Chapter

Environmental Problems and Coastal Mitigation in South America: Examples from Northeast Brazil and Northern Colombia

Vanda Claudino-Sales, Ping Wang, Fábio Perdigão Vasconcelos and Adely Pereira Silveira

Abstract

In the state of Ceará, northeast Brazil, in the 1950s, an industrial harbor was built. The harbor structures and other factors, such as the destruction of the bypass of dunes, produced a large erosive process downstream, responsible for the loss of 400 m of beach in six decades. In Canoa Quebrada beach—an internationally famous tourist area—recently, the partial collapse of sea cliffs occurred because of inappropriate uses and occupations, causing landscape and economic damage. In Colombia, beaches are under an intense process of erosion, due to construction for housing and tourism. With the abrasive action of waves associated with rising sea level, coastal areas in both countries are under risk of major degradation. These environmental situations are the object of technical and scientific analysis and discussion in this chapter, and mitigation propositions are considered.

Keywords: Northeast Brazilian coast, northern Colombian coast, coastal erosion, coastal mitigation

1. Introduction

Coastal erosion is a worldwide concern, affecting virtually all coastal countries. In some cases, erosion reaches stages where it results in a high rate of environmental degradation. The economic repercussions are diverse, such as damage to the natural environment and loss of public infrastructure and/or private property. These facts can have extremely serious consequences in economy, ecosystems, tourism, and public health.

The main causes of coastal erosion are the rising of sea level that is underway globally and inadequate management of coastal areas. Frequently, it is associated with the installation of urban and industrial equipment or with structures dedicated to leisure, housing, and tourism.

In the state of Ceará, Northeast Brazil, in the 1950s, an industrial harbor was built. The harbor structures, with other factors such as the destruction of dune bypass, produced a large erosive process downdrift. It was responsible for the loss of more than 400 m of beach in six decades. At Canoa Quebrada beach (a nationally and internationally famous touristic area), a recent partial process of collapse of the cliffs occurred as an answer to inappropriate uses and occupation. This fact produced landscape and economic damage. In the northern coast of Colombia, anthropogenic interruption of the longshore transport caused by the construction of groins, as well as some harbors, produced severe beach erosion along the downdrift shoreline.

With the abrasive action of waves associated with rising sea level, these coastal areas in both countries are at risk of more substantial degradation. These environmental situations will be the object of synthetic technical and scientific analysis and discussion in this chapter. Mitigation propositions for both countries coastal areas are also considered.

2. Methodology

The data displayed are the result of bibliographic research, analysis of maps and satellite images, and fieldwork on the studied areas. In relation to Fortaleza, Brazil, data of direction and velocity of currents were also collected from the Brazilian Ministry of Navy. Data of bathymetry and sea level rise were digitized from the Brazilian navigation charts. Finally, measurements were made on satellite images on Google Earth, in order to define volumes of sediments available and accumulated on the shoreline. In relation to Canoa Quebrada beach, Brazil, topographic profiles covering a 300 m stretch were made in six distinct points, using a total station. High-resolution satellite images were analyzed in a 2004, 2008, and 2017 time series, in order to define the behavior of the cliff break line and determine its retreat speed. For the analysis and georeferencing of the images, the software QGIS, version 2.12, developed by the Open Source Geospatial Foundation—OSGeo, was used with DATUM SIRGAS 2000, projection UTM zone 24 S.

For northern Colombia, beach profiles along 600 km and bathymetry survey were conducted. The beach profiles were made using a total station. The bathymetry survey (10 m water depth) was conducted using a precision echo sounder and a GPS (Global Positioning System) mounted on a vessel. The bathymetry beyond 10 m water depth was digitized from the south Caribbean navigation charts. A total of 270 sediment samples were also collected. The up-to-date nearshore bathymetry data were used in the modeling of nearshore wave field. Finally, time-series aerial photos available from Google Earth were analyzed to depict beach/dune changes at various locations.

3. Environmental problems in the coast of Ceará State, Northeast of Brazil

3.1 Natural settings of the study area

Ceará is one of the states of the Brazilian equatorial northeastern region. Its coastal area spans between the latitudes of 2°47′S and 4°50′S for 573 km and is characterized by long and gently sloping sandy beaches, irregularly interrupted by headlands, small estuaries with mangroves, sea cliffs, and beach rocks, with large dunes and small barrier islands [1–2] (**Figure 1**).

The headlands are characterized, with few exceptions, by the occurrence of sea cliffs with heights varying from 2.7 to 20 m. Tertiary rocks are present, named Barreiras Formation, and create a low-lying tabular surface with less than 40 m in elevation, which extends from the shoreline up to 60 km inland. It outcrops as sea cliffs 3 to 15 m high [e.g., 3] (**Figure 1**).

