Chapter 7
The Beaches of Ceará

Lidriana de Souza Pinheiro, Jáder Onofre de Morais, and Luis Parente Maia

Abstract The coastal zone of Ceara State, in Northeastern Brazil, extends for 573 km in a SE- NW direction. It is predominantly composed of sandy sediments of Upper Tertiary-Quaternary age with several generations of Pleistocene transgressive dunes, together with beaches, estuarine plains and localized occurrences of cliffs. The Precambrian rocks also occur on some beaches. The climate is semi-arid tropical and the rivers only flow into the sea during the rainy season. The dunes, beaches and estuary margins have experienced serious problems derived from the loss of sand material that have been taken to be used in coastal engineering, edifications and natural environmental degradation processes concerned to the sediment budget. In this context, this chapter focuses the description of the morphodynamics characteristics of the beaches of Ceara State, highlighting the factors controlling spatial and temporal processes, as well as discussing the impacts, potential uses and limitations of these areas. The results indicate that today this coastal erosion, either natural or induced by man, is perceived as the most significant threat to maintaining services in areas that depend upon tourism, traditional economic activities, housing and other pertinent uses of the beaches. It has been pointed out that the natural and human impacts represent the main and outstanding challenges for dwellers and the coastal managers who need to find out the new ways of living and occupation, includes redesigning the processes of house constructions and keeping up with minimizing the impacts. Then, the main actions that deal with the use and abuse of this littoral are discussed in this chapter. The environmental problems have to be strictly controlled, particularly stabilization of the mobile dune and preventing development of cliffs and headlands.

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7.1 Introduction

The State of Ceará lies between 2°S–7°S and 37°W–41°W and has an area of 146,000 km². It extends from the border of Piauí in the west to Rio Grande do Norte and Paraiba in the east; with Pernambuco forming the southern border (Fig. 7.1). The northern coastal zone is aligned in a general west-east direction from the estuary of the Timonha river to Itarema beach, it then trends northwest to southeast to Icapui municipality, at the Rio Grande do Norte border.

The coastline extends for 573 km, with the coastal zone having an area of 146,000 km² which represents 14.38 % of the state (IPECE 2013). Municipalities bordering the sea have the highest population densities in the Ceará state, ranging between 200 and 2000 inhabitants per km², peaking in the city of Fortaleza, the State Capital (IPECE 2013).

The coastal zone extends inland from 2 to 5 km to the landward limit of the dune fields. Wide sandy beaches, paleodunes, transgressive dunes, sand spits, estuaries with mangroves, canals, lagoons, and bedrock headlands make up the framework of the coast.

The fishermen, native people and maroon represent the traditional coastal communities. In the nineteenth century the production of sea salt was one of the main activities. Today the main economic activities are coastal tourism, aquaculture in estuaries, deep-sea fishing and industrial activities associated with the Pecem and Mucuripe harbours, and industrial complexes. Urban and coastal sprawl commenced in the 1980s, to support leisure and tourism activities with visitors from Ceará State, as well as from all over Brazil and abroad.

Property speculation and the land subdivision in the vicinity of towns and small fishing have been responsible for village stress and the coastal urbanization. This

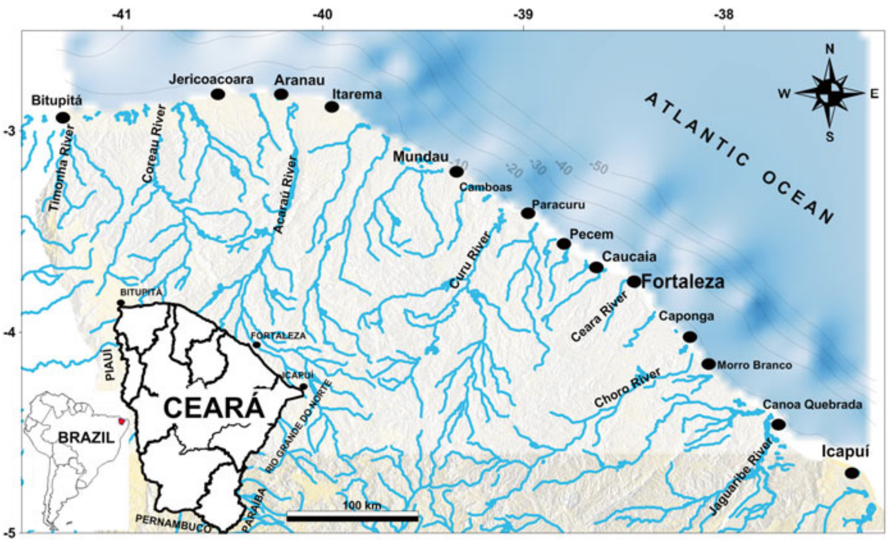

Fig. 7.1 The Ceará coastal zone

has resulted in a series of impacts which led to serious beach erosion, loss of urban infrastructure, cultural heritage, uncertainties in investment, as well as to economic depreciation of property and seaside services (Morais et al. 2006a, 2008).

The purpose of this chapter is to describe the main characteristics of the beaches of Ceará State, highlighting the factors controlling spatial and temporal processes and systems, as well as discussing the potential use and limitations of these areas.

7.1.1 Geology

The Ceará coastal zone is predominantly composed of sandy sediments of Upper Tertiary-Quaternary and contains several episodes of dunes, beaches, estuarine plains and active and paleo-sea cliffs (Fig. 7.2), all activated during period of high sea level. The Precambrian only occurs as headlands on the beaches of Pecem, Meireles, Iguape and Jericoacoara (Morais 2000).

