St. Croix is roughly 354 kilometers or 191 nautical miles south-southwest of Barbuda and thus is not expected to provide any meaningful shelter from winds or waves, particularly from the southeast to northeast direction.

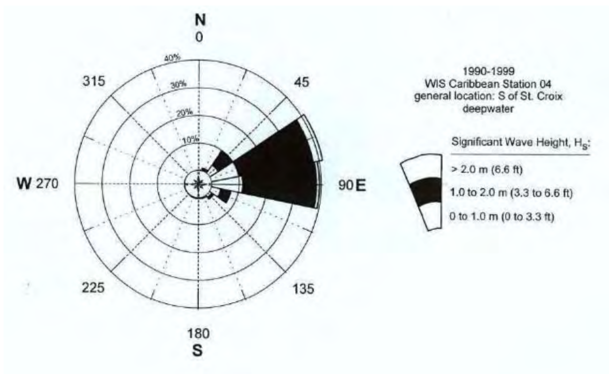


Figure 7. Annual distribution of significant wave height and direction based on hindcast wave data from the U.S. Army Corps of Engineers' wave information studies.

Figure 6 depicts the annual distribution of wind direction and wind speed, clearly indicating the predominance of easterly winds. For 40 percent of the year, winds are from the east, and for almost 25 percent of the year, the area experiences winds of 10 to 15 knots from the east. Seasonally, the average wind direction varies throughout the year according to the following general pattern:

- December to February from east-northeast.
- March to May from easterly directions
- June to August from east to east-southeast
- September to November from the east to southeast

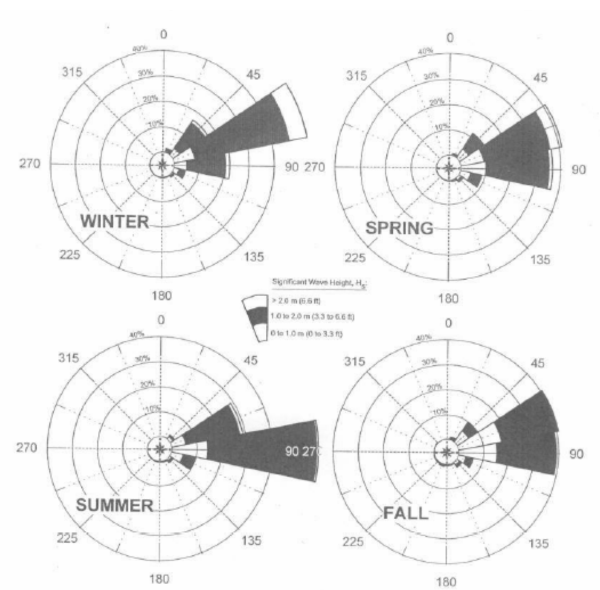


Figure 8. Seasonal variations in significant wave height and direction, based on hindcast wave data from the U.S. Army Corps of Engineers' wave information studies for Station L1-04, south of St. Croix (LAT:17.00 N, LON:-65.00W). The figure plots the hindcast significant wave height through the entire series from 1990 to 1999 and highlights extreme wave events each year, especially those associated with hurricanes and tropical storms.

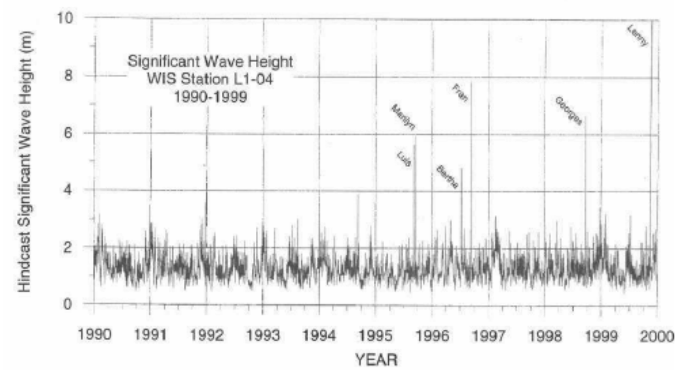


Figure 9. Time series of hindcast-predicted significant wave height for Station L1-04 south of St. Croix, based on hindcast data from the U.S. Army Corps of Engineers' wave information studies.

We obtained wind data from the MET office at the Antigua airport showing an average wind speed of 12 knots. Speed measured during two site visits (August and September) on the sand beams was 14.6 knots.

Waves. Wind patterns are generally reproduced in hindcast wave data. Figure 7 plots the annual distribution of significant wave heights and directions from the same WIS station. Wave directions indicate a slight shift to the east-northeast as compared to the wind data. This may be the result of Atlantic Ocean swell components being included in the local hindcast. These swells, known locally as ground seas, are frequently observed in winter.

The wave hindcast suggests that 67 percent of the time, waves are between 3.3 and 6.6 ft high, and 80 percent of waves are directed from the east or east-southeast. As discussed for the wind data, the wave data exhibits noticeable variations in incident direction through the seasons. Figure 8 illustrates seasonal variations in wave height and direction for Station L1-04. Similar to the winds, incident wave directions shift slightly to the east-northeast in winter and are predominantly from due east in the summer.

While the data in the wave roses do include the influence of these events, their duration is too short to have a meaningful influence on seasonal or annual averages. However, records clearly describe the individual passage of these events. Of recent note are the impacts from Hurricanes Luis in 1995 and Donna in 1960.

Tides. Tides in the area are mixed and predominantly diurnal, ranging from approximately 1.1 ft at spring tide to roughly 0.1 ft at neap tide. Figure 8 illustrates the seasonal fluctuation in overall tide level. In the late summer and fall, tides are typically 0.4 ft higher than in spring.

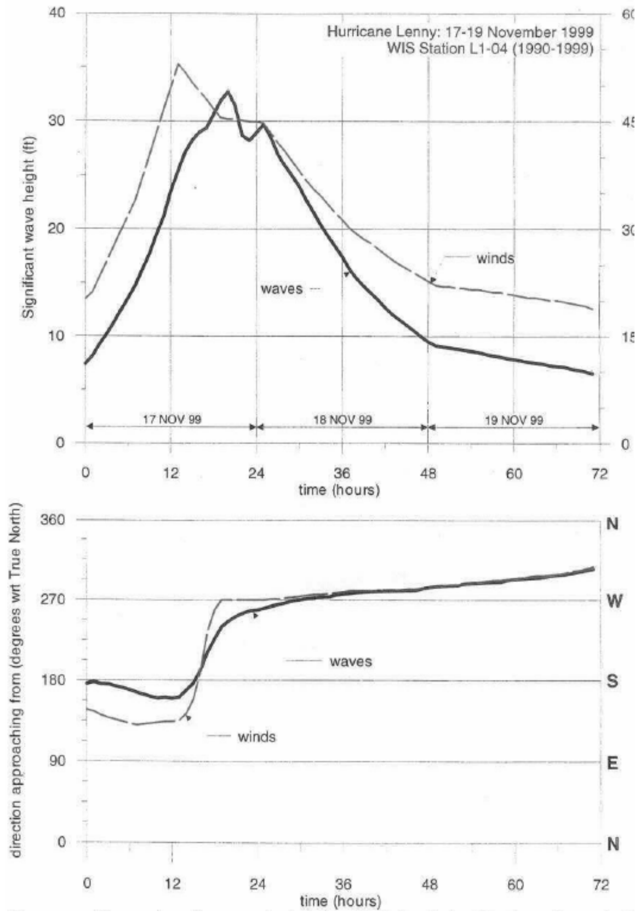


Figure 10. Time series of wave and wind characteristics during Hurricane Lenny in 1999. Data from the U.S. Army Corps of Engineers Waves Information Studies for Station L1-04, south of St. Croix (LAT: 17.00 N, LON:-65.00 W).

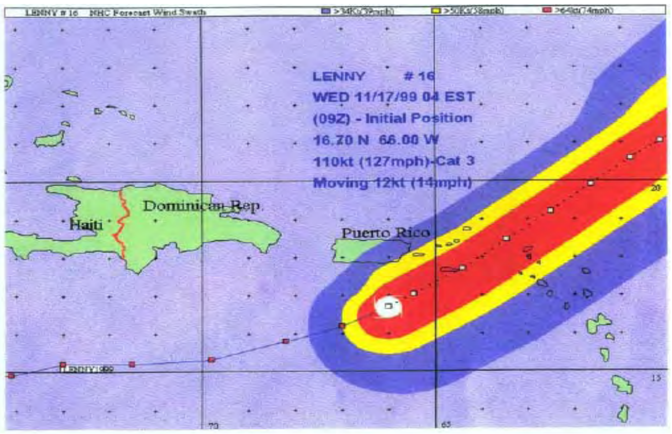


Figure 11. Projected path of Hurricane Lenny.

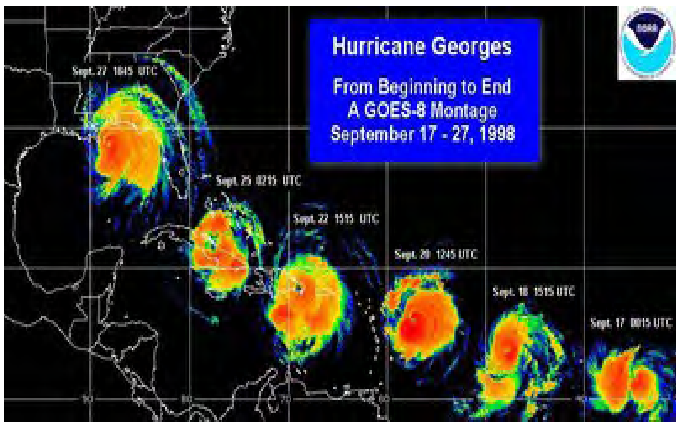


Figure 12. Projected path of Hurricane Georges.

Hurricanes. Hurricanes generate storm surges through three factors: wind set-up (onshore winds piling up against the coastline), pressure set-up (where atmospheric pressure is low, sea level tends to rise, and vice versa), and wave set-up (sea levels rise near the coastline due to waves).

In Barbuda, hurricanes have a more varied effect than in many other Caribbean islands due to its low elevation and the removal of sand dunes for commercial purposes. During 1989 to 2001, the most serious erosion in Barbuda occurred on the north coast.

There is a clear relationship between the proximity of a hurricane center and beach erosion. Other influences on erosion include the characteristics of a particular hurricane, coastline shape, offshore shelf, and local features such as coral reefs.

Storm surge analysis. A storm surge analysis has been done for the purpose of this report and to establish some basic guidelines for design criteria. We estimate that the maximum wave height for a 100 year event at 95 percent prediction limits to be 3.95 meters and the maximum surge of 4.15 meters. We also estimate that the maximum wind speed is 186 knots.

Long-term sea level rise. There are many causes of long-term sea-level change, each occurring on different temporal and spatial scales. On the largest scale, eustatic (or global) sea level rising is due to the melting polar ice packs and thermal expansion of seawater. The eustatic sea level has risen between 100 and 250 mm (about 4 to 10 inches) during the past century and will inevitably be affected by climate changes in the future. That rate is nearly 2 mm (0.1 inches) per year and is overall higher than the averages over the last several millennia. By 2100, the projected rise is 90 mm to 800 mm (3.5 to 34.5 inches) (IPCC, 2001). On passive margin coasts (coasts that are not tectonically active-like Barbuda) with slopes between 1:100 and 1:1,000, a 90 mm (3.6 inches) rise would result in a corresponding landward shoreline shift of between 90 and 900 meters (280 to 3,000 feet).

To estimate the likely sea level in the future, and given the absence of tectonic data for Antigua and Barbuda, global warming should be taken into account. At present, there is no sign in the tide gauge in Barbuda, which indicated accelerations in the rate of sea level change. Nevertheless, for planning purposes, it would be prudent to account for some degree of sea level rise resulting from this phenomenon. Assumptions for rising under a greenhouse scenario vary significantly from approximately 0.3 cm/year to 1.0 cm/year. The United Nations Environment Programme/Intergovernmental Oceanographic Commission task team adopted a figure of 0.5 cm/year for modeling and planning. Maul (1993) proposed a regional rate of induced sea level changes of 0.28 cm/year for the Caribbean. We recommend that rate for this analysis.

For the purpose of defining water levels for the creek and in Codrington Lagoon, we recommend a value of 0.09 to account for the global rise in sea level. This effectively takes into account the greenhouse phenomenon up to the year 2020.

Water levels. Several components of water level have been considered for this analysis, which was static, quasi-static, and dynamic in nature. These include:

- Tidal fluctuations.
- Inverse barometric rise, caused by the difference in atmospheric pressure between the extreme low within the eye of a hurricane and the normal pressure at its periphery.
- Wave set-up, a piling-up of water on the shoreline caused by the transfer of wave energy from kinetic to potential mode, resulting from the wave-breaking process.
- Long-term sea level rises due to global warming predictions.
- Wave run-up.

When inverse barometric rise is maximized, the wind set-up component of storm surge is minimized, and vice versa. In detailed work on water levels in Barbados (DELCAN, 1994), in nearly all cases, inverse barometric rise is dominated by wind set-up. This is why the wind set-up component was selected for inclusion in the determination of storm surge.

Design of water levels is influenced by the following factors: astronomical tides, storm tides (or surge), tsunamis, climatologically variations, and sector variation. For engineering purposes, we looked at differences in tide levels, as no long-term data is available for astronomical, storm tides, or tsunamis.

There are two high and two low tides in Barbuda every day, each of unequal height. The average rise and fall is relatively small, usually less than 0.8 feet. The highest tide during storms may be two feet above mean low water, whereas the lowest low may be about one foot below mean low water.

Tide gauge. We recommend setting up a tide station at the existing dock at the pier in Codrington Lagoon to record actual tides and rise in sea level. The gauge will be especially helpful during the beach monitoring phase of construction and post-construction activities.

Erosion. Erosion is part of a process known as littoral transport, the movement of material by waves and currents on the coastline. Transported material is primarily sand, broken coral cobbles, silt-sized particles, and rocks from the foreshore. The source of nearly all sand in the littoral transport system in Barbuda is from the erosion of coral reefs and waves on the foreshore and sediments traveling down hillsides.

Beach enhancement. Beach enhancements are intended to improve aesthetics and the recreational value of the shoreline along the sand dunes off Barbuda's west coast. The dunes also function as storm protection for the beach. Enhancements include selective cleaning and grading of the site, construction of a sand fence in the areas that have been breached by storm surges, and revegetation of breached areas.

Other enhancements include reestablishing lost and damaged wetland areas, particularly in front of the power plant, airstrip, and hospital.

Sand budget. With respect to sand supply, a given length of coastline might have a surplus, balance, or deficit in its budget. For example, a sand-supply budget would be considered in balance for a particular area if the amount of sand leaving the area was replaced by an equal amount arriving from adjoining areas. Over short periods, a build-up of sand (accretion) might follow erosion, but over the long term, the area would be in a state of dynamic equilibrium. It appears that most of Barbuda's coastline has a deficit; however, before any final conclusion is made, more studies are required.

Changes in beach profiles. There was considerable variation in profile area and width, based on several factors including location in Barbuda and level of development on the beach. The effects of Hurricane Luis (1995) may also factor — until then, erosion was the dominant process on most of Barbuda's beaches. After Luis, however, there was a shift and accretion is now more prominent. This is typical after a hurricane, when sand moved offshore is redeposited onto a beach. The following site-specific information is from Antigua's Fisheries Division (2003):

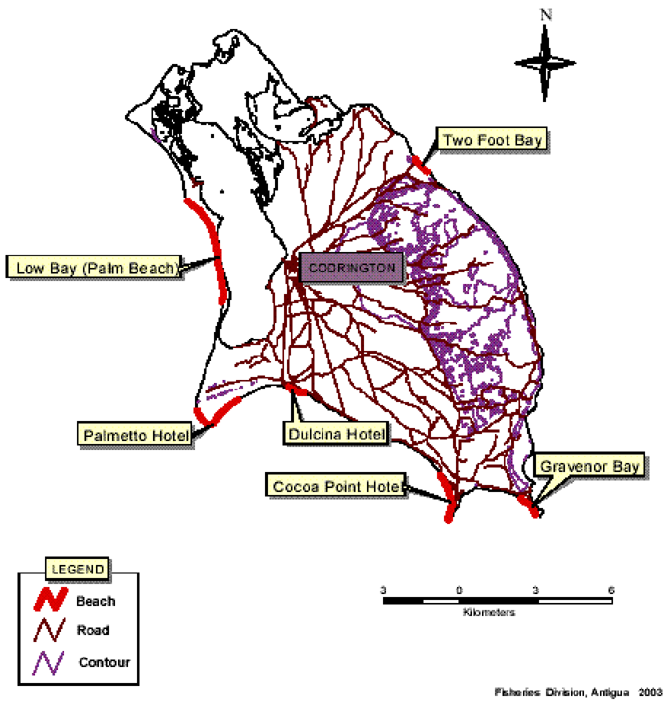


Figure 13. Areas of severe erosion –Courtesy Fisheries Division, Antigua 2003.

Cocoa Point Beach: Between 1996 and 2000, accretion was the dominant process along the three sites measured on this beach. Though the southern point was eroding, the mean profile area and width were 0.23 m^2 and 0.73 m/yr, respectively.

Gravenor Bay (Spanish Point). Between 1996 and 2000, accretion was dominant. The mean profile area and width were 0.67 m^2 and 1.01 m/yr, respectively.

Dulcina Hotel. Accretion was dominant between 1996 and 2000, and the mean profile area and width were 0.18 m^2 and 1.32 m/yr, respectively.

