Erosion in the Brazilian Coastal Zone: An Overview

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ABSTRACT


Coastal erosion along the Brazilian shoreline although widespread and in some segment severe is not yet a serious threat considering the coast as a whole. Major problems are most frequently associated to human intervention in the sediment flux or associated to the morphodynamic of river mouth. But, regional vulnerability also occurs in areas of permanent loss of sediments or due to tectonic subsidence. Regionally differentiated climatologic and oceanographic forcing mechanisms imposes different responses to the also varied geologic-geomorphic environments. Seven distinct coastal environment are analyzed, ranging from the muddy coast of Amapá under strong influence of sediments from the Amazon river, to the semi-arid coast of Ceará and Rio Grande do Norte with permanent loss of sediments to the dune fields as also localized erosion of sedimentary cliffs, to the barrier coast of Rio de Janeiro and the barrier coast of the subtropical Rio Grande do Sul.

INTRODUCTION

The Brazilian coastline extends from the equatorial North hemisphere to subtropical latitudes of the South, facing the West Atlantic Ocean along a length of more or less 8,000 km, according the cartographic details considered (Figure 1). As a consequence of this large extension, the coastal zone crosses areas of different climates ranging from equatorial and tropical humid to the semi-arid Northeast and the sub-tropical climate in the South, as also of different geologic and geomorphic environments.

Human occupation of the coastal area is relatively low as only about 20% (about 30 million people) of the country population lives in coastal counties (MUEHE and NEVES, 1955). Major concentration occur in the neighborhood of the capital cities with the highest densities near Rio de Janeiro, Salvador, Maceió, Recife and Fortaleza, followed by Vitória and São Luís. It is in the area of higher occupation where coastal erosion becomes a concern and is also frequently aggravated by human interference in the sediment budget through edification of buildings in the immediate vicinity to the beach as also trough structures associated to stabilization of river mouth, to the construction of port and harbor installations or for the protection of the coastline.

The identification of the causes of coastal erosion has been frequently a guesswork due to the lack of long term monitoring of the sea level, wave climate and coastline evolution. Therefore, it has been difficult to distinguish between episodes of erosion or progradation from long-term trend. Furthermore, due to differences in the methods of investigations or in the considered time span, there are sometimes large disagreements between researchers about the evolutionary trend of a specific coastline.

In the last years an effort has been made by the research groups associated to the Programa de Geologia e Geofísica Marinha (PGGM) to map the Brazilian coastline for an assessment of the main trends of erosion and progradation as a first step to define the areas to be researched and monitored in more detail. This paper is an overview of the main results of this investigation together with information collected from published papers.

GENERAL COASTAL PROCESS VARIABLES

Most of the coast from the extreme South to the state of Alagoas in the Northeast, is submitted to micro-tidal regime (<2m). In Rio Grande (South region) the spring tide range reduces to only 0.6 m. Spring tidal ranges of over 4 m (macro-tidal) occur in the states of Maranhão, part of Pará (Salinópolis) and south of Amapá. The remaining coastline including small coastal segments like the interior of Todos os Santos bay (Bahia) and the port terminal in Sergipe, are of the meso-tidal regimen.

The back-ground of offshore wave climate is basically defined by the intensity and direction of trade winds generated by the Southern Tropical semi-stationary high pressure cell of the South Atlantic, with waves traveling from East and South-East in the equator-near areas, gradually shifting to the Northeast direction with the increase in latitude. Significant offshore wave height ranges typically between 1 and 2 m with...
an increase to 1.5 m and 2.5 m in the extreme South. Wave periods range between 4 s and 6 s. The propagation of waves generated by South winds associated to cold front penetrations significantly changes this more or less homogeneous pattern, with the generation of storm and swell waves with increase in several meters of the wave height and periods of up to 17 s. In the coastal zone this alternation between fair and bad weather defines the wave climate and sediment transport most significantly from the extreme South up to Cabo Frio and with decreasing influence of the South waves up to Salvador and Recife. Waves (28%) generated by tropical storms in the North hemisphere reaches the Northeast region (Ceará) in the form of swell, with periods of up to 18 s and important erosional effects, as described by MAIA (2002).