The basal layer of the Barreiras Formation has been eroded to form rock platforms, cliffs and headlands at Morro Branco, Caponga, Bitupita, Taiba and Camocim, as well as elsewhere in northeast Brazil (Bittencourt et al. 2005). The sediments are supposed to be continental colluvial-alluvial origin and occur throughout the Northeast coast (Bigarella 1975). Rossetti et al. (2013) also discuss the marine origin of these deposits in some parts of the Northeastern Brazilian coast. The Formation also occurs along the coast in parallel sequences, as well as a sequence of transgressive episodes in Jericoacoara, Barra Nova and Canoa Quebrada (Irion et al. 2012; Morais et al. 2009). Where submerged, these cause wave refraction, diffraction and reflection of waves in the shadow zone of headlands and thereby play an important role in wave energy distribution, sediment transport and shoreline

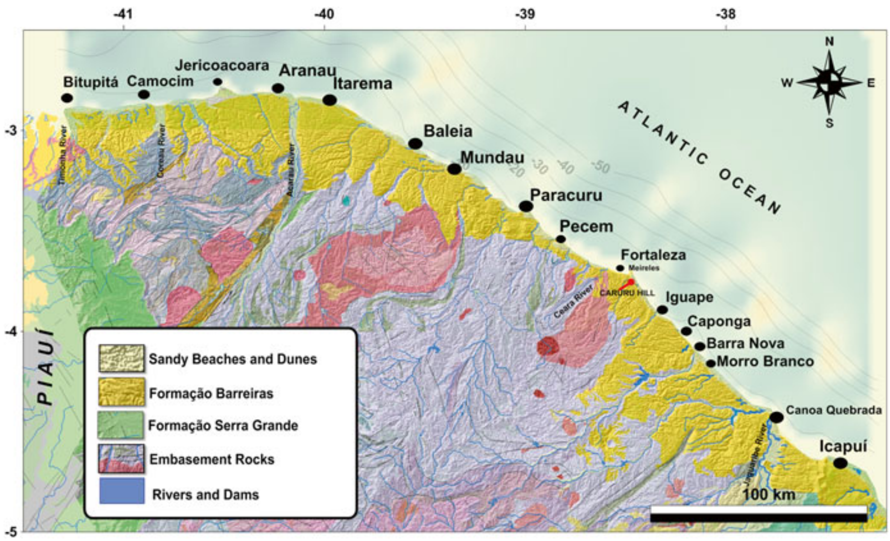

Fig. 7.2 Geological Map of Ceará coastal zone (Source: CPRM 2009)

alignment and erosion (Carvalho et al. 2007). Beachrock, is aligned parallel to the shoreline at the depth of 23 m, 30 km from the coast of Icapui on the eastern coast of the state, and appears to represent old shorelines (Monteiro and Maia 2010).

Consolidated cliffs are carved in limestones of the Jandaira Formation and sandstone of the Açu Formation of Cretaceous age at Icapuí and extend as far as Rio Grande do Norte. At Caruru hill near the mouth of the Pacoti estuary, volcanic rocks have filled areas of tension in the old Oligocene host rocks (28.6–9 Ma), with chemical and petrographic similarity to the phonolite of Fernando de Noronha (Vandoros and Oliveira 1968). This has been confirmed by Morais (1969) using a seismic profile from the archipelago of Fernando de Noronha to Fortaleza coastline.

7.1.2 Climate

The climate is warm semi-arid tropical (IPECE 2013). However, the Baturite, Maranguape and Pacatuba mountains (altitude > 700 m), influence the climate between the cities of Caucaia and Pindoretama, resulting in a tropical warm sub-humid climate. The intensity and frequency of the rainy season is dependent on the position of the Intertropical Convergence Zone (ITCZ). The ITCZ migrates in annual cycles bringing the rainy season to Ceará between March and May.

From July to November the ITCZ moves gradually to the north of the equator, bringing dry conditions, with approximately 91 % of the rainfall concentrated in the first half of the year. Campos and Studart (2003) observed that the annual rainfall rate decreases from Fortaleza (1338 mm) toward Icapui (949 mm). Toward the west coast there is also a decrease of the total rainfall, with annual averages of 650 mm.

The temperature ranges from 22 °C to 33 °C, with an average of 27 °C with the lowest temperatures during the rainy season. The wind regime is also strongly seasonal with lower wind velocities prevailing during the rainy season (average velocity 5.47 $m.s^{-1}$) and higher velocities during the dry season (average velocity 7.75 $m.s^{-1}$) (Jimenez et al. 1999). Wind direction does not show a clear seasonal pattern, being mainly easterly all year round due to the dominance of the trade winds.

Along the Ceará coast wind speed increases towards the northwest, with direction slowly varying from southeast to northeast towards the north (Maia et al. 2005). These changes may be due to the latitudinal position of each site with respect to the average ITCZ position (Jimenez et al. 1999).

7.1.3 Drainage

The rivers are intermittent and only reach the coast during the rainy season (Cavalcante and Cunha 2012). Six watersheds are located in the coastal zone: Coreaú Basin (annual run off: 1625 $hm^3\ yr^{-1}$), Acaraú Basin (annual run off: 17.4 $hm^3\ yr^{-1}$), Curú Basin (annual run off: 1.1 $hm^3\ yr^{-1}$), Litoral Basin (annual run off: 1.2 $hm^3\ yr^{-1}$), Metropolitan Basin (1.5 $hm^3\ yr^{-1}$) and Lower Jaguaribe Basin (705.6 $hm^3\ yr^{-1}$)

(established by COGERH, Hydric Resources Management company). Although the river headwaters are located in areas of higher rainfall than the coast, they flow through large areas of semi-arid climate, which causes a reduced freshwater to the coast due to evaporation and blockage by dams. There is a flow regularization during dry season to supply cities and agriculture needs. There are no perennial rivers.

Ceará State has more than 3500 dams larger than 5 ha (COGERH 2008), which means that across the state, the river flows are virtually blocked by reservoirs. Along the 299 km river course between the Castanhão Dam and Jaguaribe River mouth, in Aracati city, there are 15 dams to supply the population (Cavalcante and Cunha 2012). The dams have reduced the flow of fresh water during the rainy season by 80 % for the Timonha, Malcozinhado and Acaraú estuaries (Morais and Pinheiro 2011). The decrease in flow has resulted in silting of valleys, and prevents the transport of sediments to the coast during the rainy season thereby increasing coastal erosion processes. Freshwater from coastal sand dunes forms coastal lagoons and flow directly onto the beaches and form sandy cliffs with ephemeral channels.

7.1.4 Waves and Tides

Tides in Ceará are semidiurnal mesotidal with a maximum amplitude of 3.2 m (Morais 1981; Maia 1998). Waves are 80 % sea waves ($1 \leq T \leq 9$ s) and 20 % swell, with periods > 10 s (Carvalho et al. 2007). The swell waves reaching the Ceará coast, with peak period greater than 10 s are frequent between December and April (Silva et al. 2011).