Palmetto Hotel. Accretion was dominant. And from 1996-2000, the mean profile area and width were 1.6 m^2 and 5.97m/yr, respectively. Shifting dunes characterize this beach.

Low Bay (Palm Beach). Between 1996 and 2000, erosion was dominant with mean profile area and width of -0.10 m^2 and -0.80 m/yr, respectively.

Two Foot Bay. For 1996-2000, accretion was the main process. The mean profile area and width were 0.26 m^2 and 2.40 m/yr, respectively.

Figure 14. Individual Beach Changes

Beach	Change in Profile Area, in m^2, 1996-2000	Change in Profile Width, in m^2, 1996-2000
Gravenor Bay	0.67	1.01
Two Foot Bay	0.26	2.40
Low Bay/Palm Beach	-0.10	-0.80
Palmetto Hotel	1.60	5.97
Dulcina Hotel	0.18	1.32
Coco Point		
Site A	0.44	1.04
Site B	0.33	3.05
Site D	-0.07	-0.19
Mean	**0.23**	**1.3**

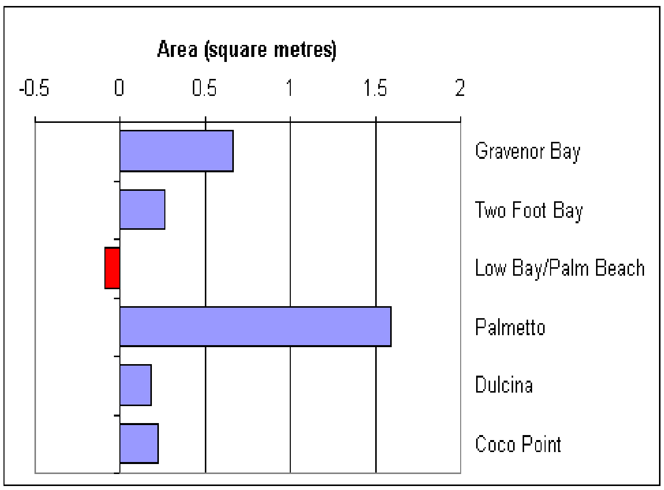


Figure 15. Erosion area in square meters.

Discussion

Most of the monitored beaches in Barbuda expanded in profile width during 1996-2000. The average rate of increase for the entire island was 0.27 m/yr. However, all of the monitored Palmetto Hotel/Sand Mining/Dickenson Bay beaches that were accreting fell within 1.01 to 5.97 m/yr — well above the average for monitored beaches on the island. Sections of these beaches have periodically experienced erosion, especially when Barbuda was under the influence of tropical weather systems. The beach along Palmetto Point experienced considerable variation in profile width throughout the year, which may account for its high accretion rates. The Palmetto Hotel is always in danger as it is close to the coastline. Even though Two Foot Bay is exposed to the trade winds on the windward side, it still experienced high accretion. Offshore coral reefs provide temporary shelter.

Figure 16. The Palmetto Hotel.

Figure 17. Sand mining.

Low Bay (Palm Beach) is the only monitored beach in Barbuda that experienced an overall decrease during the reporting period. This beach borders the narrow strip of land enclosing Codrington Lagoon. The fact that Palm Beach is eroding may have implications for proposed development in the area.

Vegetation

Vegetative communities. For purposes of this report, the vegetation of Barbuda has been characterized using the USVI Rapid Ecological Assessment Vegetation Classification system as developed by the Virgin Islands Conservation Data Center at the University of the Virgin Islands, Nature Conservancy, and Island Resources Foundation in 1998.

Plant species compositions were assessed in August and September using a rapid quantitative planting sampling. This methodology is designed for situations and conditions where time, energy, resources, and sites do not allow for more detailed and long-term methods.

Much — if not all — of the vegetation of Barbuda is secondary. However, some patches of forest in upland areas may be old growth forest. This area has not yet been investigated.

There are five general vegetation community types on Barbuda. These communities are mainly dry forest types, with the dry semi-deciduous woodland and semi-deciduous forest being the main types.

The physiognomic structure and species composition of these community types are strongly influenced by a number of factors, including prevailing wind patterns, wind velocity, length of the dry season, rainfall, aspect and slope, and land use. The proximity of some vegetation to strong onshore winds, in the presence of heavy salt spray, reduces vegetation height, altering the composition and diversity of the forest. For most plant communities, tree strata are generally limited to two layers (emergents and canopy layers) with a maximum height of 16-30 ft (5 to 9 m).

A brief description of the five vegetation community types are described below:

- *Drought-deciduous forest*. This community, characterized by greater than 75 percent deciduous species, is found on the steeper lopes of highland areas. The forest is relatively low in stature, with emergents reaching 25 to 52 ft (7.8 to 16.25 m) The shrub layer is sparse to abundant, sometimes with numerous vines forming relatively dense entanglement. The herbaceous layer is ephemeral, dying during the dry season.

- *Thicket/scrub*. This community in intermixed with drought-deciduous woodlands on the lower highlands and some limited areas on the west coastline.

- *Coastal hedge*. This community is found along the coast with exposure to prevailing winds and salt spray. The species is generally wind- and salt-tolerant and found along the coastline.

- *Rock pavement*. This community is limited to rocky outcrops and coastal cliffs on the eastern side of the coast. The vegetation is usually sparse, sometimes covering less than 10 percent of the surface. All species are influenced and affected by the strong winds and salt spray, growing mostly as low shrubs.

- *Beach sand, including cobblestone, rubble, and coral*. This community comprises sandy areas throughout the coastline with less than 10 percent vegetative cover.

Beach volumes in the wider Caribbean decreased on average by 28 percent following the 1995 storms (Chambers 2001).

Suggestions. Figures 18-20 show vegetative suggestions that we have found useful in preventing sand erosion along island coastlines.

Vetiver seed is sterile and will not produce stolons or rhizomes; therefore, it will not become a weed. Its crown is below the surface and resists fire and overgrazing and trampling by livestock. It is salt tolerant and capable of forming a dense, ground-level, permanent hedge as an effective filter, preventing soil loss to runoff.

Vetiver could be planted along the beachfront and kept short like a lawn to mitigate the loss of sediment seaward, especially during tropical storms and hurricanes.

Figure 18. Vetiver grass that was underwater for three weeks after a hurricane. The root system is still good.

Figure 19. This vetiver grass, which had been underwater for three weeks after a hurricane, shows some color coming back. The root system was not affected.

Figure 20. Two-year-old, two-meter root system — Mpa 75 — equivalent to 1/6 the strength of mild steel.

Coastal Processes

An investigation is being carried out to define the prevailing coastal processes for Barbuda. This work considers day-to-day and seasonal conditions as well as extreme conditions caused by hurricanes. The day-to-day wave climate and swell conditions were obtained by analyzing wind and wave data collected in the northeastern Caribbean Sea and Atlantic Ocean by Volunteers Observing Ships. This database of ship observations has been enhanced to reduce observational error by combining wave observations with more precise wind measurements and eliminating acknowledged errors in reported wave periods by correlating wave height with period. The resulting database is considered very reliable and has been used throughout the Eastern Caribbean with success. Further, it includes swell occurrences, although the frequency of swell waves is underestimated, particularly on leeside coasts. This occurs with swell conditions as a secondary wave field (i.e., extra tropical) that only become dominant if the main waves are filtered by island landmass. It should be noted, however, that this database is biased against hurricanes, as most ships will alter course to avoid large waves in a storm, hence the need for an analysis addressing hurricanes only.

We used the Volunteers Observing Ships database for Area 47, applicable to the Eastern Caribbean. This data is presented seasonally (March-May, June-August, September-November, December-February) and on an eight-point compass. Seasonal data is presented in a graphic format; Figure 21 shows the predominant wave direction to east to southeast sector, followed by north to northeast. It also shows some seasonal variations; however, the predominant wave direction remains the same. For waves from the western sector (i.e., south to southwest and west to northwest) September to November is the season of most occurrences. This wave data is presented for all directions in a bivariate manner (wave height and period).

Wave Height (m)	Wave Period (sec.) <4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	>12	Totals
0-1	8	35	48	23	6	1					121
1-2	2	37	124	135	70	22	5	1			396
2-3		10	59	104	81	38	12	3	1	1	309
3-4		2	14	35	38	22	9	3	1		124
4-5			3	9	11	8	4	1			36
5-6				2	3	3	1	1			10
6-7					1	1	1				3
7-8							1				1
Totals	10	84	248	308	210	95	33	9	2	1	1000

Figure 21. Bivariate wave table — operational conditions, all directions.

Littoral Cell

Erosion occurs at sites of divergence, where the amount of sediment mobilized and lost exceeds the amount deposited. Accretion occurs at sites of convergence, where sediment deposition exceeds loss.

Littoral cells are defined as sections of coast for which sediment transport processes can be isolated from adjacent coasts. The two headlands that define the area from Palmetto Point to Coco Point seem to stop or act as quantifiable sinks. Another littoral cell seems to be along the east coast from Castle Hill to Spanish Point.

A littoral cell consists of three broad zones: erosion, transport, and accumulation or deposition. No clear demarcation exists between the zones; rather, they gradually merge in broad bands along the shore (Taggert and Swartz, 1988; Myers, 2005). A breach is a segment of shoreline that generally coincides with the lateral extent of a single littoral cell.

The coastal segments of Barbuda’s western and southern coastline seem to represent a single littoral cell with three components: erosional as indicated from Martello Tower to the airstrip west of Coco Point, accretionary on the west boundaries and in between, and transitional or transport that carries material from the erosive to the accretionary segment. This characterizes the shore platform of a reach.

We would like to develop a three-dimensional perspective of the shoreline by doing upland topography, shoreline, and nearshore bathymetry surveys on the same scale to better understand the transportation of sand and sediment along the coastline.

Beach Rock

The western foreshore Barbuda from the boat harbor to the airstrip at Coco Point includes sedimentary beach rock. Beach rock occurs when sand slightly below the surface is cemented into rock. It becomes exposed when the sandy beach surface is stripped away by wave action.

Figure 22. Broken beach rock along the western coastline. Note the sea urchins.

Figure 23. Large sections of broken beach rock along the coastline near the harbor.

Beach rock consists of calcareous cemented beach sand, which form sandstone slabs. It is most prominently exposed between the boat harbor and the airstrip at Coco Point.

Beach rock takes 10 to 200 years to form. When its surface is exposed to weather and wave action, it becomes irregular with sharp edges, poses a hazard to swimmers, and becomes a habitat for sea urchins.

We reviewed the following literature:

- USACE Shore Protection Manual, U.S. Army Corps of Engineers, Coastal Hydraulic Laboratory, Vicksburg, Mississippi, 1994.
- CIRIA (Construction Industry Research and Information Association**)** Beach Management Manual, report 153, circa 1996.
- Chambers, Gillian, Coping With Beach Erosion, UNESCO, 1998.

- Coastal Engineering Consultants, Inc., Review of Pressure Equalizing Modules (PEMs) for Shoreline Erosion Control, October 2004**.**
- Maine Geological Survey, Coastal Sand Dune Environments.
- Caribbean Environmental Programme, United Nations Environment Programme, Manual for Sand Dune Management in the Wider Caribbean, November 1998.
- Caribbean Environmental Programme, United Nations Environment Programme Regional Coordination Unit, Port Royal Street, Kingston, Jamaica**.**
- NORA Tide date information for Christainsted Harbor, St. Croix, Virgin Islands, Station ID 9751364.
- Holmberg Technologies, Inc., Slope Erosion Report, 2004**.**
- Environmental Protection, The rules are based on the location of Diego, California, p. 617. Kaufman, W., and Pilkey, O., 1979. The beaches are moving: Anchor the project within the sand dune system, Press, Garden City, New York, p. 326.
- Analysis of Beach Changes in Antigua and Barbuda, 1996-2001 Volume 1 assessment report, CSI, June 2003.
- Wise Practices for Coping with Beach Erosion: Antigua and Barbuda, CSI publication.
- 1996 Analysis of Beach Changes in Antigua and Barbuda between 1992 and 1995, Black, Chambers, Farquhar, and Jeffey.
- Handbook of Coastal Engineering, Herbich, John B., P.E., PhD., McGraw Hill press.
- Ivor Jackson and Associates, environmental impact assessment, Southern Cross at Low Bay Barbuda, draft, December 2002.
- Ivor Jackson and Associates, environmental impact assessment, Palm Beach Resort, Barbuda, draft, February 2003.
- Jarecki, Lianna, M.S., Proposed Lagoon Monitoring Plan for Codrington Lagoon, June 2000.
- Organization of Eastern Caribbean States, Natural Resources Management Unit, Reparation of Technical Document for Shoreline Protection in Antigua, February 2002.

Two site visits were made to Barbuda: August 9-18 and September 14-21.

Executive Summary Reviewed

Preliminary engineering report. With respect to the threat of storm surges to the lagoon and to the town of Codrington, there are two issues. Solving the first problem will create favorable conditions for preventing the second.

1. Potential breaching/overtopping of the coastal barrier from elevated wave and storm surges in the bay, with consequent lagoon flooding.

2. Potential flooding of Codrington and the surrounding environment.

To support this analysis, we would need to produce wave height and storm surge elevations in the bay for a variety of return periods (25, 50, 100 years). To produce these estimates, we simulate all historic storms since 1871 at a 180 m resolution, capture the hazard values at each analysis cell in the study area, and perform a statistical analysis on the results to determine the return period based hazard estimates for each cell.

For outputs, we could provide wave and surge estimates at the point on the ocean side of the barrier where the highest values occur, together with a GIS map of wave and surge values in the bay. Alternatively, we could go to a specific point and determine wave and surge values — for example, a point identified as particularly vulnerable.

These results would provide USAID with the ocean conditions and probabilities of occurrence that would determine where and how likely the barrier is to breach.

We would propose a study at a grid resolution of 6 arcseconds (180 m). This is a higher grid resolution than the standard for a Level 1 study of 12 arcseconds (370 m), but this higher resolution is likely necessary to resolve the barrier between the bay and Codrington lagoon. Any data sets for the barrier and lagoon, such as elevation data, would be a useful addition to ours.

The cost for this study — estimated between $6,000 and $15,000 — are not included in the cost of the project.

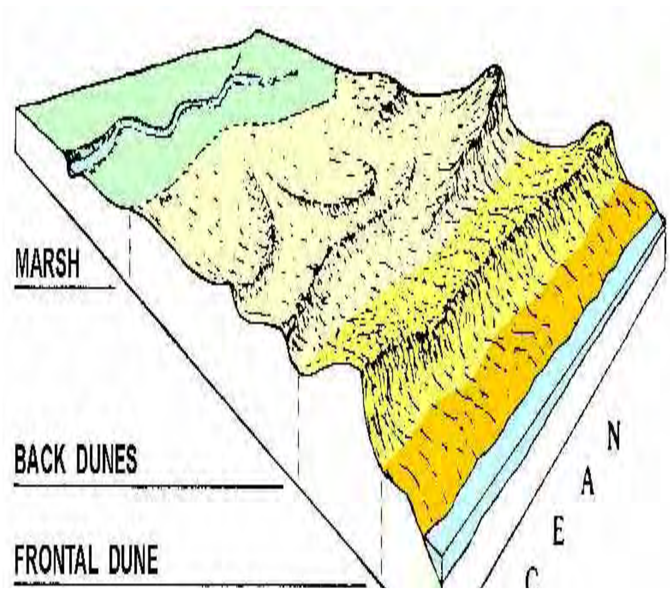


Figure 24. Cross-section of a typical sand dune in Barbuda.

Barbuda's coastal sand dunes. Sand dune systems are sand and gravel deposits within a marine beach system including, but not limited to, beach beams, frontal dunes, dune ridges, back dunes, and other sand and gravel areas deposited by waves or wind action. Coastal sand dunes may extend into coastal wetlands. The dune system includes areas artificially covered by structures, lawns, roads, and fill. Sand dune systems also include all vegetation native to and occurring in the system.

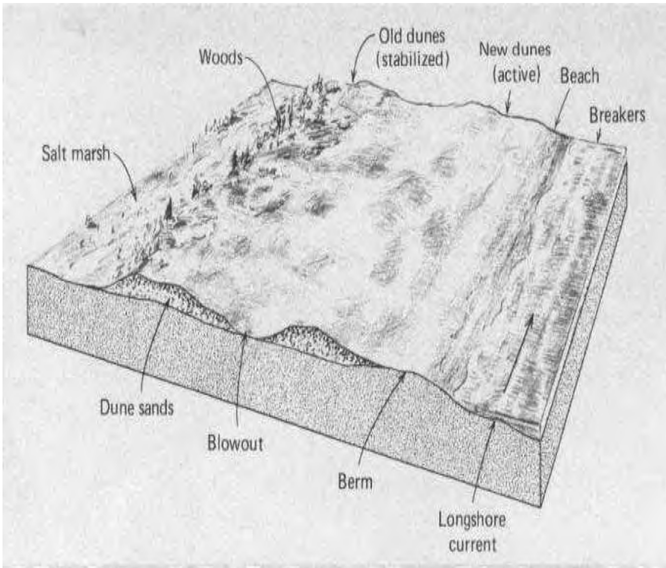
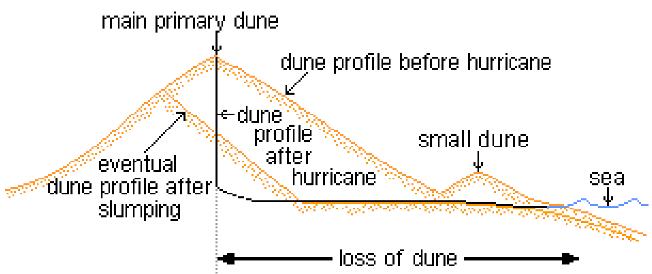


Figure 25. Cross section of a typical coastal area in Barbuda.