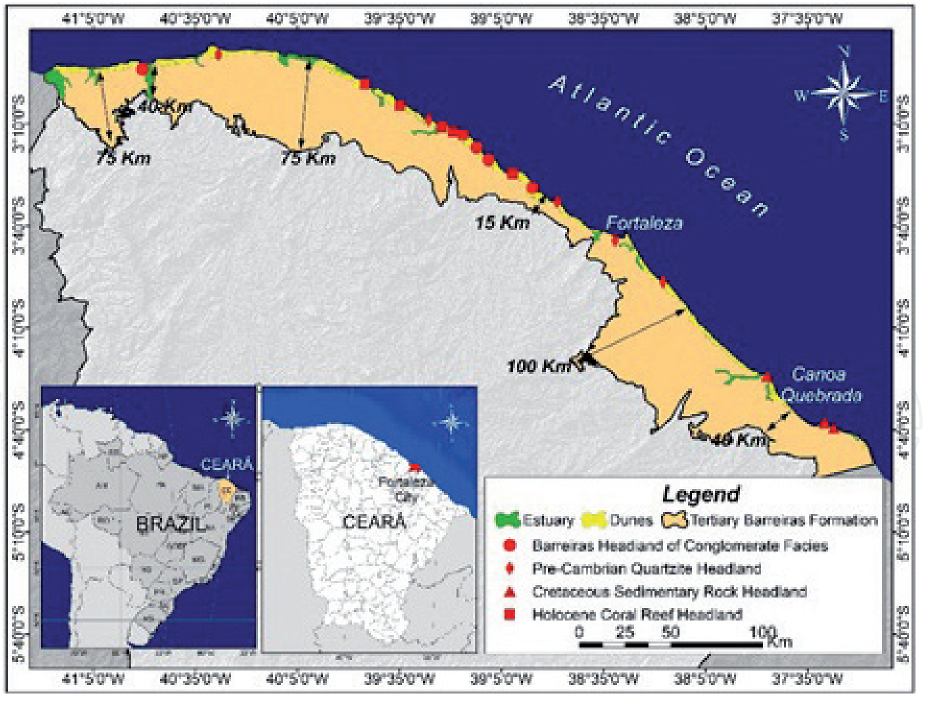

Figure 1.
Location and geological/geomorphological settings of Ceará state coastal area, northeast Brazil.

The mobile dunes orient E to W and are mostly barchans and transverse dune ridges [4–7]. The rate of dune migration ranges from 9 m/y to 22 m/y, with an average of approximately 11 m/y [4–7]. Frequently, the dunes bypass across the headlands, nourishing the beaches downdrift. This process is an important element of the sedimentological budget of this coastal area, considering that it counterbalances the downdrift erosion resulting from the impoundment of the longshore sand by the headlands.

Climatic conditions are controlled by the ITCZ [8]. During fall, the ITCZ is at its southernmost position, resulting in the rainy season. After April, the ITCZ shifts northward, leading to the dry season [9]. The climate is tropical subhumid, with average precipitation between 1000 mm and 1420 mm/y [3]. Temperatures remain largely constant throughout the year, with monthly averages ranging between 25.5° and 27.5°C [10].

The trade winds dominate the area and present a similar pattern to that of precipitation but with an opposite trend: As the precipitation rate decreases, the wind speed increases; during the wet season, the average wind speed is approximately half of that in the dry season. On average, maximum wind speed is around 8 m/s in the dry season. A particular characteristic of the wind condition is its constant easterly direction, coming from southeast or northeast [10].

The predominant wave direction is 90°, with heights ranging from 1.0 to 1.5 m [4, 11]. The waves are mainly of the sea type, with occasional occurrence of NE swell [12]. The area is characteristic of a semidiurnal mesotidal regime with a spring tidal range of approximately 3.1 m [13]. The most referenced Holocene sea level curve [14] indicates +5 m at 5.1 Ky BP, followed by two rises and falls until the present level.

A unique aspect of this stretch of coastal area is that it is not influenced by storm-induced surge and extreme wave conditions. Instead, extremely persistent unidirectional wind and wave forcing dominate, creating a strong and persistent longshore forcing that induces a large net rate of longshore sediment transport [15].

The mean sea level rose 14 cm in the last 73 years, as seen in Fortaleza (for location, see **Figure 1**). The data was obtained by the analysis of the nautical maps of 1945 and 2018 of Fortaleza coast, taking into account the level of the sea in both years in each map [16]. It indicates that a rising of sea level is an important element of the present dynamics in the area.

The rising of sea level, with inadequate and inappropriate uses, occupation, and development of the coast and of the shoreline, is producing large degradation of this coastal area, destroying ecosystems, construction, and equipment, thus causing economic, social, and environmental problems. The situation will be analyzed in two segments of the state coastal area, which are Mucuripe harbor headland, in Fortaleza city, and Canoa Quebrada beach, on the east coast (for location, see **Figure 1**).

3.2 Coastal environmental problems in Fortaleza area

The Mucuripe headland, in Fortaleza city, is characteristic of a low-lying (~1.5 in mean tide) outcrop of Precambrian quartzite (**Figure 2A**). It trends ESE-WNW and has been heavily engineered since the 1950s, following the installation of a harbor (**Figure 2B**).

The longshore current and transport of sand in the area take place from east to west. The sands, before the installation of the harbor, bypassed the headland and were transported to the west, nourishing the beaches downdrift, for dozens of kilometers. The two extensive jetties built to protect the harbor from waves and silting interrupted the longshore current, eliminating the transport of sediments downdrift [4, 12, 16–18]. Quantification of the sand intercepted by the headland and harbor structures yielded a reasonably accurate estimate of longshore sand transport rate of approximately 860,000 m^3/y [12].

This interruption of littoral drift induced a large accumulation of sand updrift, of the order of 825,000 m^3/y [16, 19]. Since the installation of the harbor, the total amount of sand accumulated updrift is approximately 26.4 million m^3, creating a new beach of 65.5 ha of area (Serviluz beach, for location, see **Figure 2B**) [16].

However, part of the sand accumulated in Serviluz beach, despite the jetties, bypasses them and the headland, being transported around these features and deposited by wave diffraction along the northern side of the harbor, creating the Mansa Beach and silting the harbor's basin (**Figure 3**). For this reason, dredging is frequently needed in the harbor basin, in order to let large boats dock without stranding. Surveys carried out by [16] indicated that the amount of sand dredged from the harbor's basin since the 1950s is of the order of 21 million m^3.

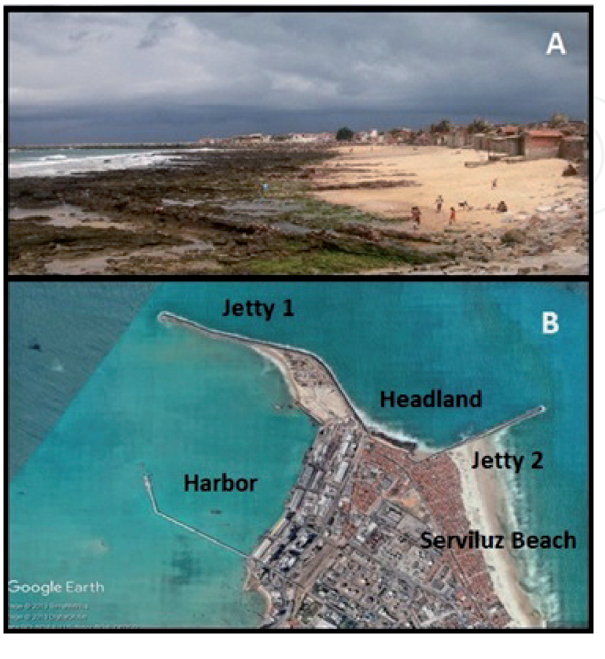

Figure 2.
(A) Mucuripe low-lying headland, in Fortaleza city, a natural feature that changes the orientation of the shoreline, from SE-NW to NE-SW. (B) The Mucuripe/Fortaleza harbor, installed in the 1950s, and the jetties built to protect the harbor's basin from waves and silting. The jetties interrupted the longshore transport, which came from the east.