In Pecem Port, on the west coast of Ceará, the significant wave height is (H_s) is predominately (75 %) between 1.1 and 1.6 m, with higher values from August to December (Silva et al. 2011). The highest recorded H_s was 2.3 m in October (Silva et al. 2011). In the Port of Fortaleza, waves with $0.8 \leq H_s \leq 1.7$ m account for 85 % of the occurrences (Maia 1998). At Aracati on the east coast of Ceará State, the most frequent H_s is between 1.3 and 1.73 m (Maia et al. 2005).

At Caponga, Futuro, and Paracuru beaches, the most frequent (75 %) breaking wave height (H_b) ranged 0.90–1.05 m, 0.50–1.1 m and 0.4–0.9 m, respectively (Pinheiro et al. 2003; Albuquerque et al. 2010; Souza 2005). The wave height is attenuated in embayed beaches and crossing longitudinal bars and rock outcrops. The predominant wave direction is east-southeast, but the most common swell direction of the first half of the year is north-northeast (Maia 1998; Carvalho et al. 2007).

7.2 Coastal Sediments

Beach sediments are predominantly medium bimodal quartz sand (Morais et al. 2006a). Figure 7.3 shows the distribution of D_{50} (mm) for 216 beaches. Fine sand dominates 32 % of the beaches, very fine sand and gravels 15 % and 8 %, respectively, while medium size sand is the most dominant on 45 % of Ceará beaches (Fig. 7.3).

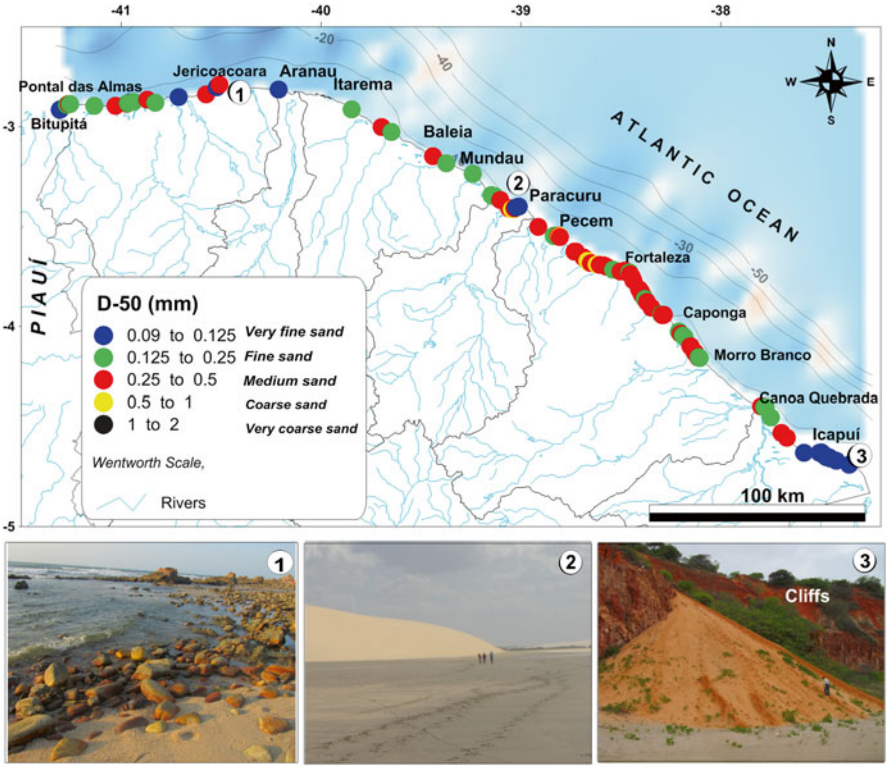

Fig. 7.3 Sediment size distribution (modal value of D_{50} (mm)) along the coast of Ceará. (*1*) Pebbles on the Jericoacoara beach; (*2*) Dunes migration towards the Paracuru beach; and (*3*) sand running down from the dunes on the cliffs top (Source: Data from the Coatal and Oceanic Systems Group coordinated by Morais, J.O- CNPq)

Longshore sand transport is to the west driven by east-southeast waves that occur 80 % of the year. Dunes also play an important role in sediment supply in some sectors of the coast, as observed in the headland overpassing at Jericoacoara, Paracurú, Icapui. Overwashing occurring during periods of high swell and contributes to a reduction in D_{50} at the Cascavel and Aquiraz beaches (Lima 2012; Maia 2014).

In areas with sandy-clay cliffs, that predominate along the east coast of the state, the rainfall in the first half of the year and groundwater discharge contributes to the input of fine sediments (silt and clay) to the beaches of Redonda and Peroba (Barros 2013; Oliveira 2012). On the west coast the presence of fine sediments is associated with proximity to the mouths of river estuaries and lagoons. Lithoclastic gravels are observed near the outcrop of conglomeratic rocks on the beach of Taiba, while the beachrock at Boi Choco, Iparana and Pacheco has resulted from marine abrasion.

Bioclastic gravels are found on the far west coast of Ceará and are cemented by calcite (Morais and Pinheiro 2005). The Fortaleza city coastline has predominantly medium siliciclastic sand out to the 15 m isobath. The inner shelf environments are characterized by the occurrence of terrigenous sediment that extends from the low-water mark to a depth of 10–20 m (Coutinho and Morais 1970; Kempf et al. 1967; Morais 2000; Freire and Cavalcante 1997). At the contiguous shelf break are thin bioclastic sands derived from the fragmentation of algae *Halimeda incrassata* and *Lithothamium* (Kempf et al. 1967; Freire and Cavalcante 1997).

7.2.1 Coastal Provinces and Geomorphology

Morais (2000) and Bensi (2006) divide the Ceará coast into two macro-compartments located east and west of Fortaleza. The eastern sector is characterized by a rocky coast with abrasion platforms and tabular sandy-clay deposits derived from cliffs and paleocliffs. Marine and rain erosion of the cliffs delivers fine-grained sediments (silt and clay) to the beach as can be seen at Morro Branco, Praia das Fontes and Redonda beaches (Morais et al. 2006c; Oliveira 2012). The west coast is dominated by mobile dunes, barrier islands backed by lagoons and mangrove areas (Bensi 2006; Morais et al. 2006a). The predominance of aeolian deposits is favored by the topography and angle of arrival of easterly waves that supply of sediments to the beaches and dunes.