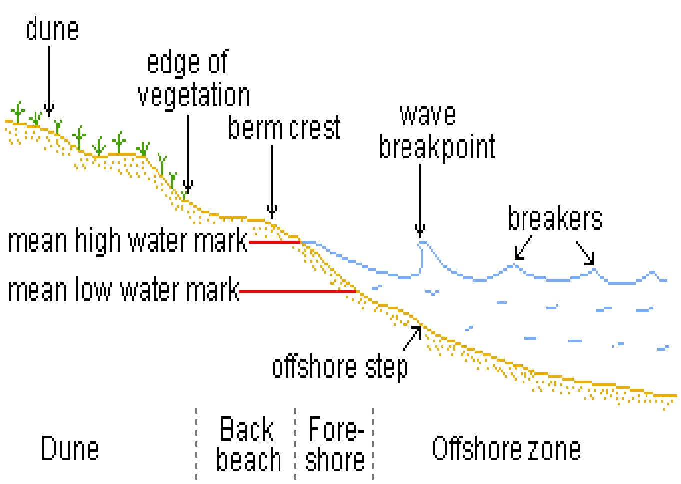


Figure 26. Cross-section showing typical beach slope from dune to offshore zone.

Palmetto Point

Palmetto Pont is the most dynamic area in Barbuda and any development in this area should be severely restricted. All sand mining in this area should be stopped immediately.

Figure 27. Typical sand dunes along Barbuda's eastern coastline.

Figure 28. Barbuda's southwest coast.

Figure 29. Typical sand dune in Palmetto Point area before sand mining.

Figure 30. Path through sand dunes near Palmetto Point.

Figure 31. Sand mining near Palmetto Point.

Figure 32. Ongoing sand mining near Palmetto Point.

Figure 33. Vast sand mining operation near Palmetto Point.

Figure 34. Sand mining operation near Palmetto Point. The elevation difference between the top of existing sand dunes and the excavation area varies between 1.8 and 3.2m.

Figure 35. Exposed ground water in the sand mining operation.

Figure 36. View from the Beach House Hotel. Sand dunes that used to occupy this area were removed to provide hotel guests with a view of the ocean.

Figure 37. Another view of what used to be sand dunes near the Beach House Hotel, taken during Hurricane Dean in August 2007.

Figure 38. After removing its neighboring sand dunes, the Beach House Hotel lost several buildings.

Figure 39. Sand enters a saltwater pool during a tropical wave in 2005.

Figure 40. Flooding in front of the Beach House Hotel during Hurricane Dean in August 2007.

Sand Berms

A sand berm separates Codrington Lagoon from the Caribbean Sea. The width of the berm varies from 44 to more than 120 m, while the estimated depth of sand on the berms varies between 2.5 to more than 16 m. Due to the hard compaction of sand along the berm, it was not possible to measure its depth, except in a few areas.

Canal Breach Photographs

Figure 41. Study area and the sand berm.

Figure 42. Breached section of the Canal sand dune.

Figure 43. Canal breach looking south.

Figure 44. Canal breach looking from the Caribbean Sea to the south.

Figure 45. Healthy mangroves on the lagoon side near the Canal breach. We hope to completely restore the forest along both breached areas.

Lewis Breach

The following are photographs of the Lewis breach area, which is currently used by residents and tourists for picnicking, swimming, camping, and sports.

Figure 46. Breached section of Louis Beach dunes.

Figure 47. Lewis breach from the lagoon.

Figure 48. From the Lewis breach looking north. The grasses and trailing vines are starting to grow and several coconut trees have been planted.

Figure 49. Swimming area on the lagoon side of the Canal breach.

Figure 50. Western end of the Canal breach. The vegetation is being naturally reestablished.

Figure 51. Limited vegetation on the breached section of Louis Beach.

Figure 52. Severe beach erosion on the western section of the sand beam, 600 m past the Lighthouse Bay Resort. This picture was taken the day after Hurricane Dean in August 2007. Vertical erosion was measured at 1.3 m.

Figure 53. The day after Hurricane Dean, near Lighthouse Bay Resort. Note the exposed broken branches/trees that were covered pre-hurricane, indicating that a tremendous amount of sediment was taken seaward.

Figure 54. Lagoon side of the sand beam next to the Lighthouse Bay Resort. Note the path cut through the mangroves.

Hurricane Dean

The following photographs were taken in Barbuda during Hurricane Dean on August 16 and 17, 2007.

These photographs show the damage done in Barbuda by a hurricane that was 207 km, or 112 nautical miles, away.

Figure 55. Track of Hurricane Dean through the Caribbean, August 2007. The closest the hurricane passed to Barbuda was the Commonwealth of Dominica, 207 km away.

Figure 56. 5,000-ton barge hits a pier in Dominica, 207 km away.

Figure 57. Nearly every piece of heavy equipment in Barbuda was used to hold the sand barge in place.

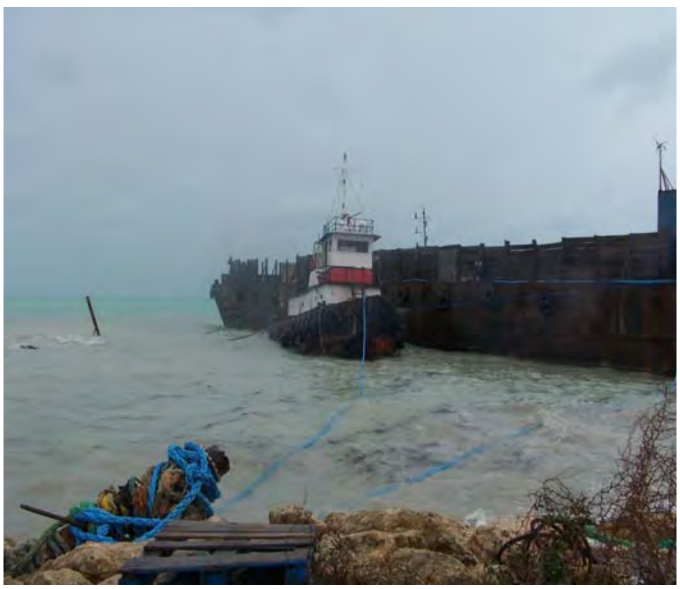


Figure 58. Two tugboats (one on each side) held the barge in place during Hurricane Dean.

Figure 59. Culvert connecting the inner harbor with the ocean.

Figure 60. Erosion along the shoreline near the pier.

Figure 61. North side of the pier during Hurricane Dean.

Figure 62. Pier during Hurricane Dean.

Figure 63. Ocean water collects near Martello Tower as a result of area development and loss of vegetation.

Figure 64. From the Martello Tower during Hurricane Dean. The water depth was estimated at 30 to 60 cm.

Quarry Activities

The following photographs show rock and limestone quarry activities in the highland area. The material is used to construct and reservice roads throughout Barbuda.

Figure 65. Quarry operation-crusher and cuts in the limestone cliff face.

The following photographs show the rock and limestone quarry activities being conducted in the “Highland Area”. The material is being used to construct and re-service roads throughout Barbuda.

Figure 66. Crusher and ongoing quarry operation.

August Survey of Indiantown Trail BA001

This pre-Columbian archaeological site is slightly inland from Two Foot Bay at the base of an active limestone quarry. BA001 had been recently disturbed by land clearing related to the quarry. The initial assessment determined the extent of the damage and provided recommendations to preserve BA001. Dr. Murphy’s report suggested that the site be protected and all land clearing activities stop. Furthermore, he was also recommended that the Barbuda Council collaborate with researchers from the City University of New York and the University of Calgary, under the supervision of the Nelson’s Dockyard

National Park Museum and Research Unit, to establish an archaeological research project to protect and preserve BA001. (Refer to the full report in Annex B.)

Figure 67. Aerial photograph of Indiantown Trail archaeological site.

Mangroves

An extensive mangrove forest is situated along the north, east, and south shorelines of Codrington Lagoon, extending in some places more than a kilometer inland (J. Mussington pers. comm.).

A mangrove forest regulates biological exchanges between land and marine systems and is an important source of dissolved organic carbons for the marine community. These forests also stabilize the shoreline, trap pollutants like sediments and nutrients before contaminating lagoon waters, and their roots shelter juvenile fish and invertebrates.

Some shoreline mangroves have been cleared around Codrington, and others have been destroyed by careless oil dumping from the power plant.

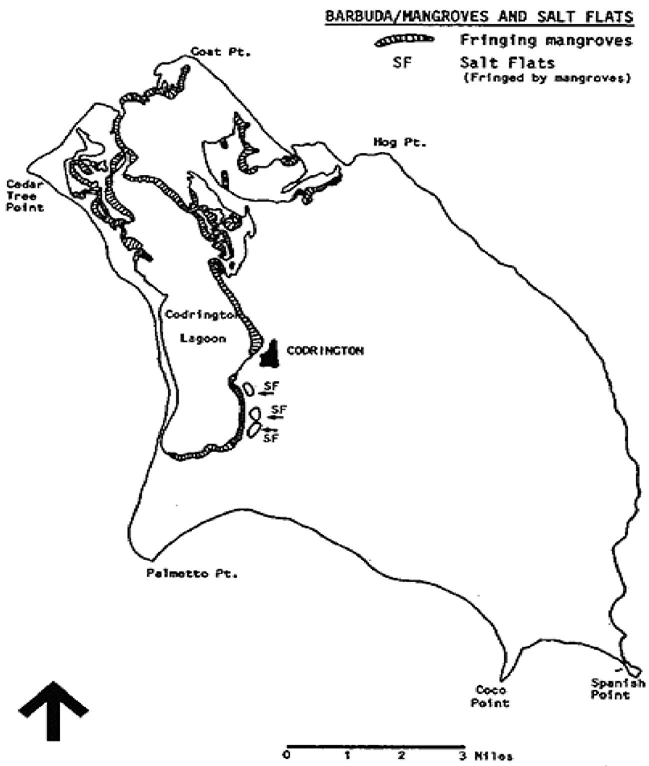
Apart from the areas where dumping or clearing has taken place, the mangrove forest of Codrington Lagoon is quite healthy. It houses four species of mangrove: white (*Laguncular racemosa*), black (*Avicennia germinans*), red (*Rhizophora mangle*), and buttonwood (*Concarpus erectus*).

Also found along the shoreline of the lagoon is a coastal dry forest species, Touchwood (*Jacquinia arborea*).

Extensive studies of Codrington Lagoon, including the mangrove system and dry forest species, have been done by John Mussington and Lianna Jerecki, Ph.D. (Proposed Ecosystem Monitoring Plan for Codrington Lagoon, prepared for the Environmental Awareness Group of Antigua and Barbuda, June 2000, Dr. Lianna Jerecki) and are not part of this brief study.

Figure 68. The mangroves have been completely destroyed in front of the power plant.

Figure 69. An area behind the power plant that has been destroyed by oil and waste.



Source: Antigua and Barbuda's First National Report to the Convention on Biological Diversity

Figure 70. Barbuda mangroves and salt flats.

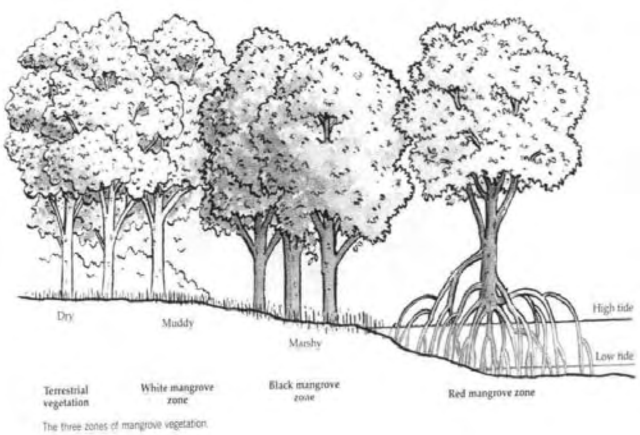


Figure 71. Cross-section of the three mangrove zones found along the coastline and wetlands of Barbuda.

Figure 72. Red mangroves (*Rhizophora mangle*) along the lagoon shoreline.

Figure 73. Red mangrove seedlings near the hospital.

Codrington Lagoon

The following underwater photographs were taken during the initial site visit on August 14, 2007.

Figure 74. The only coral reef in the lagoon.

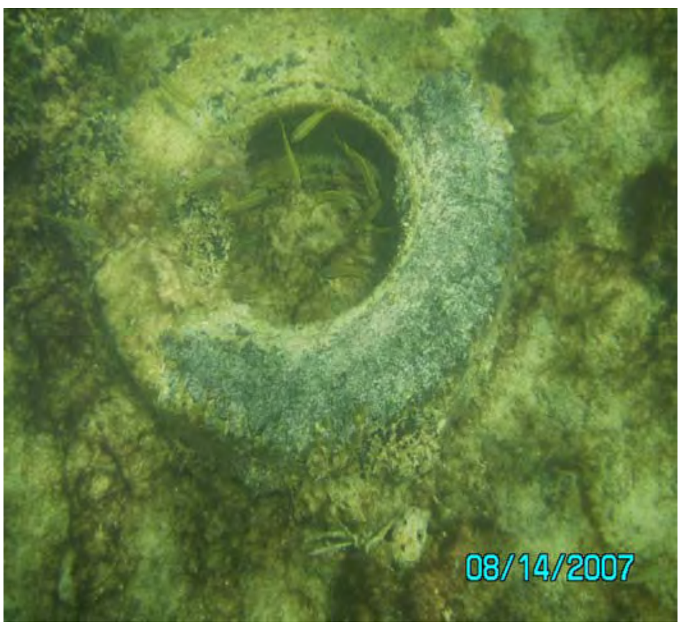


Figure 75. One of many old tires found during the underwater reconnaissance survey.

Figure 76. Another view of the only coral reef in the lagoon

Figure 77. Typical view of the lagoon ocean floor.

Figure 78. Typical seaweed along the coast.

Figure 79. Typical seaweed found along the coast.

Figure 80. Caribbean spiny lobster on the coral reef.

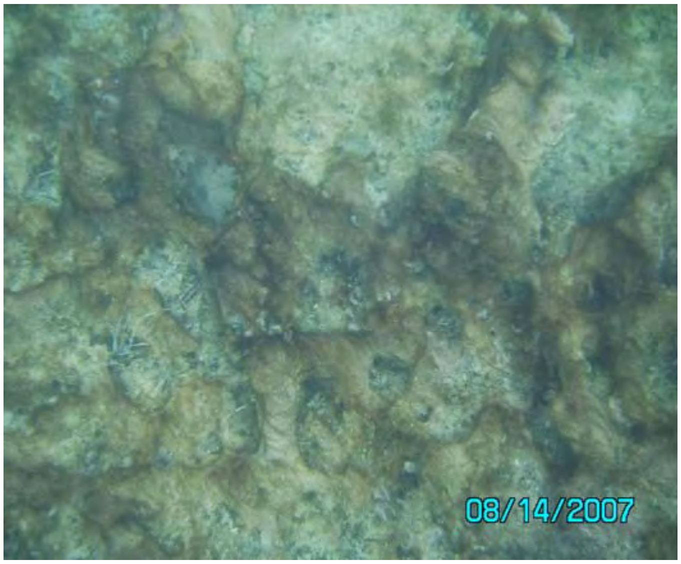


Figure 81. Dead seaweed.

SECTION IV. PROJECT OBJECTIVES

Objectives and Tasks

- Determine the level of threat posed to Codrington Lagoon and town of Codrington from storm surge and elevated flood levels in the lagoon.
- Investigate breached sections of the sand beam.
- Identify and demarcate potential high-impact areas from storm surge and flooding within the town and environs.
- Assess weak points in the lagoon where breaching from storm surges has occurred or is possible.
- Debrief the Barbuda Town Council on the report's findings and recommendations; make a similar public presentation.
- Develop and distribute printed material for both presentations.

Scope of Work

The scope of work was extended to design and incorporate an environmental education component into the project. The educational component includes three subcomponents:

1. The design, funding, and construction of a nursery at the Sir McChessney George Secondary school. The nursery will:

— Supply indigenous plants, trees, and shrubs for revegetation of breached sections of the sand dunes.
— Grow and supply mangroves and seagrape seedlings for the reestablishment of destroyed wetlands along the coastline.
— Teach schoolchildren in Barbuda the techniques of grafting and growing; how to care for indigenous plants, trees, and shrubs; and how to grow ornamental plants, trees, and shrubs to sell to local and regional hotels and resorts.

2. The design and construction of a sand-trapping fence in line with best management practices and to inform children that sand dunes cannot be viewed in isolation from other components of the coastal system. Sand dunes and beaches are so interdependent that they have to be managed together. Sand dune management, furthermore, should be viewed within in the overall context of integrated coastal area management through linkages with the physical, economic, and social components of coastal systems.

3. To teach bioengineering and bioremediation to the children:
— How to use vetiver grass to stabilize and protect the infrastructure, including roads, wetland areas, and construction/home sites.
— How to use vetiver grass to rehabilitate areas where sand has been taken.