DOI: http://dx.doi.org/10.5772/intechopen.87959

Figure 3.
The residual bypass of sand across the jetties and the headland created the Mansa Beach and keep nourishing it regularly. The bypass also produces the silting of the harbor's basin, which has to be frequently dredged.

Figure 4.
Jetties installed in Fortaleza coastal area, in order to protect the shoreline against the erosion resulted from the interruption of the longshore transport produced by the harbor and associated jetties constructed updrift (east of the shown area) (source: Google Earth, 2019).

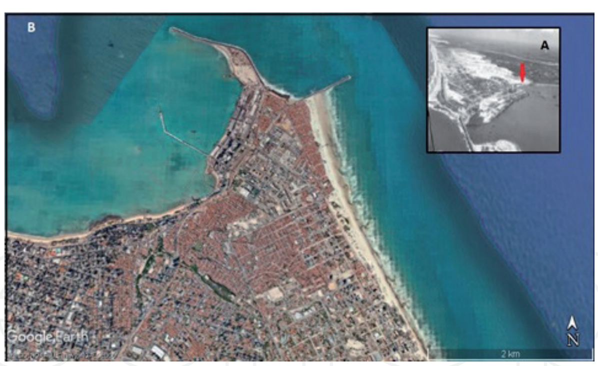

Figure 5.
(A). East coast of Fortaleza city and Mucuripe harbor vicinity, with large dunefields. The red arrow shows the area where the bypass of dunes still took place after the construction of the harbor. (B). Complete urbanization of the dunefields, with cessation of dunes bypass.

The aggressive interruption of the tremendous amount of net longshore sand transport has induced up to 100 m of beach erosion downdrift of the headland/harbor between 1960 and 1970 [17]. Numerous shoreline structures, such as groin fields, were constructed to protect the shoreline from this beach recession (**Figure 4**), further disrupting the longshore sand transport system and extending the artificial influence further downdrift [12, 17].

In addition to the blockage of longshore bypassing, the dune bypass is also completely obstructed by buildings densely constructed over the entire area during the last decades [4] (**Figure 5**). Practically no sand reaches the downdrift beach through headland dune migration anymore [4] or through the flux of the Ceará river mouth, to where the dunes of the western segment of Fortaleza city migrated before [16] (for location of Ceará river estuary, see **Figure 4**).

The consequences of these processes in the coastal dynamics are dramatic. The shoreline retracted some 400 m in 60 years at places 15 km from the headland [4, 13]. The erosion is still happening: In Icarai Beach, 25 km downdrift, beach recession of magnitude of 100 m took place between the years 2004 and 2016 [4].

The retraction of the beaches indicates that the coastal dynamics in the area are completely disturbed. The sand introduced in the littoral drift by means of this erosion is the probable source of the sediment that is now accumulating in the area around the pier of another harbor, the Pecém harbor, located in the next headland downdrift, 60 km west of Fortaleza harbor [4]. The degradation illustrates the changes related to extreme human interventions on a unidirectional system, associated with rising sea level.

3.2.1 Coastal mitigation in the metropolitan region of Fortaleza

As erosion travels west, real estate owners along the shoreline try to protect their property by building coastal protection with their own resources or by pushing public power to build structures with public resources. In this way, several interventions were made in the last decades, of the rock-fill and bag-wall types.

The rock-fills protect the coast from erosion; however, it results in the loss of the beach area and in increased erosion downdrift (**Figure 6A**). The bag-wall, built in the 2010s, on the other hand, has already been destroyed by the action of the waves (**Figure 6B**), showing it completely inefficient for solving the kind of problems created by the construction of the Mucuripe harbor and by the unsustainable type of urbanization of Fortaleza city.

Figure 6.
(A) Erosion in Icarai Beach, 25 km downdrift of Mucuripe harbor, resulting from the interventions in Fortaleza city and in the area around the harbor. The rising of the sea must also be a factor producing the erosion. (B) Bag-wall installed in Icarai Beach in the 2010s, already destroyed by the waves.

It seems clear that the erosion in the area will not cease with the kind of intervention that has been taking place in the last six decades. Effectively, it is necessary to consider that the waves are very active and that sand is missing in the shoreline. In addition, the sea level is rising. In [19], it is pointed out that the sands which are dredged from the harbor's basin could be used to mitigate the erosion, by means of artificial nourishment of the beaches, as it takes place in other countries (e.g., [20]). Vasconcelos [16] advanced in this point of view, considering that the sand of the dredging could be dispersed along the littoral of Fortaleza, at the bathymetry of 5 m. Effectively, at 5 m deep, the longshore current would naturally transport the sands to the beaches downdrift, rebuilding coastal dynamics. This measure would waive nourishment of beaches, as well as the installation of rock-fills, bag-walls or other engineering structures and actions, implicating in less cost and less disturbance of the shoreline and of the social life related to it.

Nevertheless, these suggestions have not yet been considered by public authorities. In fact, a new dredging took place in August/September 2018, and as before, the sands were transported offshore, to be deposed and lost in areas far away from the shoreline. Meanwhile, the aggressive, dramatic, disastrous, and degrading erosion and destruction of the north part of Ceará State coastal area keep taking place.