The headlands are composed of pre-Cambrian rocks, beachrock and cliffs of consolidated Barreiras Formation, and Tibau, Camocim and Cretaceous rocks that comprise the sedimentary Potiguar basin (Morais 2000). These form a sequence of embayments with a flat concave shape facing the sea, resulting wave alignment following wave refraction, diffraction and reflection around and in lee of the headland area.

7.3 Ceará Beach Systems

Morais et al. (2006a) divided the 573 km long coast into five sectors, based on watershed boundaries, sediment delivery and the morphological characteristics of the beaches. Within each sector beach morphology, type of occupation of the beach and homogeneity in the modal values of H_b, T, D_{50} (mm) and tidal range, based on 216 data points, were used to characterize the sector. The modal morphodynamic feature of beaches was assigned based on Ω and RTR parameters described by Short (1999). The sectors were divided as follows: (a) Sector I (SI): Pontal das Almas – Aranaú (≈98 km); (b) Sector II (SII): Aranaú – Paraipaba (≈155 km); (c) Sector III (SIII): Curú river mouth – Pecém Port (43 km); (d) Sector IV (SIV): Cumbuco – Choró river mouth (≈162 km); and (e) Sector V (SV): Rio Choró – Requenguela (≈115 km) (Fig. 7.4). These sectors are used in the following sections to describe the beach systems and their behavior.

7.3.1 Beach Types and Morphodynamic States

Ceará beaches are predominantly tide-modified (RTR > 3). This is to be expected in a moderate wave energy mesotidal environment with a spring tide range of 3 m (Masselink and Short 1993). Considering the modal values of the sediments,

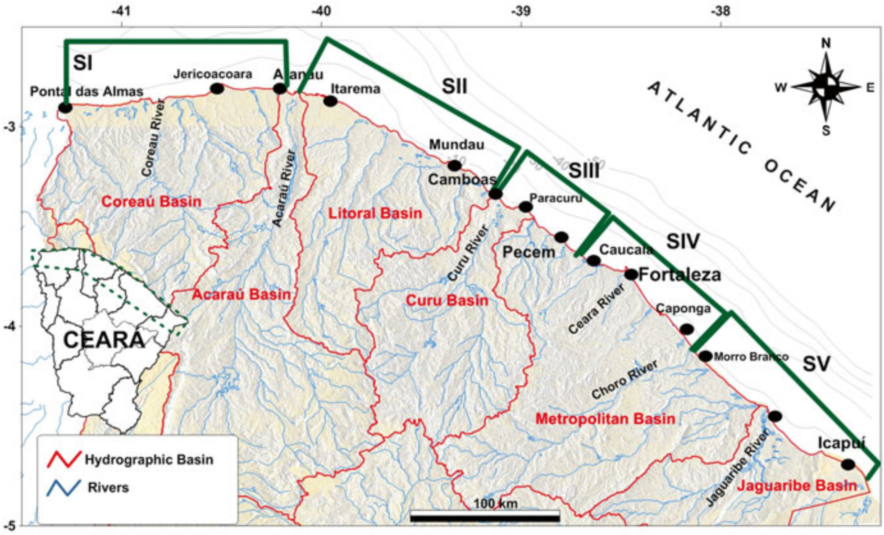

Fig. 7.4 The five coastal sectors, major drainage basins and the name of beaches mentioned in the text

Table 7.1 Ceará beach morphodynamics state

	Beach state	Number beaches	%	Beach (width) (average – m)	SD (m)
	Wave dominated (Ω = Hb/WsT)[a]				
1	D (Dissipative)	3	1.3	183.3	23.6
2	LBT (Longshore bar & trough)	22	10.1	207.3	5.4
3	RBB (Rhythmic bar & beach)	1	0.4	150.0	–
4	TBR (Transverse bar & rip)	2	0.9	200.0	–
5	LTT (Low Tide Terrace)	2	0.9	200.0	–
	Sub-Total	30	13.9	–	–
	Tide-modified (RTR)[b]				
6	R + LTT (Reflective plus Low Tide Terrace)	47	21.8	352.4	197.7
7	R + LTR (Reflective plus Low Tidal bars and rips)	56	26.0	158.5	106.8
8	UD (Ultradissipative)	1	0.46	>600	–
	Sub-Total	104	48	–	–
9	Beach plus rock/reef flats	82	38	150	32.7
	Total	216	100		

[a, b]Modal Values of the Hb (m), T (s), Ws and tide range, SD = standard deviation

together with the waves and tidal characteristics at the 216 monitored points, 48.15 % of the beaches were classified as tide-modified beaches, 13.85 % as wave-dominated beaches and 38 % beaches with rock-flats (Table 7.1). The tide-modified beaches are reflective with low tidal bars and rips (R + LTR) (26 %), reflective and low tide terrace (R+LTT) (21 %) with only 0.5 % ultradissipative (UD). The wave-dominated beaches are primarily longshore bar and trough state (LBT) (10 %). Beach width varies along the coast, with the widest observed on UD (mean > 600 m), followed by R+LTT (mean = 352.4 m, sd ±197.65 m) and R+LTR beaches (mean = 158.5 m, sd ± 106.84). The narrowest beaches occur at Caucaia and Fortaleza. Praia do Futuro in Fortaleza was rated as transverse bar and rip (TBR), and is characterized by the sequences of bars and rip currents that can lead to accidents and drowning.

A number of these wide flat beaches including Redonda, Bitupita and Maceió beaches are eroded during spring tides, while low frequency swell waves from north-northeast with periods greater than 10 s are responsible for flooding along several beaches.

7.3.2 *Coastal Processes*

The morphological characteristics of the shoreline depend on coastal hydrodynamic processes across the inner shelf and shoreface, such as wave attenuation, refraction and diffraction across outcrops, spits and sand banks and within embayments. The **sector I** between the Pontal das Almas beach and Aranaú (SI) is aligned east-west and is approximately 98 km long. The average width of the beach profile is 530 m (±119 m). Sediment size ranges from very fine to medium sand and the predominant state of the 17 beaches in this sector was R+LTT (Figs. 7.5 and 7.6).