The general pattern of longshore sediment transport, considering an observer looking toward the sea, is to the left of the observer from Amapá to cape Calcanhar and from São Paulo to Rio Grande do Sul and to the right from Alagoas to the North of Rio de Janeiro state. Southward of cabo Calcanhar up to Paraíba and along the east-west striking coast or Rio de Janeiro, between cabo Frio and Marambaia island, the residual transport approaches zero.

**LARGE SEDIMENT SOURCES AND SINKS**

The genetic relation between the sandy coastal sediments and the continental shelf as the main source was first recognized by TRICART (1959, 1960). The origin of these sediments are primary the large Tertiary sedimentary flat topped, table like, accumulations of the Barreiras Formation and other similar deposits, who extends along most of the North, Northeast and part of the Southeast coast, from Amapá to the Rio de Janeiro state. With altitudes of some tens of meters they reaches the coastline in the form of active or fossil bluffs. Lateritic concretions formed in the interior of the deposits in the range of ground-water fluctuations are found dispersed over the shelf, attesting the former position of these bluffs. Their erosional retreat due to the action of waves delivered possibly the major amount of sediments to the shelf. Furthermore the deep and very large valley incision of these deposits as also the large river incision whose width show no relation to the actual size of the active river beds, as also the dense erosional excavation of the crystalline hinterlands of the Southeast and South regions, attests the huge amount of sediments transferred to the shelf during the Quaternary climatic fluctuation between the humid and semi-arid conditions.

The main sink of sediments constitutes the enormous transfer of sands from the shelf to the beach and to the large dune fields of the Northeast region, and to the construction of barrier beaches and shore terraces in the Southeast and South regions.

The largest expression is represented by the Lençóis dune field of Maranhão who extends up to 20 km inland along about 50 km of shoreline. In a discontinuous pattern with also very important accumulations of the Barreiras Formation and other similar deposits, who extends along most of the North, Northeast and part of the Southeast coast, from Amapá to cape Calcanhar and from São Paulo to Rio Grande do Sul and to the right from Alagoas to the North of Rio de Janeiro state. Southward of cabo Calcanhar up to Paraíba and along the east-west striking coast or Rio de Janeiro, between cabo Frio and Marambaia island, the residual transport approaches zero.

**ASSSESSMENT OF EROSION AND PROGRADATION OF THE COASTLINE**

A preliminary analysis of the reports from different states (ALBINO et al., 2004; ALMEIDA et al., 2004; ANGULO et al., 2004; ARAUJO et al., 2004; CALLIARI et al., 2004; CALLIARI and SPERANSKI, 2004; FREIRE, 2004; MANSO et al., 2004; TESSLER et al., 2004; TOLDO et al., 2004; VITAL, 2004), indicates that, considering the total amount of reported occurrences, erosion largely predominates over progradation with about 40% concentrated on beaches, 20% on sedimentary bluffs and 15% near the outlet of rivers and estuaries, while only about 10% of the reported cases of progradation are referred to beaches and 15% to river outlets. Therefore the morphodynamics of river outlets result in about the same amount of occurrences of erosion as of progradation, confirming the risk of intervention in this environment.

Considering the causes of the erosion, almost 80% is attributed to human impacts related to urbanization and interference in the sand budged through construction of rigid structures. Therefore natural causes of coastal erosion seem to play a subordinate role, at least considering a short-term time span. Naturally the erosion of buildings constructed too close to the shoreline can't be simply considered as an erosional trend. Nevertheless, as soon as a sequence of erosional event takes place the response of the property owners through construction of wood or stonewalls, rip-rap or groins will accelerate and propagate the effect of these events.

In short, although erosion is widespread, it is principally focused near river outlets and localized segments of urbanized areas, frequently downdrift of large artificial intervention in the sand budged, like in Fortaleza and Recife.

Despite of the relatively low endangered coast, some geomorphic compartments present important shoreline variability, which deserves a closer examination.

**COMPARTMENTS OF REMARKABLE MORPHOLOGIC AND MORPHODYNAMIC DISTINCTIVENESS**

A browse trough the literature clearly allows to distinguish at least seven representative erosional compartments:

i. The mud coast of Amapá;
ii. The dune coast of Ceará;
iii. The highly mobile spit and barrier-island coast of Northern Rio Grande do Norte;
iv. The active cliffs of the Barreiras Formation of Ceará and Rio Grande do Norte;
v. The beach-ridge coastal plains of Bahia, Espírito Santo and Rio de Janeiro;
vi. The double beach barrier coast of Rio de Janeiro;
vii. The multiple beach barrier coast of Rio Grande do Sul.