3.3 Environmental problems in Canoa Quebrada beach

The town of Canoa Quebrada is located 140 km east of the city of Fortaleza and represents one of the most visited tourist destination in the coastal zone of the Northeast Brazil. It is characterized by the presence of active sea cliffs modeled in the Barreiras Formation, with the occurrence of a narrow beach in its foothills, plus beach rocks nearshore, which partially protects the sea cliffs (**Figure 7**). Clays and friable sands make up the sediments of the sea cliffs, which are bare or only partly protected by vegetation [21].

The morphodynamics in the area is very active: the strong rains that characterize the rainy season cause ravines and acute ridges, resulting in transport and deposition of sediments in the foothills, in the form of cones of dejection (**Figure 8**). The rain also contributes to the softening of the material of the cliff and to the increase of the water table, which produces dissolution in the slope and increases the internal pressure in the sediments, thus increasing the fragilization of the feature (e.g., [22]).

An important anthropogenic factor of the dynamics of the sea cliffs is the installation of numerous tourist facilities on their top and slope. These structures cause trampling and compacting of the sands, increasing ravines and generating gullies, which contributes to the acceleration of the erosive processes caused by rainwater (e.g., [23]) (**Figure 9**).

The cliffs of Canoa Quebrada have an average height of 15 m and can be considered as small- to medium-sized cliffs. However, the volume of material that is

Figure 7.
Reef line at Canoa Quebrada beach (adapted from Google Earth image, 2018).

Figure 8.
Grooves at the top and cone of dejection at the base of the sea cliffs of Canoa Quebrada.

Figure 9.
Occupation of the top and bottom of the sea cliffs of Canoa Quebrada.

removed from these features is not negligible due to the high frequency of landslides. The occurrence of successive episodes of landslides is due to the combination of three factors: the friable nature of the clay-sandstone material, high anthropogenic presence, and strong tropical rainfall.

The sea cliffs present slope angle usually under 45° and are characterized mostly by the occurrence of retreat controlled by milder gravitational sliding more than by abrupt collapses (**Figures 10** and **11**). Together with the type of wave breaking, sea level rising, tidal amplitude, and sediment granulometry, the inclination directly influences the erosive process that characterizes the sea cliffs today [24–25].

The analysis of the set of points where topographic profiles were made indicates that from east to west (profiles 1,2,3, **Figure 11**), the slope presents relatively smooth landslides, while in the westernmost portion of the beach, where the profile assumes an angulation of more than 45° (profiles 5 and 6, **Figure 11**), landslides occur. The analysis of satellite images containing a time series of the years 2004, 2008, and 2017 indicates that the velocity of retreat of the Canoa Quebrada sea cliffs is very high when compared to hard rock cliffs.

Retreat velocity was calculated in three distinct sections, with the following results: in the east, the retreat was the smallest, of the order of 90 cm between 2004 and 2017, representing an average retreat of 8.2 m per century. In the central areas, which have many tourist developments, the retreat was slightly faster, of the order of 1.2 meters in 13 years, representing approximately 10.9 m per century. To the west,

DOI: http://dx.doi.org/10.5772/intechopen.87959

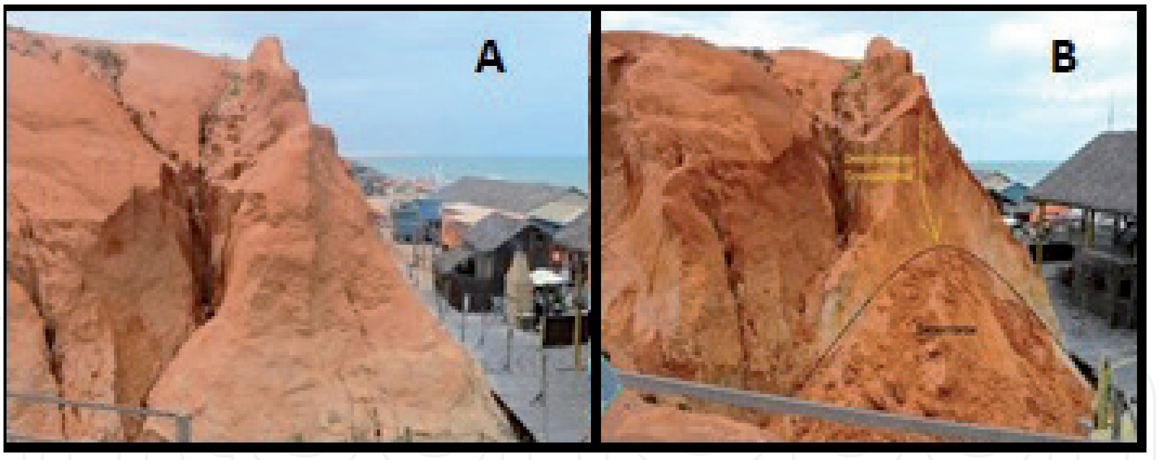

Figure 10.
(A) The cliff on January 16, 2016, and to the right on February 20, 2016. (B) The retreat of the sea cliff by gravitational slip is visible in the 2016 picture.