Summary of Proposed Activity

- Construction of sand-trapping fence along two breached sections of sand beam.
- Revegetation of two breached sections of sand beam.
- Selective cutting of dead mangroves and seagrape trees along shoreline.
- Reestablishment of wetland areas destroyed by hurricanes or manmade activities by planning seagrape trees and mangroves.
- Construction of a berm to protect critical interstructure, such as the power plant, airport, infant school, and hospital.
- Construction of nursery to provide needed plants, trees, and scrubs for project.
- Develop school curriculum for construction, operation, and marketing of plants, trees, and shrubs from nursery.
- Develop school curriculum for sand-trapping fence.
- Give school children of Barbuda an understanding of the physical, ecological, and aesthetic functions of sand dunes, the importance of dunes in protecting the nation, and recognition of the economic value of sand dunes.

Physical Elements of Project

- Construction of sand-trapping fences.
- Planting of vegetation along two breached sections of sand dunes.
- Construction of nursery.
- Reestablishment of wetland areas.
- Construction of barrier reef units.
- Deployment of barrier reef units.

Consultant's Recommendation for Mitigation of Storm Surges on Codrington

Ocean Caraibes recommends construction of two sand-trapping fences along the two breached sections of the sand beams.

Dunes

Dunes are created by the accumulation of wind-blown sand transported landward from the backshore and higher portion of the intertidal foreshore. To successfully trap and retain this sand, dunes rely on vegetation, especially certain species of grasses, which reduce wind velocity close to the dune face, allowing deposition and retained moisture, which increases the threshold of motion of the sand grains.

Dunes on the backshore of a sandy beach are important in the development of the profile of that beach. They provide a capacity to store more sand than can be accommodated on the foreshore of the beach. They are a reservoir of material during storms and, if necessary, enable the beach profile to adjust to a flatter profile and absorb incoming wave energy. A well-stocked dune system also acts as a direct, cost-effective defense to flooding during extreme storm events. In addition, damage during storms is usually repaired naturally, unlike manmade defenses. These actions will protect Codrington from flooding and the full impact of storm surges.

Figure 82. Map of the two breaches in the sand beams.

A typical fully developed dune may reach 15 m, with a maximum height of 30 m. The rate of accretion depends on the strength and persistence of onshore winds, the rate of drying of sand particles on the beach surface and backshore, growing conditions for dune-building vegetation, and available sand supplies. Quantitative evidence for the natural rate of dune build-up is rarely available, but Ranwell and Boar (1986) quoted a vertical accretion rate of about 20 cm/yr at Newborough Warren, implying that a dune may take 75 years to reach its full height there. It is clear, however, that accretion can involve hundreds or even thousand of cubic meters per linear meter of coast during a single year, hence comparing in scale to major artificial recharge exercises.

It follows that reducing the capacity of dunes to accrete during favorable conditions is likely to increase the risk of damage and flooding to Codrington.

Presently, the dune's sand beams act as the major flood defense along the coastline of western Barbuda.

USAID's efforts to mitigate damage from storm surges on Codrington will result in the preservation and enhancement of the dunes.

Figure 83. Revetment along West Bay Street, Bahamas. We considered revetments along sections of the critical internal structure, but due to their unsightly nature and high cost, this option was ruled out.

Figure 84. Rebuilt dune at White Sound, Elbow Cay, Abaco, Bahamas. This is a preferred method because of its cost and aesthetic appeal.

Rebuilding. Lost dunes must be rebuilt with nearby sand in conjunction with beach feeding, if necessary, and vegetation replanting. A successful example of dune restoration is currently being monitored in Guana Cay.

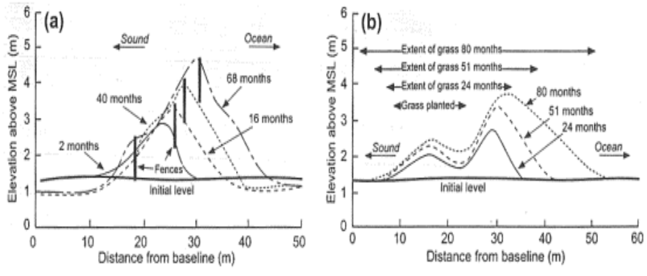


Figure 85. Two examples of dune reconstruction with fencing and planting (a) and by planting sea grass without fencing (b), Outer Banks, North Carolina. (Masselink and Hughes, 2003.)

Management. Active dune management can be a cost-effective and environmentally friendly defense for Codrington. Dunes act as barriers against sea flooding, as reservoirs of sand replenished when beach levels are high, feeding extra material to beaches during hurricanes. Dune management for Barbuda should consist of:

- Reducing and eliminating damage to natural dunes by human activities.
- Improving the natural capacity of dunes to attract and store sand.
- Artificially adding material to dunes or creating new dunes by construction of a sand-trapping fence.

Dune management can produce aesthetically pleasing, environmentally friendly beaches while reducing the need for expensive defensive structures like seawalls, breakwaters, retaining walls, and bulkheads. However, such management can also require regular monitoring and intervention, labor-intensive management techniques (planting/fencing), and limit access by vehicles or heavy equipment, including light pick-up trucks, bobcats, and small backhoes.

Interaction between foreshore and dune system. The beach and dune systems are interrelated — management of one has repercussions for the other — as material is naturally exchanged between the two. When sand dries on the foreshore, the particles are no longer cohesive and may be picked up and transported to the dunes by the wind. Conversely, the dune system acts as a sand reservoir. Sand released from dunes and eroded by wave action during storm events, replacing what is lost from the foreshore and raising and flattening the beach profile.

Wind and wave energy. The nucleus for dune formation is often an obstacle on the strand line of the upper beach, such as a pile of driftwood or seaweed. Sand particles carried by the wind are deposited on the windward side of the obstacle. The pile increases until the tidal litter is buried, the surface of the pile is smooth, and wind resistance no longer enhanced. Further accumulation of sand is unlikely unless pioneer vegetation colonizes the embryo dune.

Embryo dunes are highly unstable. Their form and fate are governed by wave and wind energies. Embryo dunes will only mature into vegetated, stable dunes if they develop above the main high water spring mark. Without plants to stabilize shifting sand and increase accretion by trapping sand in aerial shoots, the embryo dune cannot grow vertically or laterally. Furthermore, the destabilized dune may be destroyed by the wave energy of the next tide, which can remobilize the sand and displace the litter nucleus.

A dune will grow in height as long as accretion outpaces wind erosion. The degree of erosion of the crest depends on the climate and supply of sand. The velocity of wind tends to become stronger at higher elevations, hence wind erosion on the dune crest increases as dune accretion grows vertically. Humidity, rainfall, and temperature are other climatic variables that affect dune morphology.

Vertical growth may cease if a dune ridge develops in front and intercepts wind-blown sand. This is particularly common on accreting sand shores, where successive dune ridges are formed in front of existing ones, as on the east coast of Barbuda.

If the wind is variable in direction, the shape and movement of the dune is irregular. However, under more constant wind direction, morphology and movement are more predictable. The windward dune side is steeper than the leeward side (see Figure 85) as sand on windward slopes is blown over the top to the leeward side.

Vegetation. Grasses that colonize the mobile sand of embryo dunes are crucial for the development of higher, more stable dunes, which provide better coastal protection. Colonization begins by the establishment of plants from fragments of rhizomes or seeds, which may be present in the litter that formed the nucleus of the embryo. Tidal litter aids the growth of these pioneers by ameliorating the natural factors that limit dune vegetation, i.e., through stabilizing mobile sand, acting as a source of nutrients, and increasing soil moisture. Management techniques can enhance the development of embryo dunes by reproducing the effects of detritus on the strand line.

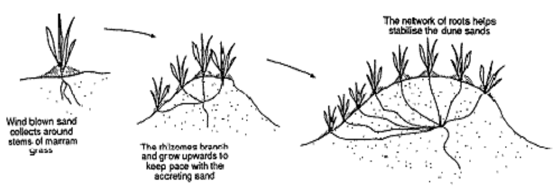


Figure 9.2 *Stylised diagram to illustrate the role of pioneer grasses in embryo dune formation*

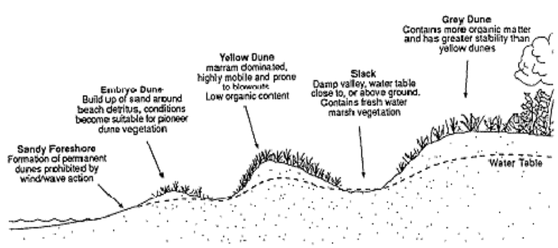


Figure 86. Cross-section of an idealized dune system as found along the eastern coast of Barbuda.

Figure 86 shows how grasses, such as Marram grass (*Ammophila arenaria*), spread as new tussocks of shoots sprouting from rhizomes. These extra shoots increase the rate of accretion by enhancing wind resistance and sand trapping. To prevent the shoots from being buried by wind-blown sand, the rhizomes grow upward and outward to keep pace with accretion. This radiating network of rhizomes improves the stability of the sand heap in the face of wind and wave action.

Sand-trapping fences and vegetation. To speed the natural rate of dune rebuilding following damage by two hurricanes and several tropical storms, USAID's priority is to construct two sand fences and plant suitable vegetation in the breached sections of sand beam.

Sand fences aid accretion. They should be positioned at a sharp angle in the direction of prevailing winds, as sand will only be deposited if the fence is a barrier to air flow. The way the dune is rebuilt can be manipulated by deploying fences in a timed sequence; their positioning and timing determines weather accretion will increase the width or height of the dune field (see Figure 87).

Solid fencing would scour the sand on the windward side of the fence and around the ends. Permeable barriers are much more effective at accelerating accretion. Option porosity is approximately 50 percent, with effectiveness decreasing significantly as porosity increases to more than 65 percent.

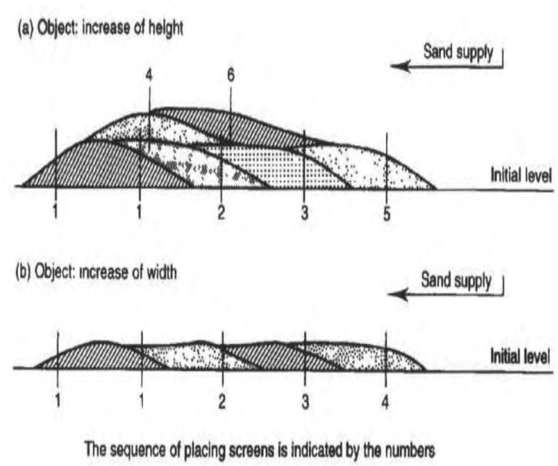


Figure 87. The use of fences to gain height (a) and increase the width of dune field (b) (Blumental, 1964).

Figure 88. Typical sand fence.

Figure 89. New sand fence.

Figure 90. Sand fence at Holly Beach.

Figure 91. Sand fence on Miami Beach.

Figure 92. Sand fence on Ocean City Beach.

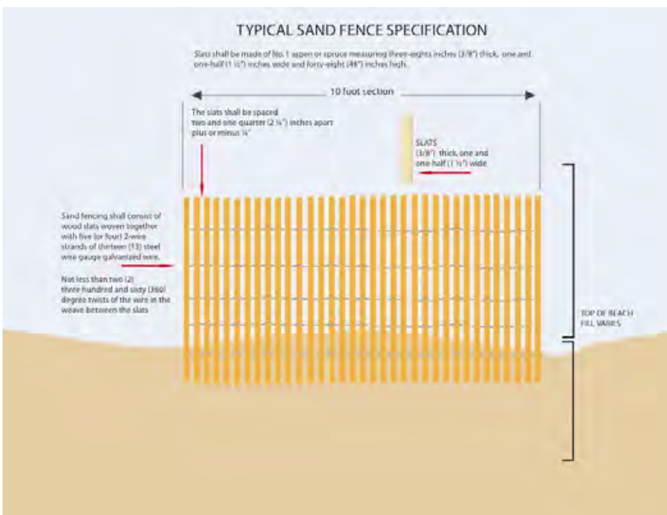


Figure 93. Sand fence specifications.

Sand Fence Design Considerations

The following are design considerations to be considered:

- Sand fencing is usually sold in 50-foot rolls.
- The sand fence is left natural to blend into the surrounding landscape, without paint, stain, or other preservatives.
- The sand fence is biodegradable and environmentally friendly.

Wind Speed

Based on fundamental research on desert dunes (Bagnold, 1954), significant sand movement will take place when wind speeds 1 m above ground level exceed 12 knots (6 m/sec). In the wider Caribbean, with its dominant northeast trade winds, average wind speeds equal or exceed this value, especially in June-July and December-March.

Wind speed measurements taken on the top of sand beams during the two site visits averaged more than 15 knots (8 m/sec).

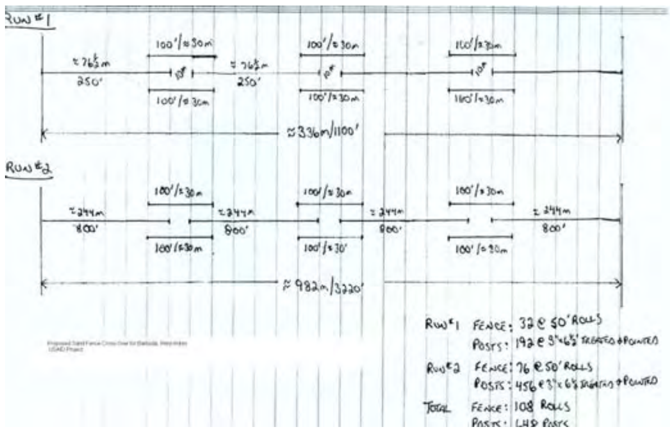


Figure 94. Sand fence specifications for Codrington.

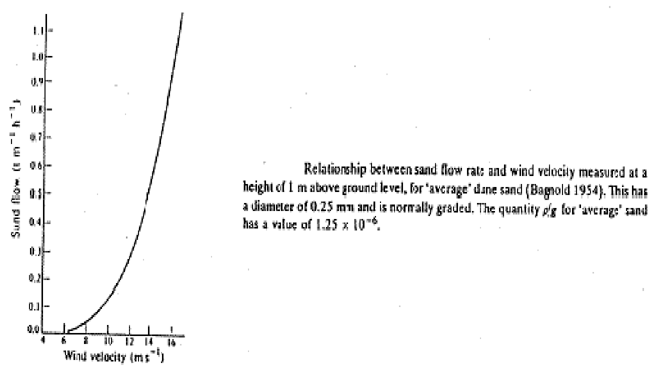


Figure 95. Relationship between sand flow rate and wind flow.

Site Assessment Survey

A site assessment survey was conducted during the initial site visit in August following United Nations Environment Programme and State of Florida best management practice guidelines for the construction of sand-trapping fences.

Left to themselves, inlets come and go naturally. Usually, an inlet forms when a storm surge carries water across a barrier island (Figure 96, part 1). When the storm ends, excess water seeks a way back to the sea, breaking through a weak spot (2). Currents carry sand along the island shore, and tides carry it in and out of the new inlet's mouth, where it is deposited in tidal fans (3). The inlet mouth fills with shoals (4) and eventually the inlet heals over (5) (Dean, 1999).

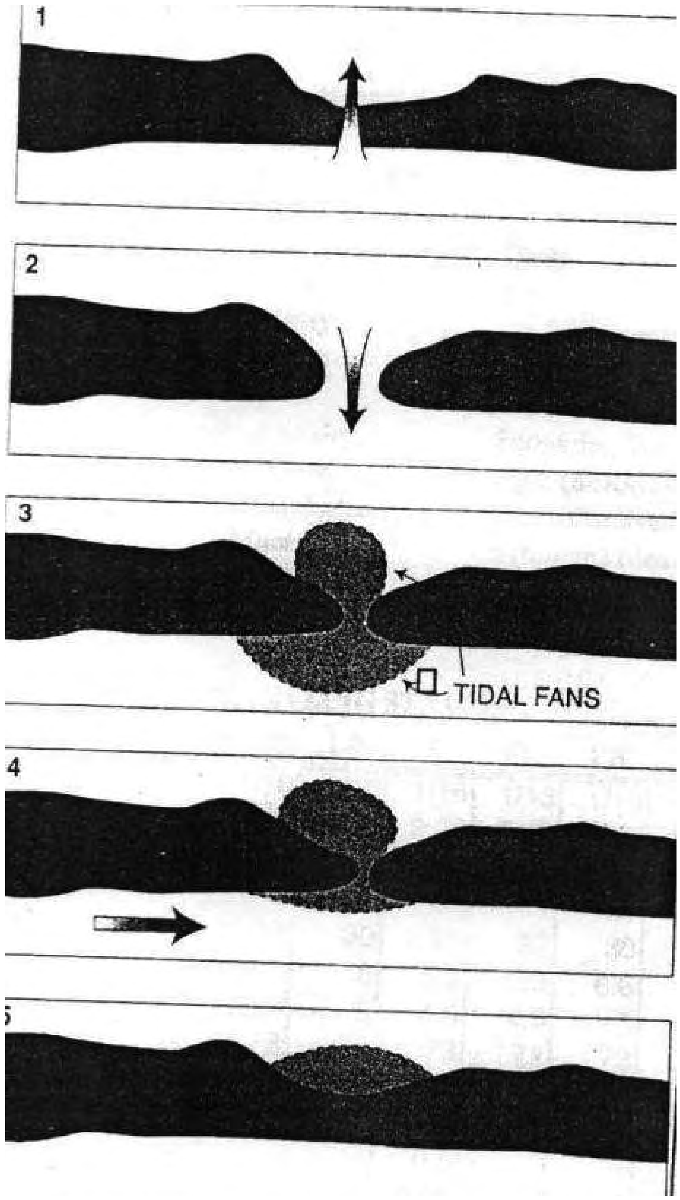


Figure 96. Taken from Dean, Cornelia, 1999, "Against the Tide: The Battle for America's Beaches," p. 73, Columbia University Press, New York.