**The Mud Coast of Amapá**

An enormous amount of fine sediments is delivered by the Amazon River and directed to the Northeast as part of the Guiana current. The shelf is very wide and shallow. The soft mud bottom damps wave height. The water is highly turbid due to the fine sediment fractions remaining in suspension. In spite of the abundance of sediments erosion is widespread along various segments of the coastline (Dias et al., 1992; NITTOUER et al., 1996).

Climate is hot and rains are abundant. The Southeast trade winds, blowing parallel to the shoreline, change direction to Northeast during January to March when they increase velocity and become perpendicular to the shore. Waves due to the

![](image)
increased wind speed become higher and instead of causing erosion they bring fine sediments from the shelf to the coast in the form of fluid mud (Kineke and Sternberg, 1995).

Tide range decreases from macro tidal regimen southward from Cabo Norte to mesotidal in the North direction. According to Nittrouer et al. (1996), the strong tidal currents, more frequently directed to offshore, seems to be the main reason for the coastal erosion. Sediment accumulation occur at capes Orange and Cassiporé, at the extreme North sector of the coastline while erosion occur along almost the entire coast between Cabo Cassiporé and Cabo Norte (Figure 2) with sediment accumulation restricted to the proximity of river mouths.

In spite of the present erosional trend, the general Holocene evolution, according to Nittrouer et al. (1996), has been of sediment accumulation with fluctuations between erosion and progradation in time spans of 100 to 1,000 years.

The Dune Coast of Ceará

The constant trade winds and a pronounced five months long dry season (August to December) during which the wind velocities are the highest (up to 8 m/s), as also an abundant sediment supply form the continental shelf associated to a wide exposition of the low gradient beach face during the meso tidal low tide, represent the condition for the large development of dunes along the entire 572 km long coast of Ceará. Average rates of migration are cited by Maia et al. (1999) of being 17.5 m/yr for barchan dunes and 10 m/yr for sand sheets. Aeolian transport has been estimated to be of the order of 300,000 m³/yr (Valentini and Rosman, 1993). The oblique wave incidence is responsible for a large volume of sand transport with rates of up to 700,000 m³/yr (Maia, 1998; Maia et al., 1999). The consequence of such a large unidirectional longshore sediment transport is a strong erosional response for any interruption of this flux. For instance the construction of a breakwater for the protection of the port of Macuripe in Fortaleza triggered an erosional process along the down drift coast affecting the city beaches and beyond. The adopted solution was the construction of a series of groins and seawalls which where not capable to halt the erosion. More recently the main beach of the city (Praia de Iracema) was recovered through beach replenishment and the construction of two long groins in order to keep the sand in place (Figure 3). Currently the possibility to construct a breakwater in front of the groins, to protect the beach against storm waves is under consideration. Northwest of Fortaleza, the construction of the port of Pecém, in spite of the caution to not interrupt the sediment flux, erosion also started to affect the downdrift area in the vicinity of the port.

Besides these localized spots of induced erosion the majority of the coast, mostly not urbanized, seems to be drown under the immense amount of sand. The widespread occurrence of beach rocks in front of the beach or covering part of the beach face are an important protection against erosion as they reduce the wave energy acting like breakwaters. While normally the beach rocks occur as compact bodies there are, nevertheless, frequent occurrences of highly fragmented and chaotically deposited sandstone covering part of the beach. It seems that they are not beach rocks but aeolianites who frequently cover the top of the foredunes some tens of meters at the back of the beach. If this is correct these occurrences are an indication of the former position of the foredunes and consequently indicate that, in spite of the enormous amount of sand, the beach is retreating. Additionally the occasional outcrop of mangrove roots at the beach berm is also an indicator of the inferred retrogradation.