At high tide the waves pass over the terrace and only break on reaching the base of high tide beach, similar to the reflective wave-dominated beach. As the tide falls,

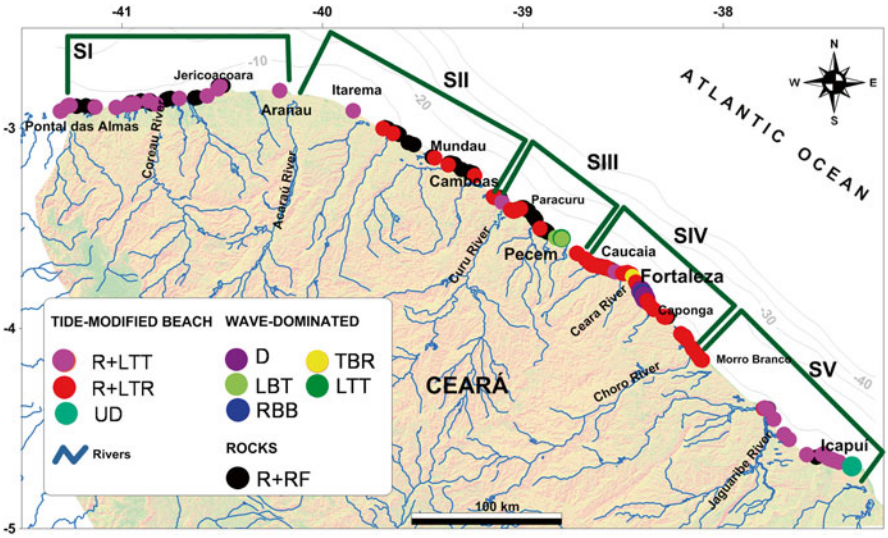

Fig. 7.5 Map showing the predominant morphodynamic states along the coast

Fig. 7.6 Sector I beaches: Reflective plus Low tide terrace beach at Camocim (**a**) and Bitupita (**b**)

waves begin to break across the terrace and at low tide they break on the outer edge producing a wide, shallow dissipative surf zone across the terrace. If rips are present, they will cut a channel across the terrace and are only active at low tide (Short 1999). Low tide also exposes the steep coarser beach face that abruptly connects to a flat low tide terrace with fine sediments, that extends for tens of meters seaward (Masselink and Short 1993; Short 1999). This region receives the discharge of the Coreaú and Acarau rivers during the rainy period, and other small drainages. Coastal lagoons formed by the closure of river mouths occur along with the dunes and sand spits.

Fig. 7.7 Sector II beaches: (**a**) Low tide terrace beach R+LTT at Almofala Beach; and (**b**) Low tide with rips with sand bars at Mundau Beach

Sector II extends from Aranaú to Camboas with the R+LTR beach state the prevalent. In the northwest, between Almofala and Aranaú, the beaches are characterized by west-trending barrier spits dominated by the R+LTT state (Fig. 7.7a), which at Itarema beach is 900 m in width. From Almofala to the mouth of the river Acaraú, the coast is characterized by sequences of coves with rocky spits dominated by the R+LTR state. High tide cusps are common and the low tide terrace may be dissected by small rip channels (Masselink and Short 1993). At high tide, surf zone processes are similar to reflective beaches with waves breaking or generally surging up the steeper beachface whereas during low tide the surf zone will be dissipative across the terrace with several lines of spilling breakers (Short 1999). The beach sediments range from fine sand to medium sand, with a predominance of fine sand suitable for aeolain transport and the average width of the beach profile is 396 m (sd ± 216.6 m). Aeolian transport is driven by east-southeast winds, which remobilization and transport of beach sediment into the dunes, with transgressive dune fields extending up to 4 km inland.

Also during the low tide, groundwater outcrops on the beach at the saturation point on the low tide terrace. The dissipative beaches are fed by fine sediments from sand dunes and the wave height is reduced by attenuation over the beachrock reefs which parallel the shoreline at the Mundaú and Fleicheiras beaches (Fig. 7.7b).

Sector III between the mouth of the Curú River and Pecem Harbor is 43 km long and aligned northwest-southeast. The morphology is similar to the previous Sector with sequences of spits, inlets and transverse dunes. About 73 % of the beaches are tide-modified with RTR > 3, with an average beach width of 216 m (sd ± 29 m). Pecém harbor is located offshore of Pecém beach through which are exported the raw material and products generated in the industrial complex located in the municipality of São Gonçalo do Amarante. This Port occupies a strategic position because it is equidistant from Argentina, Africa, Europe and North America for commerce and transport. The port also exports fish, leather and fruit produced in the Brazilian Northeast (IPECE 2013).

From the Curú river mouth to the Taiba beach R + LTT predominate (21 %). The sediments in this sector range from very fine sand to coarse sand with modal H_b of 0.90 m. There are also 15 km of beachrock coast and beaches (Fig. 7.8). Taiba's beach is predominantly R + LTR (Dias and Rocha-Barreira 2011). From the Taiba beach to Cauípe river's mouth, the wave-dominated LBT beach state (RTR < 3 and $\Omega \approx 5$) occurs on 66 % of the beaches, followed by LTT (9 %).

Sector IV is located between Cumbuco (Barraca das Velas) and the mouth of Choró river and has the highest population density on the Ceará coast. About 80 % of the beaches have RTR > 3, with a predominance of tide-modified beaches, the remainder are wave-dominated. The coast between Cumbuco and Iparana beaches is aligned northwest-southeast with beach sediments ranging from medium to coarse sand and a predominance of coarse sand ($D_{50} > 0.65$). R + LTR beach state was predominant on 12 beaches on the basis of data collected between the years 2002 and 2012.

Fig. 7.8 Sector III: Beachrock at Taiba beach

The presence of a reflective high tide beach and a more dissipative beach at low and intermediate tides is very common on all the R+LTR beaches. Beach face scarping commonly occurs at high tide but with minimal changes in the beach face. Pacheco and Iparana beaches have suffered environmental degradation owing to their proximity to the Fortaleza coastal zone and its adjoining coastal areas, which has resulted in a narrower beach backed by seawalls and buildings (Fig. 7.9). The beaches range from 60 to 120 m wide at low tide (Paula et al. 2013). Between the Iparana beach and the mouth of the Ceará River rock seawalls are prevalent with the sector between the Ceará River mouth and Mucuripe Port dominated by a sequence of 22 breakwaters, including the Titan at Mucuripe Port.