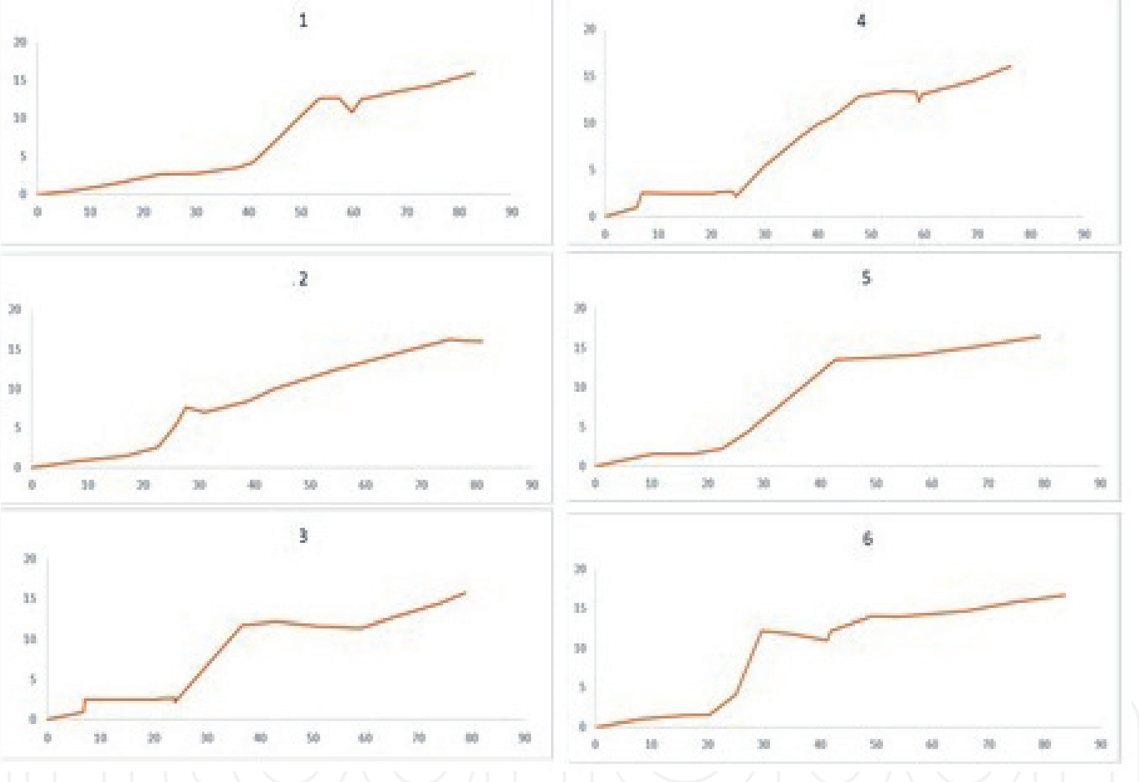

Figure 11.
Topographic profiles of Canoa Quebrada sea cliffs.

less sheltered area in relation to the attack of the waves due to smaller presence of beach rocks, the cliff receded 1.7 m in 13 years, equivalent to 15.5 m per century. The average speed of retreat of the cliff for the studied area is of 11.5 m per century.

It is also observed that the line of rupture of the sea cliff in the image of 2017 presents recesses, with gaps and gullies that did not exist in 2004, indicating morphogenetic processes acting differently over the years. In 2004, the performance of the marine processes at the base of the cliff was dominant, with more intense and uniform retreat of the slope. The presence of retreat in the image of 2017 indicates that there was a change in the relation of forces between the active processes, being now the subaerial processes more intense than the marine ones. In synthesis, it is concluded that the cliffs rapidly recede by the combined action of wave attack, rising sea levels, rainfall, and human action.

Figure 12.
Tourist equipment installed very close to the unstable sea cliffs, running the risk of being buried by landslides.

The average retreat velocity of the Canoa Quebrada sea cliff is compatible with the soft nature of the sediments that compose it. However, it is a very high speed if we consider the presence of an important urban nucleus and many tourist facilities located near or on the edge of the cliffs.

Environmental risk prevention was never present in the urban planning of Canoa Quebrada. Natural and anthropic factors were not taken into account in the expansion of the village on the cliffs. However, the cliffs of Canoa Quebrada are fragile and present strong risks of landslides, as indicated by the survey realized and exposed above. These factors must be taken into account in planning the future use and occupation of the area, under penalty of material damages, environmental degradation, and unsafety to the public. It is also noted that in the central portion of the beach, there are ventures located very close to the foot of the cliff, running at great risk of burial by materials from the top, through the frequent landslides (**Figure 12**).

In this central area, it is strongly advisable to remove part of the existing tourist structures, thus ensuring the use of this equipment safely by tourists and inhabitants of the town.

4. Coastal environmental problems in northern Colombia

4.1 Natural settings of the study area

The northern Colombia coast is located along the south side of the Caribbean Sea (latitude and longitude of the west and east boundaries are 11.1 north 74.9° west and 12.2 north 72.0 west, respectively) (**Figure 13**). The meteorological and oceanographic conditions are dominated by northeast trade wind, which results in the dominating northeasterly approaching wave occurring over 95% of the time. Effectively, northeasterly approaching waves occur by far the most frequently (**Figure 14**), driving a persistent westward longshore sediment transport.

The general shoreline orientation of the study area is roughly 60 degrees, or striking WSW-ENE. The relatively straight shoreline is interrupted by two protruding headlands, Santa Marta and Cabo De La Vela. A broad shoreline orientation change occurs near Riohacha. To the west, the shoreline orientation is roughly 68°, while to the east, the orientation is roughly 52° or a change of 16° around the broad Riohacha headland. These shoreline orientation changes play a significant role in beach processes.

Rocky coast dominates at both the Cabo de la Vela and Santa Marta headlands, with pocket sandy beaches distributing in the numerous embayment areas (**Figure 15**). Sandy beaches distribute along most of the coastline except at the

Figure 13.
The northern Colombia coast, located on the south side of the Caribbean Sea.

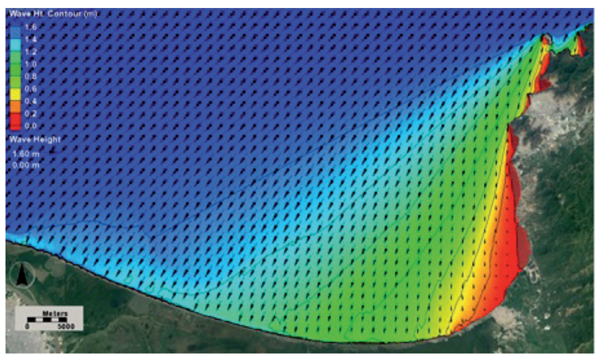

Figure 14.
Regional wave modeling results for NE (45°) approaching wave. Example of the area Santa Marta—Barranquilla Cienaga.