Figure 97. Sand dunes protected by Maccaferri's Reno mattress, Option 7.

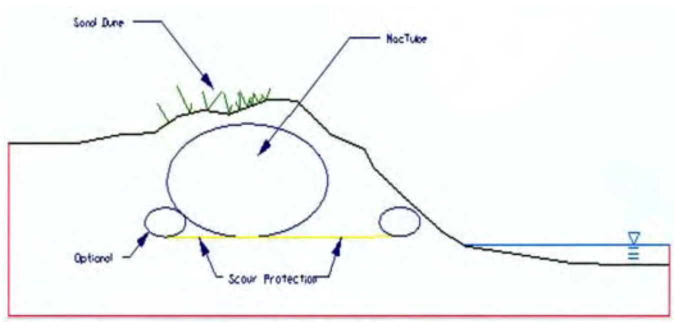


Figure 98. Proposed use of geotextile tube, which would rebuild breached sections in sand dunes. This is an example of Option 8.

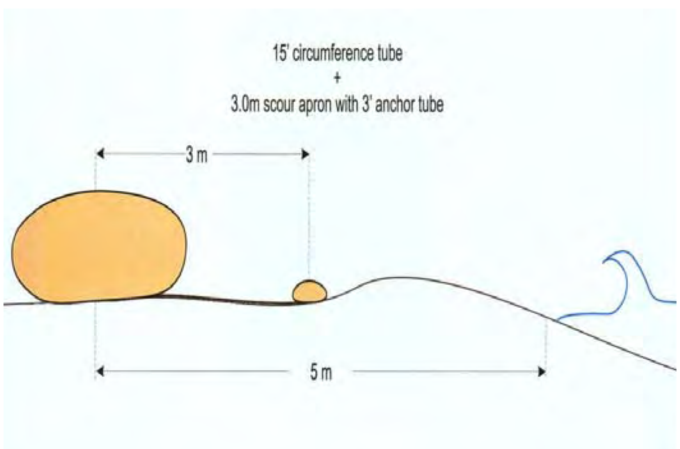


Figure 99. Geotextile tubes used to create a beam to protect the shoreline of critical interstructure around Codrington.

Nursery Location and Environmental Education Program

Figure 100. Satellite image of the Sir McChessney George Secondary School, which covers 10.53 acres.

Figure 101. Two of the McChessney school's buildings.

Figure 102. Proposed area for the nursery at the school.

Figure 103. Another view of the proposed nursery site.

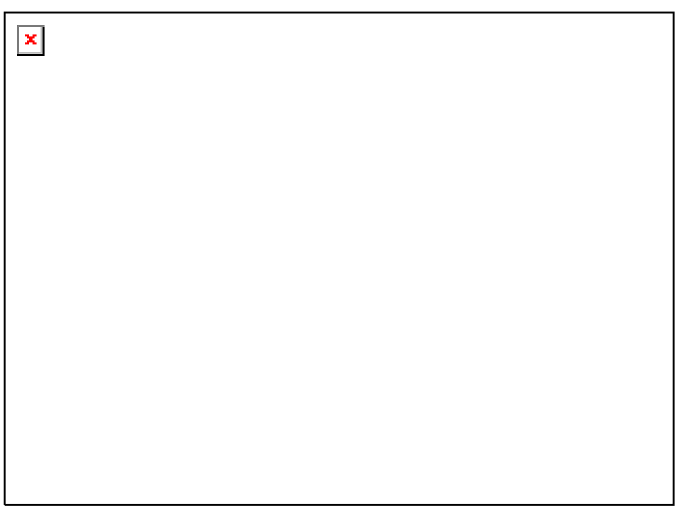


Figure 104. Site plan for the McChessney school, showing the land currently in use.

Figure 105. Aerial photographs of critical interstructure from the airport to the fishing complex.

Seismic Action

Ocean Caraibes looked at the geologic history of the area, soil conditions, and potential fluctuations of water conditions throughout the life of the structure to select the most appropriate input parameters for any seismic equation. References were made to the ASCE Geotechnical Special Publication No. 20, which are the Proceedings of the ASCE Specialty Conference on the Design and Performance of Earth Retaining Structures (Ithaca, N.Y. 1980) and a paper by Robert V. Withman, “Seismic Design and Behavior of Gravity Retaining Walls.”

Due to the flexible nature of the rock armor and barrier reef units, minor seismic action will not have an adverse effect on proposed barrier reef structures.

Logistics

Barrier reef units. For a project of this magnitude — the construction and deployment of thirteen hundred 4,000-pound barrier reef units by land — the question of construction access takes on significance. The ideal method to place the units is by barge, but the only operating barge in the lagoon is not capable of carrying more than two units at a time with a crane. Furthermore, the depth of the lagoon runs from 50 cm to a maximum 1 meter. Moving the units by barge will not be possible so deployment must be done from land.

There is no easy path between the main road and the lagoon without going through the mangroves along the shoreline and in the wetland area, thus destroying mangroves in the process.

Sand-trapping fence. Due to the sensitive nature of the sand dunes, it is strongly recommended that no heavy equipment be used — including small backhoes or bobcats. We will move the sand-trapping fence from the lagoon to the breached sections of the sand dune by manpower, which will add another day to construction time but will preserve the dune and its vegetation.

Turtle nesting. We cannot find studies or data that suggest the area is a turtle nesting site. There are some hawksbill turtles (*Eretmochelys imbricate*) living in the vegetation behind the beach, but since the fence will be constructed in areas without vegetation, the turtles will not be disturbed.

Field Data

Methodology

1. Distance measurements were done with a Bushnell Yardage Pro 800 laser rangefinder.

2. A visual underwater obstruction and inspection survey was carried out by snorkeling at different times of the day and by being pulled behind a small boat from the breached section of Louis Beach to the fishing complex.

3. Slope angles were measured along the beach by using a SOKLIA clinometer.

4. Underwater photographs were taken using a SeaLife DC500 5 mp digital underwater camera.

5. Land photographs were taken using a Kodak DX-6490 digital zoom camera.

6. Coral reef inventory and distribution patterns were examined during the site visit and recorded in field book number 16 of the 2007 USAID Barbuda project.

7. Aquatic habitats/inventory and distribution patterns were examined during the site visit and recorded in field book number 16 of the 2007 USAID Barbuda project.

8. The compaction strength of the soil was tested in various locations using a pocket penetrometer and recorded in field book number 16 of the 2007 USAID Barbuda project.

9. *In situ* notes were taken on Ziccpe underwater paper using a U/W writing pen and pad.

10. GPS readings were taken using a Magellan Exploits 450.

11. Eight sand samples were taken at various locations in Barbuda. The samples were visually inspected and then placed in zipper-locking bags and taken back to the laboratory in Dominica, where they await analysis.

12. Sand depth was measured along the sand berm using a 3-meter section of ½” rebar, marked off every 50 cm and recorded in field book number 16 of the 2007 USAID Barbuda project.

13. Taxonomic determinations were made *in situ* with the SeaLife DC500 camera. No destructive sampling was necessary.

14. Information for the possible use of barrier reef units and artificial reefs to provide habitat was provided by Scott Bartkowski, president of Artificial Reefs Inc. and Coastal Restoration Inc. of Gulf Breeze, Florida.

15. Discussions were held with several Barbudan contractors to discuss various phases of the project. Tenders were taken from two local Barbuda contractors for construction of a nursery at the secondary school.

GPS Coordinates

GPS reading were taken at key areas, including:

- Canal breach (17°.37.271 N & 061°.51.042 W)
- Louis breach (17°.38.700 N & 061°.51.176 W)
- Power plant (17°.38.335 N & 061°. 49.813 W)
- Center of airport runway (17°.38.149 N & 061°.49.849 W)
- Centre of fishing complex (17°. 38.534 N & 061°.49.748 W)

Measurements were taken of breached sections in the sand beam. The measurements were taken from the mean high tide level on the ocean side of the beam to that of the lagoon.

Canal breach. The width of the beam varied from 59 m near the northern side to 116 m on the southern side. The length of the breach section is 646 m.

Louis breach. The width of the beam varied from 44 m near the southern side to 60 m on the northern side. The length of the breach section is 336 m.

Wetland Area around Critical Interstructure

Figure 106. Looking west from the back of the airport.

Figure 107. Looking east from the back of the airport.

Figure 108. Destroyed mangroves near the fishing complex, almost directly behind the Italas James Infants Department School.

Figure 109. Typical nearshore marine life in the lagoon

Figure 110. Commercial pier in the lagoon.

Figure 111. Barbuda Fishing Council Office.

Figure 112. From the commercial pier looking south into town.

Figure 113. Barbuda Fishing Council office and the commercial pier.

Figure 114. Lagoon area looking toward town.

Figure 115. View of primary school from the fishing council office.

Figure 116. Barbuda Meeting Hall from the harbor.

Figure 117. Barbuda Emergency Response Office.

Figure 118. Area of the proposed Japanese fishing complex.

Figure 119. Lagoon looking west.

Figure 120. Geotextile tubes used to create a wetland area similar to the proposed wetland area for Barbuda, Option 8.

Vegetation Revisited

As part of beach replenishment, efforts should be made to encourage and protect vegetation near the landward edge of the beach. All leaning trees should be straightened and propped up from underneath. Palm and seagrape trees and Caribbean pines could also be planted along the beach to provide shade and beauty.

Suggestions. We also encourage planting sea grape trees (*Cocoloba uvifera*) and the Western Indian almond (*Terminalia catappa*). The coconut palm (*Cocos nucifera*), which is not native (it was introduced from the Indo-Pacific region), is very common on the island. Tourists associate the coconut palm with the Caribbean. It is a useful tree, providing milk, meat, oil, and other products. However, it is shallow-rooted and easily undermined by high waves. Several types of geofabric mats (a loose-weave synthetic material) could be fashioned into a cage around remaining root networks, providing additional protection for roots.

The dry beach area above the high-water mark is part of the salt spray zone and could be colonized by grasses like seashore dropseed (*Sporobolus virginicus*) and trailing vines like beach morning glory (*Lpomea-pes-capae*). This vine is also known as goat foot and has pinkish purple flowers. We also recommend vetiver grass (*Vetiveria zizaniodies*) in the new development. Vetiver could be planted along the beachfront and kept short like a lawn to mitigate the loss of sediments seaward, especially during tropical storms and hurricanes.

ANNEX A. MACCAFERRI QUOTES FOR RENO MATTRESSES

Of the two prices quoted, one uses Galfan and PVC Reno mattresses ($196,308) and the other uses galvanized and PVC Reno mattresses ($187,308). The design life of the latter is 20 years, while the product with Galfan lasts two to four times as long — 40 to 80 years. Therefore, we strongly recommend using the Galfan wire and PVC.

Figure 121. Quote WI-07-047A

MACCAFERRI

299 Alhambra Circle, Suite 314
Coral Gables, FL 33134 -5114
Tel. (305) 569-9890
Fax (305) 569-9124

QUOTE #: WI-07-047A

TO:	Cliff Juillerat	**PROJECT NAME:**	
COMPANY:	USAID	**LOCATION:**	Barbuda
PHONE:	767-448-5962	**BID DATE:**	
FAX:	767-440-0464	**PROJECT #:**	
DATE:	10/1/2007		

Quote WI-07-047A is based on 1800 5m x2m x.3m Reno Mattresses. necessary to cover an area of 360m x 50m using Galvanized + PVC coated type wire.

Quantity	Product Description	Unit Price	Extended Total
	6x8 Mesh, 2.2mm Mesh Wire Diameter, Galvanized + PVC Reno Mattress		
1,800	5m x 2m x .3m	$ 104.06	$ 187,308.00
			$ -
			$ -
			$ -
			$ -
		Subtotal	$ 187,308.00
		Sales Tax	
		Freight	Included
		GRAND TOTAL CIF BARBUDA	$ 187,308.00

TERMS

UNIT PRICES: FOB PLANT [x] FOB JOB SITE [ ]

Mattress unit prices as quoted are inclusive of standard amount of lacing wire for initial assembly & installation.

PAYMENT: NET ____DAYS [ ] CBD [ ] VISA [ ] MASTER CARD [ ]

DELIVERY: 45-50 days from date of order for material in stock.

VALIDITY: 30 days from above date

NOTE:
Origin: Maccaferri Brazil Plant
3- 40' containers and 1-20' container.
20' container is 60% full.
It is advisable to use fabric under the mattresses. Please advise if you need a quote on this material as well.

Best regards,

Giuseppe (Pino) Cignarella
Regional Manager of S.E. and Export

" For additional information about our products please visit us at www.maccaferri-northamerica.com"

Figure 122. Quote WI-07-047B

MACCAFERRI

299 Alhambra Circle, Suite 314
Coral Gables, FL 33134 -5114
Tel. (305) 569-9890
Fax (305) 569-9124

QUOTE #: WI-07-047B

TO:	Cliff Juillerat	**PROJECT NAME:**	
COMPANY:	USAID	**LOCATION:**	Barbuda
PHONE:	767-448-5962	**BID DATE:**	
FAX:	767-440-0464	**PROJECT #:**	
DATE:	10/1/2007		

Quote WI-07-047B is based on 1800 5m x2m x.3m Reno Mattresses necessary to cover an area of 360m x 50m using Galfan + PVC coated type wire for extended life of the mesh versus the Galvanized+ PVC type (approximately twice the life).

Quantity	Product Description	Unit Price	Extended Total
	6x8 Mesh, 2.2mm Mesh Wire Diameter, Galfan + PVC Reno Matresses		
1,800	5m x 2m x .3m	$ 109.06	$ 196,308.00
			$ -
			$ -
			$ -
			$ -
	Subtotal		$ 196,308.00
	Sales Tax		
	Freight		Included
	GRAND TOTAL CIF BARBUDA		$ 196,308.00

TERMS

UNIT PRICES: FOB PLANT [x] FOB JOB SITE [ ]

Mattress unit prices as quoted are inclusive of standard amount of lacing wire for initial assembly & installation.

PAYMENT: NET ____DAYS [ ] CBD [ ] VISA [ ] MASTER CARD [ ]

DELIVERY: 45-50 days from date of order for material in stock.

VALIDITY: 30 days from above date

NOTE:
Origin: Maccaferri Brazil Plant
3- 40' containers and 1-20' container.
20' container is 60% full.
It is advisable to use fabric under the mattresses. Please advise if you need a quote on this material as well.

Best regards,

Giuseppe (Pino) Cignarella
Regional Manager of S.E. and Export

" For additional information about our products please visit us at www.maccaferri-northamerica.com"

Figure 123. Quote WI-07-052

Coral Gables, FL 33134-5114
Tel. (305) 569-9890
Fax (305) 569-9124

QUOTE #: WI-07-052

TO:	Cliff Juillerat	**PROJECT NAME:**	Dune Core
COMPANY:	USAID Barbuda project	**LOCATION:**	Barbuda
PHONE:	767-448-5962	**BID DATE:**	
FAX:	767-440-0464	**PROJECT #:**	
DATE:	10/11/2007		

Maccaferri is pleased to submit this quote based on the products and sizes as requested:

Quantity		Product Description	Unit Price	Extended Total
		Mac Tube MT46 with Scour Apron System		
855	LFT	15' circumfrence tube, Fabric 4x6 Polypropilene	$14.99/LFT	$ 12,816.45
		(1 tube-135', 2 tubes- 160', 2 tubes- 200')		
875	LFT	Scour Apron	$18.73/ LFT	$ 16,388.75
		Subtotal		$ 29,205.20
		Sales Tax		
		Freight and Insurance		$ 1,822.15
		GRAND TOTAL CIF St. John's, Antigua		$ 31,027.35

TERMS

UNIT PRICES: FOB PLANT [X] FOB JOB SITE [ ]

PAYMENT: NET ____DAYS [ ] CBD [X] VISA [ ] MASTER CARD [ ]

DELIVERY: 10 days from date of order for material in stock.

VALIDITY: 30 days from above date

NOTE:
•PRICES ARE INCLUSIVE OF COST OF MATERIAL, INSURANCE AND FREIGHT ONLY (LOCAL TAXES, PORT COST, DUTIES, OFFLOADING OF CONTAINER, DEMURAGE, ECT.) NOT INCLUDED. FORWARDING TO BARBUDA NOT INCLUDED.

•Sailings are weekly to Antigua, materials must arrive on Tuesday by Noon for Wednesday departure to Antigua.
Total Nominal Weight: 2,915 lbs
Total Nominal Volume: 288 cubic feet

Best regards,

Giuseppe (Pino) Cignarella
Regional Manager of S.E. and Export

" For additional information about our products please visit us at www.maccaferri-northamerica.com"

ANNEX B. BARBUDA ARCHAEOLOGY REPORT

In spring 2006, the Barbuda Council contacted Dr. Reg Murphy of Nelson's Dockyard National Park Museum, Antigua and Barbuda, to assess archaeological site BA001 (see Figure 67). BA001 is a pre-Columbian archaeological site located slightly inland from Two Foot Bay and at the base of an active limestone quarry. BA001 had been recently disturbed by land clearing for the quarry. The initial assessment determined the extent of damage and provided recommendations to preserve BA001. In his report, Dr. Murphy suggested that the site be protected and all land-clearing activities stop. Furthermore, he also recommended that the Barbuda Council collaborate with researchers from the City University of New York (CUNY) and the University of Calgary, under the supervision of Nelson's Dockyard National Park Museum and Research Unit, to establish an archaeological research project aimed at the protection and preservation of BA001.