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The coast is aligned east-west with a predominance of medium sand and R+LTR beaches. Overwash episodes have been observed at Diarios beach when there is an increase of the occurrence of longer period (>10 s) north-northeast swell waves (Paula 2012; Guerra 2014,). Between the Titan jetty beach and Barra Nova beach in Cascavel, 60% of the beaches have an RTR>3 and are R+LTR. R+LTR and R+LTT types are prevalent on Caponga and Aguas Belas beaches, respectively (Pinheiro et al. 2003; Morais et al. 2006b).

Ten percent of the beaches have an R<3, particularly Praia do Futuro, Cofeco, Porto das Dunas and Prainha (Albuquerque et al. 2009). Over a period of 24 months the 8 km long Futuro beach was wave-dominated with TBR conditions in the first half of the year and LBT in the second half.

The **sector V** is characterized by the presence of sandy and rocky cliffs bordering and backing the beaches, that extend to the Rio Grande do Norte border (SV) (Fig. 7.10). R+LTT prevails on 96% of the beaches with an average beach width of 208 m (s.d. 94 m). The coastline between the mouth of the Choró River and Requenguela is 115 km in length and predominantly composed of very fine to medium sandy sediments. Very fine sand is prevalent all year between Retirinho and Requenguela beaches (Oliveira 2012; Barros 2013). Between the Choró and Pirangi river mouths there is a straight cliff coast.

West of Requenguela is an UD beach (Fig. 7.10a). The beach is 800 m wide at low-water spring tide, and is composed of very fine grain size sand and coarse silt, with some mud banks colonized by mangroves in the intertidal zone. Canoa Quebrada is a very well known and popular resort, receiving visitors from many regions of Brazil and abroad. It has experienced active erosion in the Barreiras Formation either from waves or from surface and groundwater action (Fig. 7.10b). It is now being protected by rockwalls.

Fig. 7.9 Sector IV beaches: (**a**) Erosion at Icaraí's beach; (**b**) Low tide terrace at Nautico beach – Fortaleza-City; and (**c**) Disispative beach at Serviluz beach

Fig. 7.10 Sector V beaches: (**a**) Cliffs and ultradissipative beach at Ponta Grossa beach; and (**b**) Low tide bars and rips at Canoa Quebrada beach

7.3.3 Beach-Barrier

The first studies on barriers islands in Ceará were made by Morais and Fonteles (2000), together with the Quaternary evolution of the coastal plain and barrier islands of Itarema. Hesp et al. (2009) provide an excellent description of the barriers in the state of Ceará. They divided them into three forms: attached barriers, barrier spits and prograded foredune plains barriers. Attached barriers occur across the mouths of rivers and estuaries and when the direction of the shoreline changes to

Fig. 7.11 Examples of sandy spit and wind farm on the the coast of Ceará

east-west. The presence of promontories traps sediment transported by longshore drift, which accumulates and is subjected to wind blown transport, forming large transgressive dunes, such as barchans observed in Jericoacoara and other parts of the coast.

Barriers spits are well developed from the mouth of Acaraú river, at Itarema and along the western coast. They occur on the east coast in lee of Ponta Grossa Iguape beach. Between 2001 and 2004 Morgado and Volta do Rio (Acaraú) spits migrated 18 m and 124 m, respectively, eroding the shoreline (Hesp et al. 2009). Wind farms have been built on sandy spits at Itarema beach. Groins were also built to contain waters stock for the wind turbines (Fig. 7.11).

Prograded foredunes plain barriers are characteristic of the coast of Icapui village where the waves arrive at an angle of 45° to the shoreline which is aligned northwest-southest. This results in a reduction in sediment transport and favors the formation of regressive foredunes ridges. (Hesp et al. 2009).

7.3.4 Beach-Dune Interactions

The dunes in Ceará extend inland from beaches composed of medium and fine quartz sands. Storm waves deliver the sediment, which is blown inland from the beach face as occurs at Paracurú, Icapui, Jericoacoara, Caponga, Iguape, and others beaches. In some cases the aeolian transport acts as an erosive agent, moving sediment inland form the beach to the dune fields (Fig. 7.12a). Geological records show that the formation and migration of dunes on the North-Northeast coast has occurred since the Pleistocene (Claudino-Sales 2002). During this period, the wind has acted

Fig. 7.12 (**a**) Barchans at Jericoacoara beach; (**b**) Aeolianite exposed at Baleia beach; (**c**) Paleodunes near the Choró River; (**d**) small barchan dune migrating across a beach at Itarema; and (**e**) dune slipface moving due to gravity at Icapuí

either as an erosive agent, transporting sediment from the beaches via headland overpassing, or indirectly by the input of sediments in waterways, and more recently advancing as dunes into urban areas.

The Ceará coast has paleodunes, and both fixed and mobile dunes extending inland of the deflation zone (Maia 1998; Claudino-Sales 2002). The subaerial exposure of the wide tide-modified beach face is a characteristic of Ceará beaches that favours aeolian sand transport, with sediment transported inland from the beach face (Fig. 7.12d). Dune forms include barchans, isolated barchans, longitudinal, parabolic, parabolic semi-fixed, hairpin, aeolianite, sand sheet and nebkas (Maia 1998; Maia et al. 2012) (Fig. 7.12b, c). The barchans are most common in the northeastern coastal dunes, from Maranhão to the border with Parnaíba. They are composed of fine sand dunes and form where there are changes in roughness of the terrain or aerodynamic fluctuations (Pye and Tsoar 1990). They are up to several hundred meters width and length, with an average height of 20 m, while on Iguape beach they reach 30 m. The dunes dominate the seaward edge of the coastal plains and are migrating at approximately 6 m year^{-1} in the case of sand sheets without defined shapes and from 9 to 20 m year^{-1} in the case of fields of barchan dunes (Maia 1998; Jimenez et al. 1999; Levin et al. 2008).