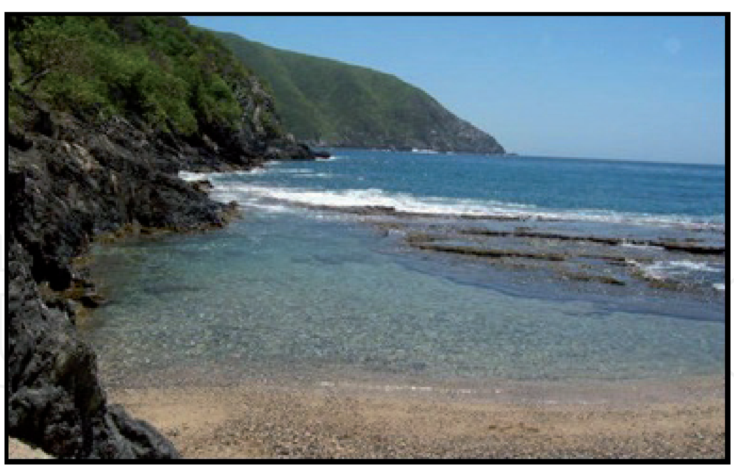

Figure 15.
Example of rocky coast at Santa Marta headland.

headlands. Numerous rivers discharge into the Caribbean Sea. Most of the sandy beaches distribute directly along the mainland. The westward longshore sand transport is illustrated in this example from Riohacha by the sand impoundment along the east updrift side of the long groin (**Figure 16**).

Several spit type barrier islands extend along this stretch of coastline, originated from westward spit growth, and are of the wave-dominated type [26]. All the tidal inlets are quite narrow with small flood and ebb deltas. This is controlled by the fact that the tidal range is mostly less than 0.3 m even during spring tides, while wave forcing is relatively strong. Therefore, beach-inlet interaction only has

Figure 16.
Example of sandy beach at Riohacha, accreted updrift by the help of jetties.

localized influences on beach erosion and accretion. Wave plays a dominant role in shaping the coastline, since it is the dominating forcing, causing beach erosion or accretion. Extreme energetic conditions associated with direct hit or nearby passage of tropical storms can have significant and long-lasting impacts on coastal morphology.

The beach processes along northern Colombia coast are relatively simple, driven predominantly by westward longshore sand transport. The trend of beach erosion or accretion and the state of the beach are largely controlled by the gradients of longshore sand transport, which can be caused by both natural and artificial factors.

4.2 Environmental problems at Santa Marta: Barranquilla area

About 19 km west of Barranquilla (km-19 site) (for location, see **Figure 13**), severe beach erosion has threatened a section of a major coastal highway (**Figure 17**). Presently, the highway is protected by recently installed riprap revetment. However, continued beach erosion is undermining the foundation of the riprap and likely the road in the near future. Furthermore, the erosion may continue to expand westward and propagate the problem over a larger area.

Figure 17.
Severe beach erosion at 19 km site threatening a major highway. The recently installed riprap is experiencing toe scour due to continued erosion.

Analysis of time-series aerial photos from Google Earth has shown that the beach along the km-19 coast is experiencing persistent rapid erosion from 2009 to 2015, at over 15 m per year. The sediment transport gradient along this stretch of coastline is caused by the shadowing effect of the Santa Marta headland, which creates a westward increasing wave height along the km-19 site. This results in more sediment being transported westward from the km-19 site than being transported into the site. A major coastal road to the city of Barranquilla is now practically at the shoreline (see **Figure 17**). Originally, the road was several hundred meters from the shoreline. In 2009, the distance was only 115 m. The waves along this section of the coast is quite energetic nearly all year round, and the longshore sediment transport gradient resulting is induced by natural morphological conditions.

4.3 Environmental problems at Riohacha coastline

The Riohacha coastline (for location, see **Figure 13**) provides an example of beach accretion and erosion associated with artificial interruption of the persistent westward longshore sand transport. **Figure 18** shows the aerial view of the Riohacha coastal line with a groin field. The groins were installed with the perspective to allow accretion of beaches.

Effectively, it is apparent that the groins at the updrift end have impounded a large amount of sand and resulted in a quite wide beach there (**Figure 19**). Several small rivers to the east and updrift of the beach contribute to the sand supply.

However, the field of these 150-m long groins nearly completely interrupted the westward longshore sand transport and resulted in severe beach erosion along a long and extending stretch of downdrift coast. **Figure 20** illustrates the erosion along the beach downdrift of the groin field. In addition, due to the depleted sand supply, the groins downdrift of the large beach failed to impound any sand. Similar sand bypassing patterns around and through a groin were found by [27] in a large-scale laboratory study on interaction of a groin with longshore sand transport.

4.4 Environmental problems at Costa Verde Cienega

Costa Verde Cienega (for location, see **Figure 13**) is located within the greater shadow zone of the Santa Marta headland and at the edge of the secondary shadow zone. The waves along this stretch of the coast are low due to the shadowing effect of the Santa Marta headland. A wave-height gradient exists along this stretch of the coast due to the secondary shadowing by the headland, although the rate of

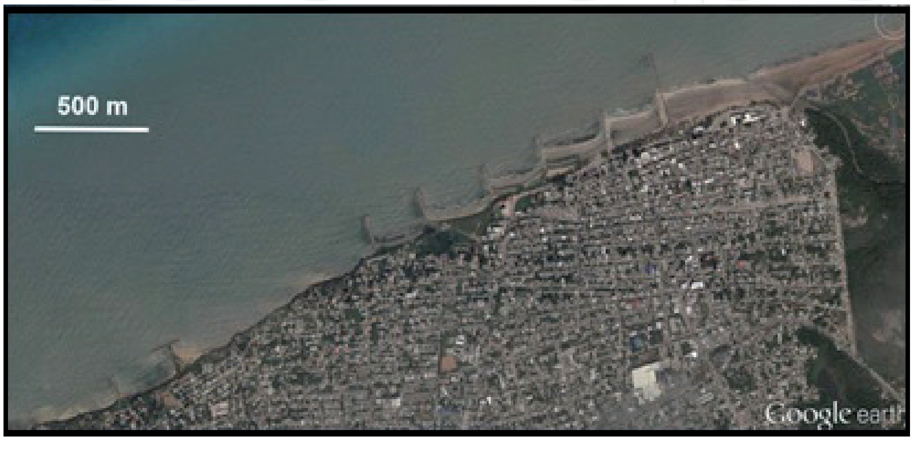

Figure 18.
Aerial view of the Riohacha shoreline. Note the large amount of sand accumulation at the east-most three groins and little to no sand accumulation at the rest of the groins and erosion further downdrift.