In July 2006, Dr. Murphy and Ph.D. students Cory Look and Matthew Brown from the Graduate School and University Center of CUNY met with Calvin Gore of the Barbuda Council to establish the collaborative project on Barbuda's cultural heritage, scientific understanding of BA001, and the archaeology of Barbuda in general. During this meeting, Mr. Gore showed the researchers a number of sites, many of which are at risk due to human and natural impact.

One of those sites was BA016 on the Atlantic coast near BA001. As a result of natural erosion and hurricane activity, BA016 was in danger of being completely lost. Archaeological material, including ceramics (Saladoid period), shell beads, lithics, and animal bones, were observed eroding from the dune face. Prior to the involvement of Dr. Murphy and the CUNY researchers, a pre-Columbian human burial was removed from the site. The remains were described as a single individual in a sitting position holding a ceramic pot. Unfortunately, this burial and all artifacts associated with it have been removed from the island without permission and have not been returned. The site has important implications pertaining to early human settlement on Barbuda and to Caribbean heritage in general.

In January 2007, a team of Dr. Murphy, Mr. Gore, Dr. Sophia Perdikaris (professor of archaeology, Brooklyn College, CUNY), Dr. Arni Einarsson, (ornithologist, director of the Myvatn Biological Station), doctoral researchers Matthew Brown and Cory Look, and undergraduate students from Brooklyn College visited the areas previously identified. Preliminary surveys and test excavations were carried out on BA001 and BA016 to begin the systematic study and preservation of these areas. This work provided the foundation for more in-depth research.

A grant to Dr. Perdikaris funded the August 2007 field work in Barbuda. This project was a continuation of the work discussed above. This project was conducted by Cory Look and Matthew Brown and undergraduate researchers Courtney Scott and Marissa Gamliel in collaboration with Dr. Murphy and Mr. Gore. Over a 3-week period, we mapped more than 1,000 m^2 of BA001 in the northwest quadrant. This included using GPS and electronic theodolite techniques to make an accurate map of the area. For each 5x5 m grid square mapped, we recorded elevation, cultural material, and vegetation.

Continuing a collaboration that began in January 2007 with Chad Knight-Alexander of the Planning Office in Barbuda, we began defining the boundaries of BA001. While our survey during August 2007 focused primarily on the northwestern quadrant, we identified the presence of pottery, shell, bone, and stone tools in the southwest quadrant. This area originated from the active limestone quarry and continued as far as the housing structure built into the limestone outcrop. We were informed by Mr. Knight-Alexander that as a result of our collaboration, an active road that truncates cultural material within BA001 would be redirected. Additional quadrants will be systematically surveyed during January 2008, assisting in the further preservation of this site.

Due to rapid erosion, BA016 was the second focus of our rescue project during January 2007. GPS points were taken along the top and bottom edge of the coastal wall where cultural artifacts had been eroding. It is unknown as to how much material has been lost due to erosion, although an attempt has been made to document the rate of erosion within the last year. We returned during August to obtain additional points along this edge. Cultural material was observed eroding along this coastal site. Further GPS points were collected in areas where cultural material had not been observed in January but were eroding during August, thus extending the coastal site. In January 2008, we will return to collect another set of points and evaluate the data. Additional notes were made on the effects of hurricane activity on this region. In late August, Hurricane Dean passed south of Barbuda. While it did not directly pass through Barbuda, increased wind and wave activity were noted along BA016. Moderate disturbance of the coastline was noted between the areas of contact between the ocean and sand.

These archaeological sites offer important information on subsistence, environment, fauna (terrestrial and marine), and flora over long periods of time. Excavation and analysis of the archaeological material (biological and non-biological) will allow us to begin to understand human behavior in relationship to change in available resources, climate, or cultural influences. Importantly, these variables must not be looked at as isolated, unrelated events. The interaction between humans and their environment (cultural and natural) needs to be looked at as a synergistic relationship. The preservation of BA001 and BA016 as well as other pre-Columbian sites on Barbuda is vital if we are to gain a more accurate understanding of human impact on island ecology.

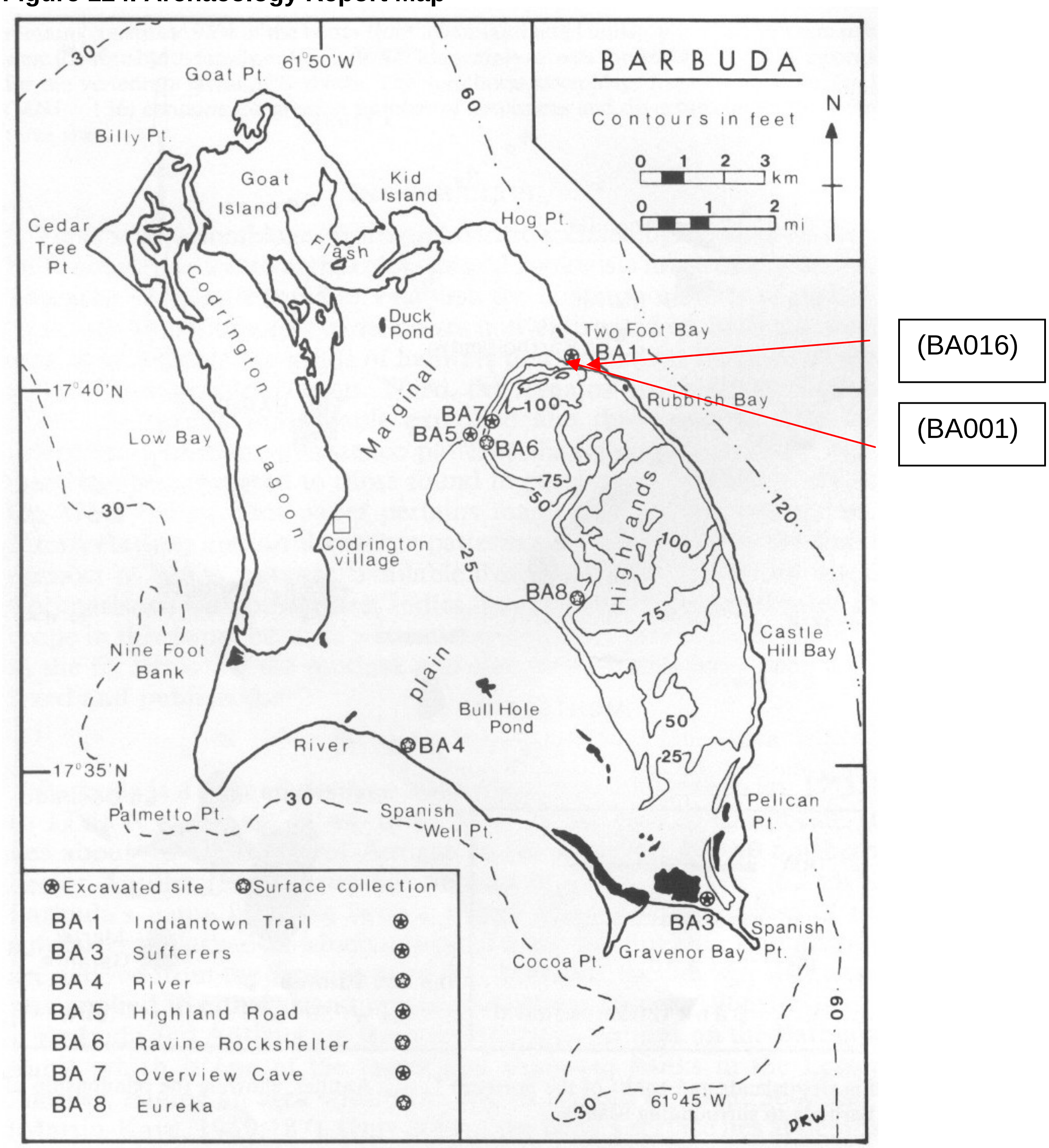
There is no question that humans, probably more than any other species, have had an impact on the natural environment. Prehistoric peoples in Barbuda were no exception. To understand the prehistoric landscape, we must have an idea of what was present (vegetation, lakes, sediments, etc.) prior to the first human settlement on Barbuda. Human decision-making is often related to local climate and availability of resources but is ultimately a complex web of cultural and natural variables.

The relationship between Amerindians and the local environment in Barbuda is currently unknown. Before we can piece together human impact on the environment, we need a baseline to compare what we see in the archaeological record. In August 2007, we began creating a picture of the environment prior to the first settlement.

With limited time, we were only able to test the possibility of obtaining sediment cores from the lagoon. With the help of Mr. Gore, we obtained three cores from different areas in the lagoon. Work proposed for January 2008 will include retrieving core samples from the lagoon and Darby's sinkhole for analysis. By looking at core samples from the lagoon area, we will look for the preservation of sediments that would provide clues to the timing of major climatic events, such as hurricanes, that may have altered the island's landscape. Darby's sinkhole will be cored to assess the preservation of pollen, phytoliths, and other plant material that may reveal the vegetation that greeted the Amerindians during their migration. Finally, lakes and ponds will be surveyed and possibly cored. These areas offer the best options for microtephra and vegetation changes through time.

Dr. Perdikaris, Matthew Brown, Cory Look, Dr, Murphy, and Mr. Gore will return in January 2008 to continue their work. They will be joined by Dr. Thomas McGovern of Hunter College and Jennifer Brown from Stirling University, United Kingdom, along with 12 undergraduates.

Figure 124. Archaeology Report Map



Researchers

Dr. Sophia Perdikaris, professor, Department of Anthropology and Archaeology, Brooklyn College. Sophia Perdikaris is an archaeologist specializing in zoo archaeology in the North Atlantic, specifically Iceland and Norway. She has extensive archaeological field experience in many parts of the world, including Iceland, Norway, Bahamas, Kenya, and Antigua. Phone: 718-951-4192.

Dr. Reg Murphy, archaeologist/curator, Antigua and Barbuda National Parks. Reg Murphy is the only full-time archaeologist for Antigua and Barbuda. He has run field schools for the University of Calgary for 15 years. He specializes in both prehistoric and historic Caribbean archaeology and is actively involved in consultation and restoration of historical monuments on Antigua and Barbuda and throughout the Caribbean.

Dr. Arni Einarsson, biologist, Myvatn Research Center and Institute of Biology, University of Iceland, Icelandic Museum of Natural History. Arni Einarsson is a biologist and naturalist specializing in ornithology, especially duck lifeways and migration. Dr. Einarsson is also an experienced surveyor of cultural monuments.

Matthew Brown, bioarchaeologist and Ph.D. student, Graduate School and University Center, CUNY. Matthew Brown specializes in bioarchaeology, human paleopathology, skeletal pathology, and health and disease in archaeological populations. He has worked on excavations in New York, Iceland, the Faroe Islands, Serbia, and Antigua and Barbuda. Phone: 718-951-4192.

Cory Look, Ph.D. student, Graduate School and University Center, CUNY. Cory Look has studied in the master's program for forensic science at John Jay College, CUNY. His research involved the chemical analysis of explosives with Raman spectroscopy. Currently an archaeology Ph.D. student working on prehistoric zoo archaeological material from Muddy Bay, Antigua. He surveyed archaeological sites in Barbuda in 2006. Phone: 718-951-4192.

Courtney Scott, undergraduate student, Brooklyn College. Courtney Scott has zoo archaeological excavation experience in Iceland and has worked on faunal material from the Muddy Bay site in Antigua. She plans to join the archaeology Ph.D. program at the CUNY graduate school and focus on Caribbean archaeology.

Marissa Gamliel, undergraduate, Brooklyn College. Marissa Gamliel has worked on excavations in Israel and Barbuda. She has also helped to analyze zoo archaeological material from Muddy Bay, Antigua.

ANNEX C. BARRIER REEF UNITS[2]

Background

Coastal Restoration, Incorporated (CRI) and Artificial Reefs, Incorporated, (ARI) are sister engineering firms involved with professional, state-of-the-art reef development and coastal protection projects. We hold numerous intellectual property rights and U.S. and international patent rights (US.. 6,186,702B1) (International Patent Application March 3, 1999 PCT Docket No# 4480)) These firms have spent more than a decade in the research and development of the world's only scientifically engineered and designed artificial marine life habitat and wave attenuation device. They are modeled for natural coastal protection and mimic marine life habitat characteristics of the world's barrier reef systems. The Fish Haven/Coastal Haven series modules were designed to promote and accelerate rapid marine growth on all hard substrate surfaces, inside the structure and out. They are specifically engineered as wave attenuation devices to protect coastlines.

> Coastal Restoration Inc. and Artificial Reefs Inc. are both registered with the U.S. government and are approved federal contractors under Central Contract Registration. Coastal Restoration Inc. is registered under DUNS# 13-438-9167 and Artificial Reefs Inc. under DUNS# 01-541-8205. This project will executed be under Coastal Restoration Inc.

The hydrodynamic engineered shape of the units and their openings were specifically developed to promote a designed flow of micronutrient rich water across all surfaces. Combined with engineered light access, these characteristics lead to unsurpassed biomass development and reef productivity. The highly functional design provides the greatest amount of productive, hard substrate, and spawning habitat/shelter of any commercial product. The Fish Haven/Coastal Haven modules are the largest, most complex designed reef/wave attenuation systems on the market. They provide a large marine developmental substrate and a more stable, taller profile essential for marine productivity and biomass development. These features allow fish to migrate vertically in the water column when seeking optimum current and temperature conditions.

Additionally, the hydrodynamic design and cyclonic flow of micronutrient rich water produces an upwelling of nutrient-rich biomass, creating a food source for baitfish and, consequently, the larger pelagic. This allows the units to attenuate damaging wave energy, thus reducing possible shoreline beach sand erosion.

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[2] Prepared by Coastal Restoration Inc. and Artificial Reefs,Inc., 10132 Bittern Drive, Pensacola, FL 32507. Tel. 850-375-6622, e-mail artificialreefs@cox.net.
Title: Barrier (Lobster) Reef Proposal
Date: October 18, 2007
Client: USAID, government of Barbuda, and local stakeholders
Project: Barrier reef protection for Town of Codrington, Barbuda, invaluable infrastructure

Introduction

On October 16, 2007, Cliff Juillerat, consultant coastal engineer for Ocean Caraibes, contacted CRI for a formal proposal on performing a site survey for a potential beach/habitat restoration and infrastructure protection effort for the town of Codrington, Barbuda, West Indies, through USAID and the government of Barbuda. Over the course of several conversations, it was determined that CRI would provide a formal proposal based on information provided from Ocean Caraibes and that a site visit would be needed to commit to a final design and fixed price for the scope of work presented. As presented, the stakeholders in this project wish to protect the shoreline and its invaluable infrastructure from the power plant, pier, and 1,000-meter area to the airport runway expansion. This area is represented in Figure 125 by the dotted line over water, bordering the shoreline adjacent to the areas of concern. Additionally, the stakeholders expressed a desire to increase marine life biodiversity in the bay and improve lobster stocks through the proven productive Lobster Haven System.

Figure 125. Proposed area for barrier reef units.

Discussion

The scientifically engineered, leading-edge technology developed by CRI and ARI is receiving worldwide acclaim, having been awarded the Coastal America Award by the president of the United States in November 2003. Since then, this technology has been successfully used all over and is now embraced in the West Indies with St. Vincent, Canouan, and Nevis gaining government approval and endorsement to restore their shorelines. Unlike permanent rock jetties, seawalls, and groynes, these wave attenuation devices are environmentally productive, portable, and adjustable to changing hydrodynamic conditions. Depending on conditions and applications, they can assist in restoring and rebuilding shorelines naturally while at the same time adding to the marine life environment. Once they have done their job, they can be moved to another area or offshore to make a thriving marine life oasis.

Figure 126. Wave energy impact on barrier reef units. Significant wave energy is attenuated between rows of Nisbet Havens on the right. Note the calm just after waves pass through the system on the shoreward side.

Conditions on Barbuda seem ideal for this application, with over-exposed beachfront and infrastructure subject to damage by wind-driven wave energy and storm surge events caused by tropical conditions. However, due to the depths just offshore of these shallow depth contours (-2 to -3 ft), low amplitude (high-energy, erosive) waves will continue to negatively impact this area unless a structure is designed to specifically attenuate wave energy prior to the breaking. We recommend a Barbuda Lobster Haven system similar to the one in Figure 134, aligned as in the configuration — parallel to the shoreline.

A Barbuda Lobster Haven wave attenuation device with a 10-foot base and 3-4-foot tall would be designed for this application. These units serve three main purposes. First, they cause the full spectrum of wave amplitudes to break through and overtop the breakwater, attenuating wave energy and minimizing dockage and coastal impact. Two, they accrete sand on the shore side of the breakwater, given seasonal littoral drift cycles and a sand source. Third, they act as a natural barrier reef system that calms the water but also provides an abundant recreational resource of marine biomass to develop lobsters and fish and plant life.

As in the accompanying illustrations, the units will be aligned in a dual row with tops above mean low water level to ensure reserve effectiveness for storm surge and subsequent wave energy developing above the structures during tropical systems. Thus, for the Barbuda Lobster Haven to be effective 100 percent of the time, units should break the surface, affecting every wave and attenuating close to 95 percent of all wave energy. When a wave attenuation device is submerged, it will only break those waves when the false bottom provided by the unit's height is roughly 66 percent of the wave height. With surges, depth over the units will increase, thus allowing shallower, lower-amplitude (higher-energy) surface waves to get by, albeit with less energy.