The dunes are responsible for obstructing drainage of medium to small channels resulting in the transformation of estuarine systems into estuarine-lagoonal, lakes and ponds, such as can be seen at Jijoca, Catu, Mundaú and Malcozinhado (Pinheiro et al. 2006; Morais and Pinheiro 2011). Tsoar et al. (2009) identified fixed dunes on the Ceará coast with ages of about 132 ka, while mobile transverse dunes were dated 1320 ± 50 BP by Castro and Ramos (2006).

On beaches with dissipative characteristics and extensive terraces ebb barchans, longitudinal dunes and sand sheets predominate (Fig. 7.12d). On beaches dominated by waves, with intermediate characteristics, the frontal dunes, with a height of approximately 1.5 m, predominate. In sectors with cliffs, dunes are located on the clifftops, forming slipfaces that feed the downwind beaches. These dunes also move by both gravity effects and aeolian transport (Fig. 7.12e).

7.3.5 Longshore Sand Transport and Sediment Cells

The orientation of the coast in a northwest-southeast alignment, together with persistent easterly waves and trade winds blowing between 5 and 8 m s^{-1}, combine with sediment availability and a wide surf zone to generate substantial westerly longshore transport along the coast. In Sector I between Pontal das Almas and Acaraú where the coastline has an east-west direction, the wind takes an offshore component, and the flow of water also has a tendency to move away from the coast creating optimal conditions for sedimentation.

Modelling of wind driven surface flow performed by Bensi (2006) found that the longshore currents parallel isobaths with an average velocity of 0.13 m s^{-1} and ranging from 0.16 to 0.24 m s^{-1} between the Baleia and Fortaleza beaches (Sectors II and III) and 0.15–0.20 m s^{-1} between Morro Branco and Icapui (Sectors IV and V) (Fig. 7.13).

On the coast between the beaches of Cumbuco and Future (Sector II) surface velocity of coastal currents varies from 0.18 to 0.68 m $year^{-1}$ (Maia 1998; Silva et al 2009). Jimenez et al. (1999) estimated sediment transport on the order of 860,000 m^3year^{-1} on the coast of Fortaleza. Using the empirical model of the CERC Department of the Army (Shire Protection Manual 1984), with breaker wave height of 0.94 m, period of 6 s and arriving at an angle of 70 ° Pitombeira and Aquino (1998) obtained a rate of transport in Pecem of 854,307 m^3year^{-1}.

In the experiments on the Barra do Ceará, Meireles and Futuro beaches using ADCP over the spring tide cycles average rates of transport of 1.3 million m^3year^{-1} have been calculated for the period 2011 and 2012 (Alves 2012). In Caponga (Section IV), the velocities of currents varied from 0.3 to 0.6 ms^{-1}, with transport rates ranging from 280,000 m^3year^{-1} per year to 1.4 million m^3year^{-1} (Pinheiro et al. 2001; Morais et al. 2006b).

In the regional context of current velocities and rates of sediment transport on the coast, macro-compartments are homogeneous and reflect the behavior of local winds and waves. The velocity of the currents are modulated by changes in coastal orientation and morphology of the continental shelf and slope similar to what observed in the Sector I. On a smaller scale headland bypassing and trapping occurs with accumulation of sediments to east and erosion to the west. The sediment

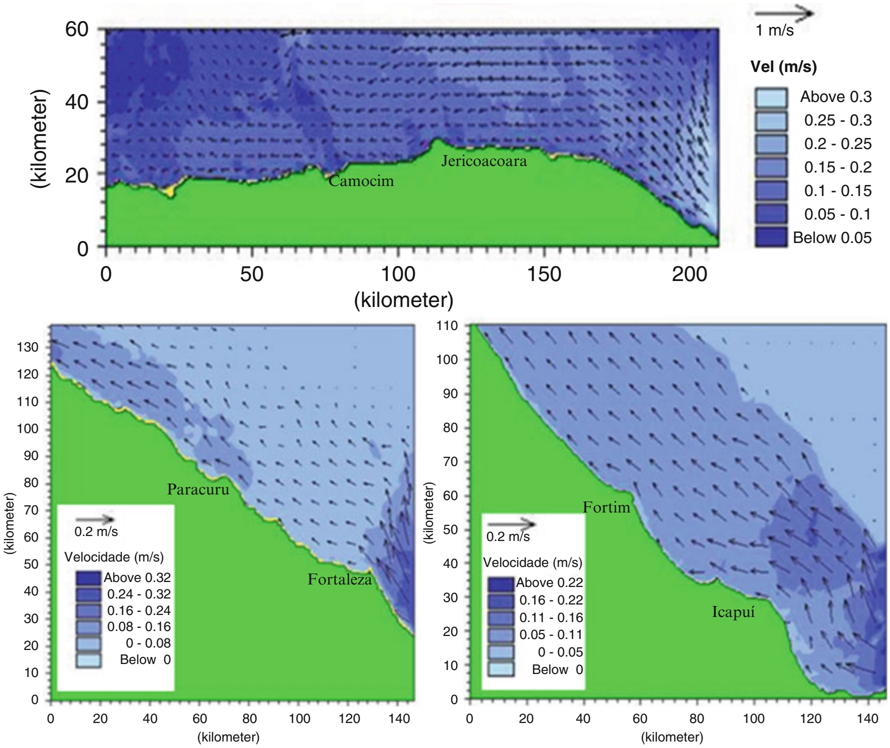

Fig. 7.13 Simulation of the surface current velocities along the coast of Ceará State (Source: Bensi 2006)

trapped by the headlands is also a source of sand for dune development and headland overpassing.

7.4 Beach Use and Abuse

7.4.1 Beach Development and Management

In recent years the Brazilian coast zone has suffered environmental degradation, generated by increasing anthropic pressures and a low capacity to absorb these impacts. The occupation of the Ceará coastal area is primarily for the industry and tourism. On the Ceará beaches, second holiday residences were the main driver of coastal development. During the seventies and eighties the coast was sought after by tourism investors for the construction of lodgings and hotels to accommodate the tourism season (Paula et al. 2012).

The dunes, beaches and estuary margins were transformed and affected by the urbanization. Today, coastal erosion is locally perceived as the most significant threat to tourism income as well as traditional economic activities. There are 20 locations experiencing coastal erosion Ceará (Morais et al. 2006a), with some locations experiencing very high rates of erosion which is resulting in serious damage to urban infrastructure as can be seen at Bitupita, Maceio, Taíba, Icaraí, Caponga, Iguape and Redonda beaches.