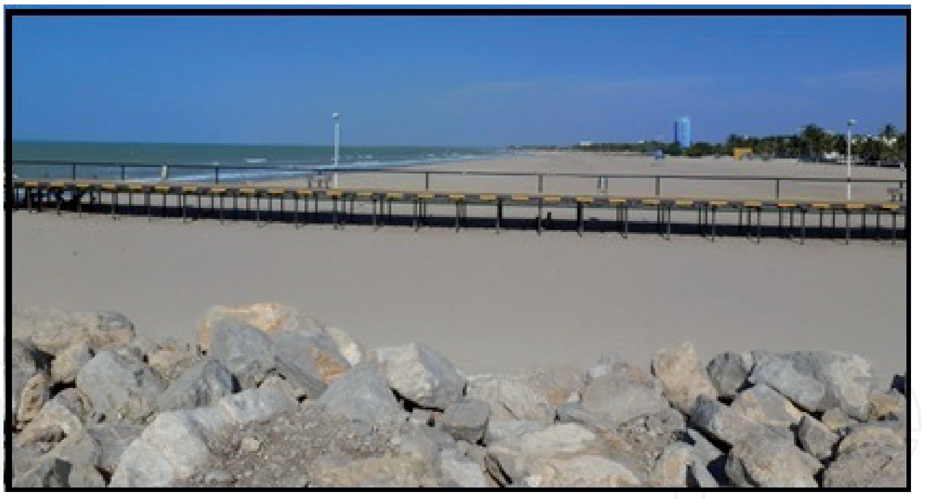

Figure 19.
Large amount of sand accumulation updrift of the first groin. The groin is considerably higher than the beach.

Figure 20.
Severe beach erosion downdrift of the Riohacha groin field, exposing a crucial infrastructure to direct wave attack.

Figure 21.
Severe beach erosion along the Costa Verde Cienega coast, exposing a crucial pipeline (yellow marker). Note the low-profile sandbag groin and the earth-moving machine at the top of the picture. The earth-moving machine was moving sand from the upland to nourish the beach and attempting to control the erosion.

longshore sand transport should be much smaller due to the low wave. Beach erosion here has exposed a crucial pipeline along the coast (**Figure 21**). Various low-profile groins made of sand bags were installed in an effort to control the erosion. Based on field observations, the sandbag groins have very limited and localized effect.

In addition to the longshore sand transport gradient induced by natural processes, anthropogenic activities also play a significant role in the beach erosion in the area. The westward longshore sand transport and a transport gradient were induced by a 140-m long groin installed between January 2011 and May 2012. Rapid sand accumulation east and updrift of the long groin occurred. By May 2012, the updrift beach had grown to about 35 m landward of the tip of the long groin. Only 5 months later in October 2012, the updrift of the long groin was filled to the tip of the groin.

The impoundment at the groin created a transport gradient at the downdrift, which further contributed to the beach erosion problems caused by the natural wave-height gradient associated with the secondary shadowing of the Santa Marta headland. Therefore, similar to the long groins at Riohacha, the downdrift beach did not benefit from sand bypassing even when the updrift beach reached the tip of the groin.

4.5 Coastal mitigation in northern Colombia

The above examples, along with numerous other cases in the northern Colombia coast, strongly suggest that caution should be carefully exercised in artificially interrupting the persistent westward longshore sand transport. Impounding the longshore moving sand by engineering structures, many times by groin field, is quite easy to do. The often very rapid beach accretion at the updrift side of the structure may lead to construction of longer and more groins. This can quickly turn into a very destructive practice along the tropical trade wind-dominated coast, where longshore sand transport is westward almost 100% of the time.

Well-planned regional scale study should be developed in order to avoid these types of problems in the future. The study should investigate (1) the source and availability of the sand to the beach, (2) rate of longshore sand transport, and (3) most importantly, existing natural and anthropogenic causes of longshore sediment transport gradient. The study should have adequate temporal and spatial scales. Spatially, the study should include a long stretch of beach, particularly along the downdrift coast, to ensure that the downdrift effect induced by the shore protection structures is fully considered over a long period.

5. Conclusions

Coasts along Northeast Brazil and northern Colombia are beautiful environments. Being popular tourist destinations as well as desirable living areas, these coasts can be very valuable economically. Tourism along the coast, particularly at sandy beaches, constitutes a large income for the two countries. The increasing of urban activities in these areas also induces to the installation of many key structures to the functioning of the urban and economic life, such as harbors. For instance, the areas are very vulnerable to numerous natural and anthropogenic stressors.

The present study showed examples of the coastal environmental degradation caused by these stressors in two areas of northeast Brazil and three areas of northern Colombia. The erosion of the beaches in Brazil and Colombia and the collapse of sea cliffs of Canoa Quebrada, Brazil, cause damage to the population, either through the alteration of marine ecosystems or through the reduction of artisanal fishing, leisure, and recreation spaces or the reduction of fishing activities, vacation, and tourism. It leads to heavy losses to economic activity, such as job losses, decrease in the income and tax generation, and real estate depreciation.

In such a context, it is necessary to better plan the occupation and uses of these coastal areas, in order to promote a sustainable development. Specifically, it is necessary to consider the fact that easterly trade wind has significant influence along the coastal area of both countries. It results in a dominating easterly approaching wave occurring over 95% of the time and then, in a unidirectional longshore transport, which has to be carefully considered in the moment to introduce equipment, structures, and housing in the shoreline. Considering that trade winds are in action in tropical areas, these findings should be applicable to many other tropical coasts.

Acknowledgements

We thank the editorial assistance of Mr. Roger Morton.