Environmental Contribution

The Coastal Haven Series wave attenuation device/artificial reef module is recommended for use in this barrier reef system design. To add species biodiversity, CRI will strive to provide habitat complexity and significant substrate for the development of marine biomass. The Coastal Haven Barbuda Lobster Haven will have 258 square feet (24 m^2) of substrate. Using the Coastal Haven Series units for this project, CRI shall provide a significant amount of productive substrate in an area void of much recreationally usable marine biomass. It is a total, value-added, environmentally contributing product with zero negative impact.

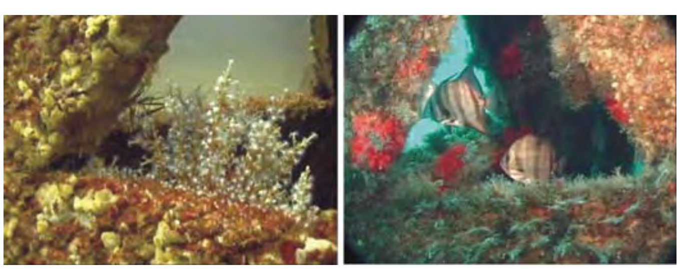

Figure 127. Marine biomass created by barrier reef units.

Using calculations through recommendations of the University of Queensland, Australia, and observations of more restrictive growth patterns here in the northern Gulf of Mexico, (cooler waters, more turbidity, and deeper reef placement) CRI can estimate that there will be hundreds of metric tons of marine biomass development in the first six months of deployment. At the one year anniversary of placement, the client can expect close to triple that amount of development. Not including resident species of fish, invertebrates, and crustaceans, the marine biomass on the physical reef structure will increase geometrically over time as added biomass results in increased surface area for additional branching growth of corals, etc.

On CRI's existing reef systems, at the one-year point, transects of species diversity and fish counts/size estimates (per surface area) have been recorded at 15 meters from the reef units. At any given time at that point, 138.5 kg/m^2 of fish biomass were observed inside and out of the reef structures. Unit measurements were averaged from single reef units. In our typical configuration, with wave attenuation devices aligned closely and using our lower observed average of 115.6 kg/m^2, an additional several hundred metric tons of marine fish biomass (resident reef species, tropicals, crustaceans, invertebrates, and pelagic) could be observed.

Figure 128. Marine biomass.

Barbuda Barrier Reef System Proposal

The client desires to protect its invaluable shoreline and infrastructure and increase its recreational assets and marine life biodiversity, which will in turn develop the tourism industry while contributing to the increased production of lobster stocks. With regard to the above discussion and pending survey, it is strongly recommended that the client seek to establish, at a minimum, a 1,000-m barrier reef system at the -.75 to -1.0 m depth contour running northeast to southwest from the pier area to approximately 20 m from the shoreline. These 1,000-m areas would consist of close to 1,300 of CRI's custom-designed wave attenuation devices that are scientifically engineered and modeled from the hydrodynamic properties of barrier reef systems.

In Figure 129, inbound wave energy comes in contact with the hydrodynamically engineered reef structures with tapered openings. Energy is dissipated in the upward plane and throughout the structure's multiple openings under Bernoulli's Continuity Theory. As an added bonus, the units provide additional productive, biomass substrate and a habitat for a complex marine-life ecosystem.

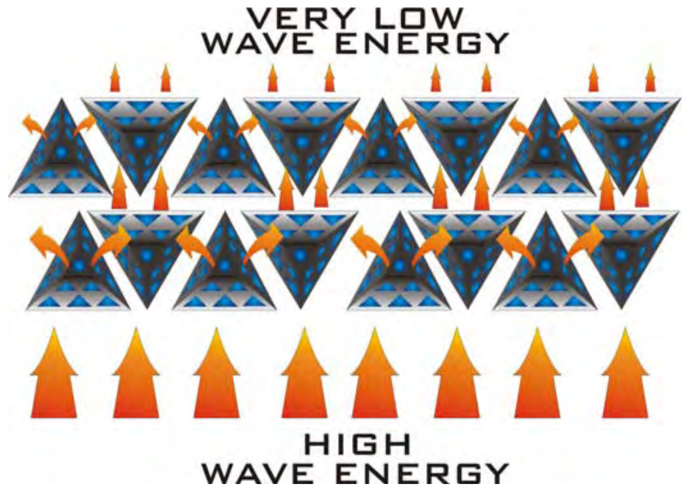

Figure 129. Wave energy simulation.

For this configuration, 1,300 Coastal Haven Barbuda Lobster Haven units would be required, measuring at a 3.0 m base and standing 1 m tall. Unit weight would be in range of four short tons. Units would be aligned in a double row as seen in Figure 129. Five scientifically engineered molds would be designed and manufactured in the United States and then shipped to a Barbudan manufacturing site. The CRI team would hire a team of Barbudan laborers to be trained and managed by CRI, which will be on-site for quality control and to ensure adherence to our strict testing protocols. The client will receive a superior quality product at a much lower cost than if the units were manufactured and shipped from the United States.

Figure 130. Local laborers on Nevis make Nisbet Havens to deploy on the north end of the island.

Waters would still flow at a rate to contribute to recreational beach area flushing and productive enrichment of marine biomass. Again, an estimated 11,544 metric tons of marine biomass (coral, etc.) would be added, plus an additional 3,602 metric tons of marine biomass (fish, etc.). Total biomass contribution after the first year of placement could conservatively be 15,146 metric tons.

Figure 131. Rebar internal support is rigged onto taller wave attenuation device. Completed units are transported to deployment site.

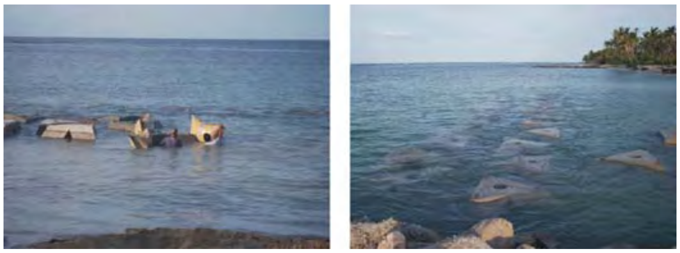

Figure 132. Nisbet Havens are placed into shallow waters using lift bags, the same method proposed for Barbuda Lobster Haven unit placement.

Project Cost: Barbuda Barrier Reef System

There are a still a few unknowns that should be answered at the completion of a full site survey by Coastal Restoration Inc. These may require minor adjustments to the exact placement of wave attenuation devices and their final size and height, but at this point we is confident that this proposal is well within 10 percent of final cost. CRI will arrange for a manufacturing site and deployment station on Barbuda. We will design and manufacture five scientifically engineered steel mold systems to yield a consistent quality of Barbuda Lobster Haven for this phase of the project. Theses molds will be manufactured in the United States and shipped to our future local manufacturing site in Barbuda.

Once the mold designs are complete, ordering and manufacturing will take approximately three months. The molds will then be shipped to the local site and units made from the mold system will be poured daily during a normal working week. Additionally, all tools and manufacturing/deployment-specific equipment, other than heavy equipment, will be purchased and shipped to the local site.

Each wave attenuation device will be made of a minimum tested 3,000 PSI marine-grade concrete, dosed with 1.5 pounds of fibermesh per yard of concrete. Each unit will be reinforced with more than 100 ft of #4 or larger rebar, totally encased within the concrete product, adding strength and durability. There will be a goal of 25 Barbuda Lobster Havens manufactured each week, then set aside for a 30-day curing period prior to deployment. At this rate, it will take just over 12 months (plus a final month of curing for the last units) to manufacture all 1,300 units. During the 3rd month, we will mobilize one of six major deployment operations, loading cured units onto flatbed trailers to the final site, where we will deploy the units per the designed configuration with a mini crane or excavator and lift bag to float the units into place. Time from start to finish could be as little as 15 months. The sooner the units are placed in the water, the sooner they will be covered with marine biomass, producing a more productive natural barrier reef system and preventing further erosion to the shoreline. Weather and safety are major factors in this process, which will take place five to six times until completion of this phase.

Following placement of the units in the wave attenuation configuration, CRI will monitor their placement and the resulting hydrodynamic patterns to ensure the desired results. If units need adjustment, CRI will make arrangements to do so.

In the first year, CRI will be on-site to monitor every six months and then annually the following year, with provisions for future monitoring. With the units gradually building up the beach shoreward, should the client wish to move the units farther from the newer beach, arrangements can also be made to handle that.

The all-inclusive cost for this Barbuda Barrier Reef System, to design it, engineer and build the Barbuda Lobster Haven molds, ship them to Barbuda, manufacture and deploy the full 1,000-meter barrier reef system and monitor it for two years, is $1,800,000.

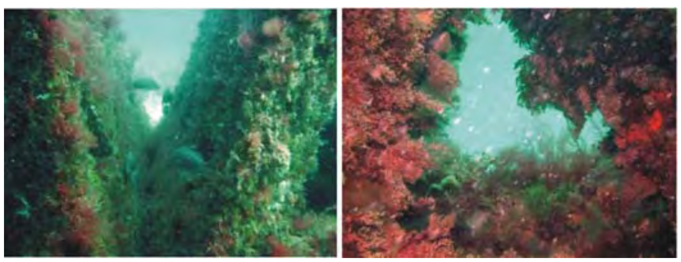

Figure 133. Marine biomass created by barrier reef units.

Educational Contribution

With the assistance of Johns Hopkins University, Virginia Tech University, and Educators for Connecting Research to the K-16 Classroom, Ocean Caraibes has successfully developed and implemented a series of marine science, environmental education, and teacher training programs in the Caribbean over the past eight years. These efforts have been successful because Ocean Caraibes bolsters local education and produces education products that support local school systems and environmental needs.

The establishment and subsequent development of a diversified marine life ecosystem in the area provides an ideal opportunity for the local population, young and old, researchers and the like, as well as increased recreational learning and enjoyment for resort guests. An academic curriculum has been created through partnerships between Artificial Reefs, Inc., Educators for Connecting Research to the K-16 Classroom (Johns Hopkins University), and the Institute for Connecting Science Research to the Classroom (Virginia Tech University). The establishment of the 1,300 reefs would be complemented by an academic curriculum that brings many parties face to face with nature and its wonders.

The artificial reefs will allow for increased tourism interaction on an educational level, as well as on a recreational level. Resort guests can interact directly with the reef systems and diverse marine species. Samples and live collections may take place as species are temporarily collected for closer observation and viewed in a hotel lobby or outdoor viewing area.

Note: A minimum two-day on-site survey is required for CRI to see the site first-hand, design the systems, evaluate equipment availability and needs, arrange a local manufacturing site, and establish partnerships with local businesses and communities to facilitate an efficient and effective process. Cost would be transportation and expenses for one person, and CRI will waive all consulting fees for this site assessment. CRI will work closely with Cliff Juillerat during the two-day visit.

Coastal Restoration, Inc. appreciates the opportunity to provide this proposal to USAID and the government of Barbuda. We believe we have been responsive to the client’s request and it should be noted that this proposal is proprietary and valid for 60 calendar days following receipt. Please contact us directly if there are any discrepancies, questions, or lack of responsiveness in any item or area of interest. It has been our pleasure to provide you with this proposal. Contact CRI by phone at 850-375-6622 or by e-mail at artificialreefs@cox.net.

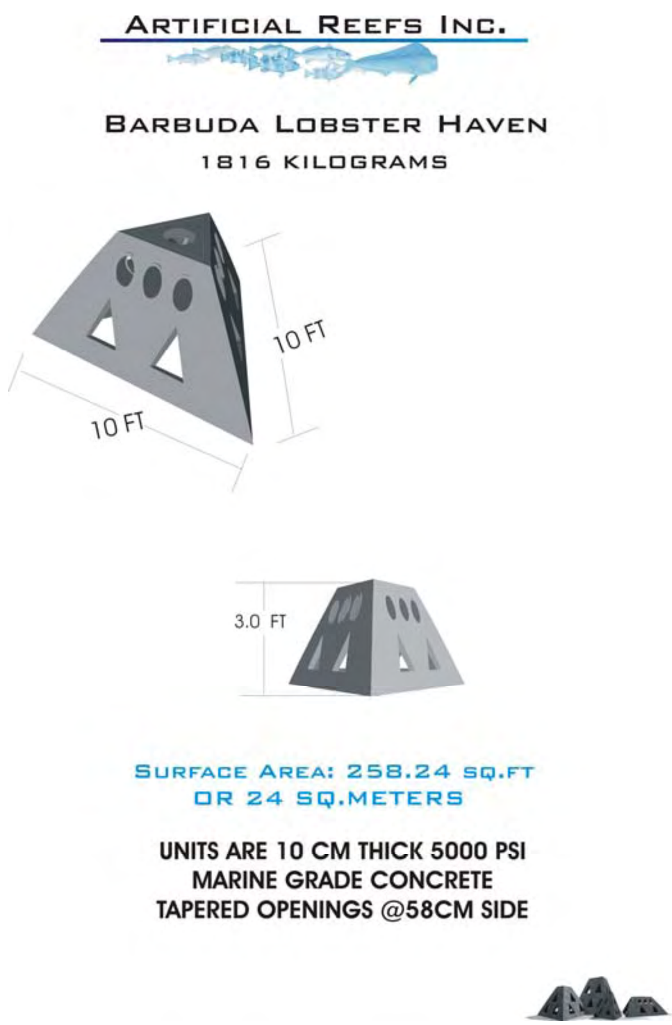

Figure 134. Proposed Lobster Haven units,

ANNEX D. GLOSSARY

In general, the terms given here are commonly found in coastal engineering practice. We have sought to be as consistent as possible with terms used in CIRIAICUR (1991) and Thomas and Hall (1992). Occasionally, a term has been selected from a range of possible terms (e.g., beach “recharge” rather than “replenishment,” “nourishment,” or “feeding”).

Abrasion platform	A rock or clay platform that has been worn by the processes of abrasion (i.e., frictional erosion by material transported by wind and waves)
Accretion	The accumulation of (beach) sediment, deposited by natural fluid flow processes
A Class tide gauge	One of a UK network of tide gauges maintained to the highest and most consistent standards
Amplitude	Half of the peak-to-trough range (or height)
Apron	Layer of stone, concrete, or other material to protect the toe of a seawall
Armor layer	Protective layer on a breakwater or seawall composed of armor units
Armor unit	Large quarried stone or specially shaped concrete block used as primary protection against wave action
Asperities	Three-dimensional irregularities forming the surface of an irregular stone (or rock) subject to wear and rounding during attrition
Astronomical tide	The tidal levels and character that would result from gravitational effects, e.g., of the Earth, sun, and moon, without any atmospheric influences
Back-rush	The seaward return of water following the up-rush of a wave
Backshore	The upper part of the active beach above high water and extending to the toe of the beach head, affected by large waves occurring during a high tide
Barrier beach	A sand or shingle bar above high tide, parallel to the coastline and separated from it by a lagoon
Bathymetry	Refers to the spatial variability of levels on the seabed
Beach	A deposit of non-cohesive material (e.g., sand, gravel) situated on the interface between dry land and the sea (or other large expanse of water) and actively “worked” by present-day hydrodynamic processes (i.e., waves, tides, and currents) and sometimes by winds
Beach crest	The point representing the normal limit of high-tide wave-induced run-up
Beach face	From the beach crest out to the limit of sediment movement
Beach head	The cliff, dune, or seawall forming the landward limit of the active beach
Beach management scheme	A specific planned investment in a set of works for managing the beach. This may be a one-off project or may be phased over a number of years.
Beach material	The non-cohesive material (e.g., sand, gravel) comprising a beach
Beach plan shape	The shape of the beach in plan; usually shown as a contour line, combination of contour lines, or recognizable features such as beach crest and/or still-water line

Beach profile	A cross-section taken perpendicular to a given beach contour; the profile may include the face of a dune or seawall, extend over the backshore, across the foreshore, and seaward underwater into the nearshore zone
Beach recharge	Supplementing the natural volume of sediment on a beach, using material from elsewhere. Also known as beach replenishment/nourishment/feeding.
Beach seining	A method of fishing carried out near the beach using a large vertical fishing net whose ends are brought together and hauled
Bed forms	Features on a seabed (e.g., ripples and sand waves) resulting from the movement of sediment over it
Bed load	Sediment transport mode in which individual particles either roll or slide along the seabed as a shallow, mobile layer a few particle diameters deep
Bed shear stress	The way in which waves (or currents) transfer energy to the sea bed
Benefits	The economic value of a scheme, usually measured in terms of the cost of damages avoided by the scheme, or the valuation of perceived amenity or environmental improvements
Berm	1. On a beach: a nearly horizontal plateau on the beach face or backshore, formed by the deposition of beach material by wave action or by means of a mechanical plant as part of a beach recharge scheme. 2. On a structure: a nearly horizontal area, often built to support or key-in an armor layer.
Boulder	A rounded rock on a beach, greater than 250 mm in diameter and larger than a cobble. See also gravel, shingle.
Boundary conditions	Environmental conditions, e.g., waves, currents, drifts, etc., used as boundary input to physical or numerical models
Bound long wave	Long wave directly due to the variation in set-down at the breaker line due to wave groups
Breaching	Failure of the beach head allowing flooding by tidal action
Breaker depth	Depth of water, relative to still-water level at which waves break. Also known as breaking depth or limiting depth.
Breaker index	Maximum ratio of wave height to water depth in the surf zone. The zone within which waves approaching the coastline commence breaking, typically in water depths of between 5 and 10 m.
Breastwork	Vertically faced or steeply inclined structure usually built with timber and parallel to the shoreline, at or near the beach crest, to resist erosion or mitigate against flooding
Bypassing	Moving beach material from the updrift to the downdrift side of an obstruction to longshore drift
Chart datum	The level to which both tidal levels and water depths are reduced. On most UK charts, this level is that of the predicted lowest astronomical tide level.
Clay	A fine-grained, plastic sediment with a typical grain size less than 0.004 mm. Possesses electromagnetic properties which bind the grains together to give a bulk strength or cohesion.
Climate change	Refers to any long-term trend in mean sea level, wave height, wind speed, drift rate, etc.
Closure depth	The depth at the offshore limit of discernible bathymetric change between surveys
Coastal defense	Coastline unit within which sediment movement is self-contained