The Fortaleza Mucuripe Harbour impacts are a classical example of the lack of knowledge of coastal processes on Ceará's coast. When the harbour was built in 1939, the jetty changed the wave refraction, stopped the longshore transport trapping sediment at Serviluz beach. At the same time there was a lack on sediment transport downdrift to the Fortaleza coast. As a consequence the Fortaleza's beaches eroded about 200 m between Mucuripe Harbour and Ceará estuarine-river mouth (Morais 1981). In response groins were built which effected the Caucaia's coast. A seawall was been built at Iparana and Pacheco beaches to combat to the erosion. At Icaraí, Pacheco, Caponga, Mundaú, Canto Verde and Requenguela there has been damage to roads, sidewalks, kiosks, sheds, and entertainment areas (Fig. 7.14). There are also problems like rocks, beach erosion, spoils, groins, garbage and difficult beach access (Pinheiro and Rocha 2007; Medeiros 2012; Medeiros et al. 2014).

The recent "Vila do Mar" project aims to rehabilitate the 18 km of coast between the Rio Ceará mouth and Nossa Senhora das Graças neighbourhood (Fortaleza City). It includes new groins, fishing ports, sidewalks, parking lots and places for sports and leisure for beach users. A similar project occurred along the central coast of Fortaleza, with rehabilitation of the Iracema and Diarios beaches.

Among the major subjects discussed at the Orla project (Brasil 2006) were coastal erosion and the health of the beaches. It turns out, however, that many municipalities do not have the Orla project or other legal obligations to protect the coast. Constant pressure is required to prevent and mitigate the negative impacts of coastal erosion and the adoption of measures to maintain or restore the beaches as a place of recreation and economic opportunities. A more strategic and proactive approach to coastal erosion is needed for the sustainable development of vulnerable coastal zones.

7.5 Beach Hazards and Safety

Ceará has a major tourism industry, attracting many tourists in the high season periods of July, December and January, with the coastal zone accounting for about 80 % of the tourists. These tourists face a number of hazards along the coast including beach rip currents, topographic rips, groins and rock walls. Praia do Futuro, the most popular touristic beach in Fortaleza is a R + LTR beach and consequently hazardous for swimming (Albuquerque et al. 2010). The high level of risk is reflected in an average of 314 people rescued annually by lifeguards without fatalities

Fig. 7.14 Severe erosion at Icaraí beach hitting urbanization

between 2002 and 2010, while during 2013 there were 456 rescues and seven fatalities at the beach. Albuquerque et al. (2010) confirmed that the main type of seasonal hazard associated with Futuro is the rip currents, which are responsible for 86 % of rescues in sectors with TBR and RBB morphology. The main victims of drowning were men (66 %) aged between 21 and 28 years, about 50 % of those not living in Fortaleza. The high number of beach users is related to the good bathing waters compared to the other beaches in the city, and the provision of services and facilities at Futuro beach.

Among the main factors that increase the risk of accidents and drowning are: the reduced number and poor siting of lifeguard towers and number of lifeguards in relation to the number of users on the beach; there are also no signals using flags or other information in public places and in the media to warn the public about the beach hazards and risk.

Caucaia town and its municipality were identified as having the highest level of beach risk. The shore platforms, coastal protection works, the beachrock at Parcheco and Iparana and house debris that are submerged in high tide, all present substantial permanent hazards to beach users according to the methodology proposed by Short and Hogan (1994). On tide-modified beaches the main risks are associated with breaking waves at high tide and the formation of rip currents and currents in the surf zone, particularly around low tide.

7.6 Summary and Conclusions

The Ceará coastal zone is predominantly composed of sandy sediments of Upper Tertiary-Quaternary age with several generations of Pleistocene transgressive dunes, together with beaches, estuarine plains and localized occurrences of cliffs. The Precambrian rocks also occur as headlands on some beaches. The climate is semi-arid tropical, while the rivers only flow into the sea during the rainy season. The temperature ranges from 22 °C to 33 °C, with an average of 27 °C. The easterly trade winds prevail year round.

Tide is semi-diurnal with a maximum range of 3.2 m. Sea waves arrive about 80 % of the time with a modal wave period of 6.5 s, while swell occurs for 20 % of the year, with periods between10 to 20s. The dominant waves (75 %) are between 1.1 and 1.6 m, with seas arriving from the east-southeast, and swell from the north-northeast. The sediments are predominantly medium sized bimodal quartz sand.

Ceará beaches are predominantly tide-modified (RTR > 3), with approximately 48.15 % of the beaches classified as tide-modified, 13.85 % as wave-dominated and 38 % beach plus rock/reef flat. Wave-dominated are primarily longshore bar and trough (LBT) occurring on 10 % of the beaches. Beach width varies along the coast with the widest beaches associated with R + LTT and UD beaches.

Coastal dunes include paleodunes, fixed and mobile dunes, which occur beyond the deflation basins. The rates of migration of sand dunes is approximately 6 m $year^{-1}$ in the case of sand sheets without defined shapes and from 9 to 20 m $year^{-1}$ in fields of barchans dunes. Sediment transport is on the order of 860,000 m^3 $year^{-1}$ at Fortaleza. Inbalance in the sediment budget occur where urban construction obstructs the headland overpassing of sediment and the longshore transport on exposed beaches.

Today, coastal erosion is perceived as the most significant threat to maintaining income in many areas that depend on tourism and traditional economic activities. Dunes, beaches, dams and estuary margins have been transformed and affected by construction without concern for the sediment budget. This has led to an increase in beach erosion over the years. This is a challenge for both coastal dwellers and the coastal managers who need to find new ways of living with the coast, including redesigning coastal occupation as well as minimizing the impacts of the sea.

Living with coastal erosion should be on the agenda of public policies in the state, with guaranteed resources to implement the most appropriate works, maintenance and long-term monitoring. The engineering works need to look beyond just blocking the advance of the sea and need to be redesigned to accommodate different types of beach uses. While the demand for industrial enterprises, growth of cities and the development of tourism near the sea continues, there is an information gap that requires Ceará to invest in long-term studies of coastal dynamics and management.

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