Author details

Vanda Claudino-Sales[1*], Ping Wang[2], Fábio Perdigão Vasconcelos[3] and Adely Pereira Silveira[3]

1 Federal University of Ceara State, and Master on Geography, Acarau Valley State University, Fortaleza, Brazil

2 University of South Florida (USF), Tampa, USA

3 State University of Ceará (UECE), Fortaleza, Brazil

*Address all correspondence to: vcs@ufc.br

References

[1] Claudino-Sales V. Les littoraux du Ceará Evolution géomorphologique de la zone côtière de l'Etat du Ceará, Nord-est du Brésil [Thesis]. Paris: Université Paris-Sorbonne; 2002

[2] Claudino-Sales V. Os litorais cearenses. In: Borzacchiello J, Cavalcante T, Dantas E. (Org.). Ceará: Um novo olhar geográfico. Fortaleza: Edições Demócrito Rocha. 2005:189-210

[3] Claudino-Sales V. Cenários Litorâneos: Natureza e Ambiente na Cidade de Fortaleza, Ceará [Master's Dissertation]. São Paulo: University of São Paulo; 1993

[4] Claudino-Sales V, Wang P, Carvalho AM. Interactions between various headlands, beaches and dunes in the coast of Ceará state, Northeast Brazil. Journal of Coastal Research. 2018;**34**:413-428. DOI: 10.2112/JCOASTRES-D-16-00173

[5] Pedrosa AA. A geodinâmica e morfogênese das dunas eólicas na Praia de Canoa Quebrada, Aracati, Ceará, Brasil [Thesis]. Fortaleza: Universidade Federal de Ceará; 2016

[6] Castro JWA. Burying processes carried out by a mobile transversal dunefield, Paracuru County, state of Ceará, Brazil. Environmental Geology. 2005;**49**:214-218. DOI: 10.1007/s00254-005-0055-6

[7] Jiminez JA, Maia LP, Serra J, Morais JO. Aeolian dune migration along the Ceara Coast, northeastern Brazil. Sedimentology. 1999;**46**:689-701. DOI: 10.1046/j.1365-3091.1999.00240.x

[8] Wang W, Saha S, Pan HL, Nadiga S, White G. Simulation of ENSO in the new NCEP coupled forecast system model (CFS03). Weather Review. 2005;**133**:1574-1593. DOI: 10.1175/mwr2936.1

[9] Zanela ME. As características climáticas e os recursos hídricos do Estado do Ceará. In: Silva JB, Dantas EWC, Meireles AJA, editors. Ceará: um novo olhar geográfico. Fortaleza: Edições Demócrito Rocha, 2a edição; 2007. pp. 169-188

[10] FUNCEME (Fundação Cearense de Metereologia e Recursos Hídricos). Dados dos postos pluviométricos do Estado do Ceará. Retrieved from www.funceme.br/calendario/produto/municipio/; 2018

[11] INPH (Instituto Nacional de Pesquisas Hidroviárias). Simulação do regime de ondas no Pecém, Ceará (Report). Rio de Janeiro; 1996

[12] Maia LP. Procesos costeiros y balancio sedimentario ao largo de Fortaleza (NE Brasil): Implicaciones para un gestión adecuada de la zona litoral [Thesis]. Barcelona: University of Barcelona; 1998

[13] DHN (Diretoria de Hidrografia e Navegação). Tábua de Marés do Porto do Mucuripe (Report). Fortaleza; 2018

[14] Martin L, Suguio K. Variation of coastal dynamics during the last 7000 years recorded in beach-ridge plains associated with river mouths: Example from the central Brazilian coast. Palaeogeography, Palaeoclimatology, Palaeoecology. 1999;**99**:119-140

[15] Vasconcelos FP, Morais JSD, Diniz MT, Rego-Filho FF, Rocha GC Determination of shoreline variations of the metropolitan region of Fortaleza (Ceará State - Brazil) using methodology of GIS. In: Proceeding of CoastGIS 2007; Vol. 2. Santander, Spain: Copicentro-Bonifaz; 2007. pp. 233-343

[16] Vasconcelos FP. Dinâmica Costeira do Litoral de Fortaleza e os impactos da construção dos aterros das praias do

Meireles (Beira-Mar) e Iracema sobre o litoral de Caucaia (Report). Universidade Estadual do Ceará - UECE. Laboratório de Gestão Integrada da Zona Costeira – LAGIZC. Fortaleza; 2018

[17] Morais JO. Aspectos de Geologia Ambiental Costeira do Município de Fortaleza, Ceará [Thesis]. Fortaleza: Universidade Federal do Ceará; 1980

[18] Pitombeira ES. Litoral de Fortaleza – Ceará – Brasil, um exemplo de degradação. In: Anais do 1° Simpósio sobre Processos Sedimentares e Problemas Ambientais na Zona Costeira do Nordeste do Brasil. Recife: ABEQUA; 1995. pp. 59-62

[19] Morais JO. Geological assessment of environmental impact on the Littoral of Fortaleza, Ceará, Brazil. Urban Risk. 1993;**4**:23-39

[20] Paskoff R. Les Littoraux: L'impact des aménagements sur leur évolution. Paris: Editora Armand Colin; 2010

[21] Meireles AJA. Falésias do litoral leste do estado do Ceará – Análise dos Processos Morfogenéticos e Impactos Ambientais. Revista Geonotas. 1999;**3**(2):1-29

[22] Veyret Y. Les Risques. Paris: SEDES; 2003

[23] Miossec A. De l'érosion cotiére em general et le cas français en particulier. La Géographie Terre de Hommes. Numéro Especial: L'érosion. Octobre - Décembre 2018;**1571**:28-34

[24] Bird E. Coastal Geomorphologie, An Introduction. Chichester: Wiley; 2000

[25] Merlotto A, Bértola GR, Isla FI, Cortizo LC, Piccolo MC. Short and medium-term coastal evolution of Necochea municipality, Buenos Aires province, Argentina. Environment and Earth Science. 2014;**71**:1213-1225. DOI: 10.1007/s12665-013-2525-6

[26] Davis RA, Hayes MO. What is a wave-dominated coast? Marine Geology. 1984:313-329

[27] Wang P, Kraus N. Movable-bed model investigation of groin notching. Journal of Coastal Research. 2004, special issue;**33**:342-368