Coastal cell	General term used to encompass both coast protection against erosion and sea defense against flooding
Coastal forcing	The natural processes which drive coastal hydro-and morphodynamics (e.g., winds, waves, tides, etc)
Coastal processes	Collective term covering the action of natural forces on the shoreline and nearshore seabed
Coastal squeeze	The effect when hard defenses (including beaches fixed in position by control structures) interrupt the natural response of the shoreline to sea level rise, restricting landward retreat and resulting in loss of intertidal habitat
Coastal zone	Some combination of land and sea area, delimited by taking account of one or more elements
Coast protection	Protection of the land from erosion and encroachment by the sea
Cobble	A rounded rock on a beach, with diameter ranging from about 75 to 250 mm. See also boulder, gravel, shingle.
Cohesive sediment	Sediment containing significant proportion of clays, the electromagnetic properties of which cause the sediment to bind together
Conservation	The protection of an area, or particular element within an area, while accepting the dynamic nature of the environment and therefore allowing change
Core	1. A cylindrical sample extracted from a beach or seabed to investigate the types and depths of sediment layers. 2. An inner, often much less permeable portion of a breakwater, or barrier beach force due to the earth's rotation, capable of generating currents.
Coriolis	The zone within which waves approaching the coastline commence breaking, typically in water depths of between 5 and 10 m
Crest	Highest point on a beach face, breakwater, or seawall
Cross-shore	Perpendicular to the shoreline
Cusp	Seaward bulge, approximately parabolic in shape, in the beach contours. May occur singly, in the lee of an offshore bulk or island, or as one of a number of similar, approximately regularly spaced features on a long, straight beach.
Deep water	Water too deep for waves to be affected by the seabed; typically taken as half the wavelength or greater
Deflation	Erosion of dunes by wind action
Depth-limited	Situation in which wave generation (or wave height) is limited by water depth
Design wave condition	Usually an extreme wave condition with a specified return period used in the design of coastal works
Detached breakwater	A breakwater without any constructed connection to the shore
Diffraction	Process affecting wave propagation by which wave energy is radiated normal to the direction of wave propagation into the lee of an island or breakwater
Diffraction coefficient	Ratio of diffracted wave height to deep-water wave height
Diurnal	Literally "of the day" but here meaning having a period of a "tidal day," i.e., about 24.8 hours
Downdrift	In the direction of the net longshore transport of beach material
Drogue	Float used to track current paths at a depth below the water surface determined by the position of vanes suspended beneath the float
Drying beach	That part of the beach which is uncovered by water (e.g., at low tide); sometimes referred to as the '"sub-aerial" beach

Dunes	1. Accumulations of windblown sand on the backshore, usually in the form of small hills or ridges, stabilized by vegetation or control structures. 2. A type of bed form indicating significant sediment transport over a sandy seabed.
Duration	The length of time a wind blows at a particular speed and from the same direction during the generation of storm waves
Ebb	Period when tide level is falling, often taken to mean the ebb current which occurs during this period
Edge waves	Waves which mainly exist shoreward of the breaker line, and propagate along the shore. They are generated by incident waves, their amplitude is at maximum at the shoreline and diminishes rapidly in a seaward direction.
Epifauna	Animals living in the sediment surface or on the surface of other plants or animals
Event	An occurrence meeting specified conditions, e.g., damage, a threshold wave height, or a threshold water level
Exponential distribution	A model probability distribution
Extreme	The value expected to be exceeded once, on average, in a given (long) period of time
Flood defenses	See sea defenses
Forecasting	Prediction of conditions expected to occur in the near future, up to about two days ahead
Foreshore	The intertidal area below highest tide level and above lowest tide level
Freeboard	The height of the crest of a structure above the still-water level
Friction	Process by which energy is lost through shear stress
Friction factor	Factor used to represent the roughness of the sea bed
Frontager	Person or persons owning, and often living in, property immediately landward of the beach
Fully-developed sea	A wave condition which cannot grow further without an increase in wind speed. Also fully-arisen sea.
GIS	Geographical information system. A database of information that is geographically orientated, usually with an associated visual system.
Gravel	Beach material, coarser than sand but finer than pebbles (between 2 and 4 mm diameter)
Group velocity	The speed of wave energy propagation. Half the wave phase velocity in deep water, but virtually the same in shallow water.
Groyne	Narrow, roughly shore-normal structure built to reduce longshore currents, and/or to trap and retain beach material. Most groynes are of timber or rock and extend from a seawall, or the backshore, well onto the foreshore and rarely even further offshore. In the United States and historically called a groin.
Groyne bay	The beach compartment between two groynes
Gumbel distribution	A model probability distribution, commonly used in wind and water level analysis
Hard defenses	General term applied to impermeable coastal defense structures of concrete, timber, steel, masonry, etc., which reflect a high proportion of incident wave energy. See also soft defenses.
Headland	Hard feature (natural or artificial) forming local limit of longshore extent of a beach
Hindcasting	In wave prediction, the retrospective forecasting of waves using measured wind information

Historic event analysis	Extreme analysis based on hindcasting typically 10 events over a period of 100 years
Incident wave	Wave moving landward
Infauna	Animals living in the sediment
Infra-gravity waves	Waves with periods above about 30 seconds generated by wave groups breaking in the surf zone (also known as long waves)
Inshore	Areas where waves are transformed by interaction with the sea bed
Intertidal	The zone between the high- and low-water marks
Isobath	Line connecting points of equal depth, a seabed contour line connecting points on the seabed with an equal depth of sediment
Joint probability	The probability of two (or more) things occurring together
Joint probability density	Function specifying the joint distribution of two (or more) variables
Joint return period	Average period of time between occurrences of a given joint probability event
JONSWAP spectrum	Wave spectrum typical of growing deep-water waves
Limit of storm erosion	A position, typically in a maximum water depth of 8 to 10 m, often identifiable on surveys by a break (i.e., sudden change) in slope of the bed
Littoral	Of or pertaining to the shore
Littoral drift, littoral transport	The movement of beach material in the littoral zone by waves and currents. Includes movement parallel (longshore drift) and perpendicular (cross-shore transport) to the shore.
Littoral zone	Zone from the beach head seaward to the limit of wave-induced sediment movement
Locally generated waves	Waves generated within the immediate vicinity, say within 50 km, of the point of interest
Log-normal distribution	A model probability distribution
Long-crested random waves	Random waves with variable heights and periods but a single direction
Longshore	Parallel and close to the coastline
Longshore bar	Bar running approximately parallel to the shoreline
Longshore drift	Movement of (beach) sediments approximately parallel to the coastline
Long waves	Waves with periods above about 30 seconds generated by wave groups breaking in the surf zone (also known as infragravity waves)
Macro-tidal	Tidal range greater than 4 m
Managed landward realignment	The deliberate setting back of the existing line of defense to obtain engineering and/or environmental advantages. Also referred to as managed retreat.
Marginal probability	The probability of a single variable in the context of a joint probability analysis
Marginal return period	The return period of a single variable in the context of a joint probability analysis
Mean sea level	The average level of the sea over a period of approximately 12 months, taking account of all tidal effects (see tides) but excluding surge generated by meteorological effects. Variation in mean sea level may well occur in the longer term.
Mean water level	The average level of the water over the time period for which the level is determined
Mean wave period	The average wave period derived from integrating the wave energy spectrum

Mud flat	An area of fine silt usually exposed at low tide but covered at high tide, occurring in sheltered estuaries or behind shingle bars or sand spits
Nearshore	The zone which extends from the swash zone to the position marking the start of the offshore zone, typically to water depths on the order of 20 m
Ness Numerical modeling	Refers to the analysis of coastal processes using computational models
Offshore	The zone beyond the nearshore zone where sediment motion induced by waves alone effectively ceases and where the influence of the sea bed on wave action has become small in comparison to the effect of wind
Operational	The construction, maintenance, and day-to-day activities associated with beach management
Overtopping	Water carried over the top of a coastal defense due to wave run-up exceeding the crest height
Overwash	The effect of waves overtopping a coastal defense, often carrying sediment landwards which is then lost to the beach system
Peaks over threshold (POT)	Refers to the maximum value of a variable during each excursion above a threshold value
Pebbles	Beach material usually well-rounded and between about 4 mm and 75 mm in diameter
Persistence of storms	The duration of sea states above some severity threshold (e.g., wave height)
Phase velocity	The velocity at which a wave crest propagates. See also group velocity.
Physical modeling	Refers to the investigation of coastal processes using a scaled model
Pierson-Moskowitz spectrum	Wave spectrum typical of fully developed deep water waves
Piezometric surface	The level within (or above) a soil stratum at which the pore pressure is zero
Pocket beach	A beach, usually small, between two headlands
Preservation	Static protection of an area or element, attempting to perpetuate the existence of a given state
Probability density function	Function specifying the distribution of a variable
Profile of storms	Refers to the persistence of storms coupled with the rate of change of sea state (e.g., wave height) within the storms
Recycling	The mechanical movement of beach sediment from downdrift to updrift
Reflection	See reflected wave
Refraction coefficient	Ratio of refracted wave height to deep-water wave height
Refraction (of water waves)	The process by which the direction of a wave moving in shallow water at an angle to the contours is changed so that the wave crests tend to become more aligned with those contours
Regular waves	Waves with a single height, period, and direction
Residual (water level)	The components of water level not attributable to astronomical effects
Return period	Average period of time between occurrences of a given event
Revetment	A sloping surface of stone, concrete, or other material used to protect an embankment, natural coast, or shoreline against erosion
Rip current	Jet-like, seaward-going current normal to the shoreline associated with wave-induced longshore currents
Risk analysis	Assessment of the total risk due to all possible environmental inputs and all possible mechanisms

Roller	Rotational eddy with a horizontal axis driven by breaking wave action
Runnel	Channels on a beach, usually running approximately shore-parallel and separated by beach ridges
Run-up, run-down	The upper and lower levels reached by a wave on a beach or coastal structure, relative to still-water level
Salient	Coastal formation of beach material developed by wave refraction and diffraction and longshore drift comprising a bulge in the coastline towards an offshore island or breakwater, but not connected to it as in the case of a tombolo. See also ness, cusp.
Sand	Sediment particles, mainly of quartz, with a diameter of between 0.062 mm and 2 mm, generally classified as fine, medium, coarse, or very coarse
Scatter diagram	A two-dimensional histogram showing the joint probability density of two variables within a data sample
Sea defenses	Works to alleviate flooding by the sea, sometimes known as flood defenses
Sea level rise	The long-term trend in mean sea level
Seawall	Solid coastal defense structure built parallel to the coastline
Sediment	Particulate matter derived from rock, minerals, or bioclastic debris
Sediment cell	In the context of a strategic approach to coastal management, a length of coastline in which interruptions to the movement of sand or shingle along the beaches or nearshore seabed do not significantly affect beaches in the adjacent lengths of coastline
Sediment sink	Point or area at which beach material is irretrievably lost from a coastal cell, such as an estuary or a deep channel in the seabed
Sediment source	Point or area on a coast from which beach material arises, such as an eroding cliff or river mouth
Shallow water	Water of such depth that surface waves are noticeably affected by bottom topography. Typically this implies a water depth equivalent to less than half the wavelength.
Shingle	A loose term for coarse beach material; a mixture of gravel, pebbles, and larger material, often well-rounded and of hard rock, e.g., chert, flint.
Shoaling	Decrease in water depth. The transformation of wave profile as they propagate inshore.
Shoaling coefficient	Ratio of shoaled wave height to deep water wave height
Shoreline	One characteristic of the coast, often poorly defined, but essentially the interface between land and sea
Shoreline management	The development of strategic, long-term, and sustainable coastal defense policy within a sediment cell
Shore normal	A line at right angles to contours in the surf zone
Short-crested random waves	Random waves with variable heights, periods, and directions
Significant wave height	The average height of the highest one-third of the waves in a given sea state
Silt	Sediment particles with a grain size between 0.004 mm and 0.062 mm, i.e., coarser than clay particles but finer than sand
Soft defenses	Usually refers to beaches (natural or designed) but may also relate to energy-absorbing beach-control structures, including those constructed of rock, where these are used to control or redirect coastal processes rather than opposing or preventing them

Spit	A long, narrow accumulation of sand or shingle, lying generally in line with the coast, with one end attached to the land the other projecting into the sea or across the mouth of an estuary. See also ness.
Standard of service	The adequacy of defense measured in terms of the return period (years) of the event which causes a critical condition (e.g., breaching, overtopping) to be reached
Still-water level	Average water surface elevation at any instant, excluding local variation due to waves and wave set-up, but including the effects of tides, surges, and long-period seiches
Strand line	An accumulation of debris (e.g., seaweed, driftwood, and litter) cast up onto a beach and lying along the limit of wave up-rush
Sub-tidal beach	The part of the beach (where it exists) which extends from low water out to the approximate limit of storm erosion. The latter is typically located at a maximum water depth of 8 to 10 m and is often identifiable on surveys by a break in the slope of the bed
Surf beat	Independent long wave caused by reflection of bound long wave
Surf zone	The zone of wave action extending from the water line (which varies with tide, surge, set-up, etc.) out to the most seaward point of the zone (breaker zone) at which waves approaching the coastline commence breaking, typically in water depths of between 5 to 10 m
Surge	Changes in water level as a result of meteorological forcing (wind, high or low barometric pressure) causing a difference between the recorded water level and that predicted using harmonic analysis; may be positive or negative
Suspended load	A mode of sediment transport in which the particles are supported and carried along by fluid
Swash zone	The zone of wave action on the beach, which moves as water levels vary, extending from the limit of run-down to the limit of run-up
Swell (waves)	Remotely wind-generated waves. Swell characteristically exhibits a more regular and longer period and has longer crests than locally generated waves.
Threshold of motion	The point at which the forces imposed on a sediment particle overcome its inertia and it starts to move
Tidal current	The movement of water associated with the rise and fall of the tides
Tidal range	Vertical difference in high- and low-water level once decoupled from water level residuals
Tidal wave	The rise and fall in water level due to the passage of the tide
Tide	The periodic rise and fall in the level of water in oceans and seas; the result of gravitational attraction of the sun and moon

Tides	1. Highest astronomical tide, lowest astronomical tide: the highest and lowest levels, respectively, that can be predicted to occur under average meteorological conditions. These levels will not be reached every year. They are not the extreme levels that can be reached, as storm surges may cause considerably higher and lower levels to occur. 2. Mean high water springs, mean low water springs: the height of mean high water springs is the average throughout a year of the heights of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is greatest. The height of mean low water springs is the average height obtained by the two successive low waters during the same periods. 3. Mean high water neaps, mean low water neaps: the height of mean high water neaps is the average of the heights throughout the year of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is least. The height of mean low water neaps is the average height obtained by the two successive low waters during the same periods. 4. Mean high water, mean low water: for this manual, mean high and low water, as shown on ordnance survey maps, is defined as the arithmetic mean of the published values of mean high/low water springs and mean high/low water neaps. This ruling applies to England and Wales. In Scotland the tidal marks shown on ordnance survey maps are those of mean high or low water springs.
TMA spectrum	Wave spectrum typical of growing seas in limited water depths
Tombolo	Coastal formation of beach material developed by refraction, diffraction, and longshore drift to form a “neck” connecting a coast to an offshore island or breakwater. See also salient.
Tsunami	Seismically induced gravity waves characterized by wave periods in the order of minutes rather than seconds
Updrift	The direction opposite to that of the predominant longshore movement of beach material
Up-rush	The landward return of water following the back-rush of a wave
Water depth	Distance between the seabed and still-water level
Water level	Elevation of still-water level relative to some datum
Wave celerity	The speed of wave propagation
Wave climate	The seasonal and annual distribution of wave height, period, and direction
Wave climate atlas	Series of maps showing the variability of wave conditions over a long coastline
Wave direction	Mean direction of wave energy propagation relative to true north
Wave directional spectrum	Distribution of wave energy as a function of wave frequency and direction
Wave frequency	The inverse of wave period
Wave frequency spectrum	Distribution of wave energy as a function of frequency
Wave generation	Growth of wave energy by wind
Wave height	The vertical distance between the trough and the following crest
Wavelength	Straight-line distance between two successive wave crests
Wave peak frequency	The inverse of wave peak period

Wave peak period	Wave period at which the spectral energy density is at a maximum
Wave period	The time for two successive wave crests to pass the same point
Wave reflection	See reflected wave
Wave set-up	Elevation of the water level at the coastline caused by radiation stress gradients in the surf zone
Wave steepness	The ratio of wave height to wavelength, also known as sea steepness
Wave rose	Diagram showing the long-term distribution of wave height and direction
Wave transformation	Change in wave energy due to the action of physical processes
Weibull distribution	A model probability distribution, commonly used in wave analysis
Wind rose	Diagram showing the long-term distribution of wind speed and direction
Wind sea	Wave conditions directly attributable to recent winds, as opposed to swell