The Highly Mobile Spit and Barrier Island Coast of Northern Rio Grande do Norte

The Northern sector of Rio Grande do Norte encompasses a 100km long North facing shoreline with strong and steady westward directed longshore sediment transport. The climate is dry and continental sediment input is almost absent. Two main interrupting sets of faults, the NW-SE oriented Afonso Bezerra fault system and the NE-SW Carnaubais fault system form the tectonic borders of a triangle whose base is delimited by the coastline in front of a prograded coastal plain. The tectonic influence on the bathymetry as also the submergence of the west of Carnaubais fault control the wave propagation and associated coastal processes (Vital et al., 2003).

The Active Cliffs of the Barreiras Formation of Ceará and Rio Grande do Norte

In both the Southeast coast of Ceará and southern East Coast of Rio Grande do Norte the predominance of coastal dunes is interrupted by active cliffs of the Barreiras Formation. They are not restricted to these areas but occur localized in other states as well with similar problems as the ones related below. Morro Branco in Ceará and Pipa in Rio Grande do Norte are representative sites and largely attract tourists due to its beautiful landscape. In Rio Grande do Norte the cliffs extend along most of the Southern shoreline, from Tibau do Sul down to the border of Paraiba (Figure 6). As shown by Silva et al. (2003), the active cliffs are limited to the central sector of this stretch where the waves excavates the toe of the cliffs during high tide resulting in the collapse of the cliff front and their gradual retreat. As buildings are frequently located at the top of the cliff, with swimming pools preferentially located near the edge causing an additional force to disrupt the shear strength, the whole area is submitted to a high level of risk.
The Beach-Ridge Coastal Plains of Bahia, Espírito Santo and Rio de Janeiro

Located at a latitude range where the longshore net sediment transport direction is defined by the dominance between the obliquely approach of Northeast sea-waves driven by the trade winds and swell waves originated from high latitudes storms of the South, the evolution of the beach ridge coastal plains of the São Francisco (AL-SE), Jequitinhonha (BA), Doce (ES) and Paraíba do Sul (RJ) rivers (Figure 7), has been strongly influenced as described by DOMINGUEZ et al. (2003).

Two mechanism of induced shoreline movement have been recognized: the hydraulic groin mechanism with increase in progradation of the updrift river mouth side in relation to the downdrift side resulting in river mouth asymmetry and migration of the river mouth in the downdrift direction during decreased river discharge; and the reversal of longshore sediment transport direction according to changes in relative frequency in the direction of wave incidence (DOMINGUEZ et al. 2003).

A reconstruction of longshore direction reversals based on the orientation and truncation of beach ridges, the growth and truncation of the cuspatte configuration of the river mouth respectively associated to periods of high and low river discharge was presented by DOMINGUEZ et al. (2003) for the Jequitinhonha river coastal plain. The same authors described that in the last 300 years three major cuspatte forms have developed at the river mouth interrupted by episodes of severe erosion, the last one in 1906 with an afterward large progradation. These changes are tentatively explained by the authors as being the result of a decrease in the advance of cold fronts with consequent reduction in precipitation over the river basin, reduction of sediment discharge and reduction in the frequency of Southeast and South-Southeast wave penetration.

Important in the recognition of the multiple interplay between river discharge, climate, wave direction and sediment source, is the inherent instability of river mouths. Actually the São Fransisco and the Paraíba do Sul river mouth present severe erosion at their South margin, with the complete destruction of the small village of Cabeço in the first and severe erosion with destruction of houses in Atafona at the second (Figure 8). Both were affected by the reduction of river discharge due to the construction of dams. But other causes must also be considered. For instance the segment under erosion in Atafona is the updrift sector of a sediment transport cell with seasonal net transport always directed to the South, away from the river outlet. Furthermore, the retention of sands in the river channel, the transformation of a seawall into a jetty due to recession of the coastline and principally the trapping of sands by the mud deposits near the river mouth are all contributing to shorten the delivery of sands to the beaches.

The Double Beach Barrier Coast of Rio de Janeiro

From Cabo Frio, where the coastlines changes abruptly to and East - West orientation, up to the Ilha da Marambaia in front of Sepetiba bay in the West, the coastline faces the ocean with long and straight beach barriers (Figure 9). These occur frequently as double barrier, inclosing lagoons at their backside, where all sediments from the nearby coastal range are collected. Therefore no continental sediments are delivered to the sea, a reason of the well polished and well selected sands of the beaches and shoreface.

The coastline is exposed to the storm and swell waves from the South with large response in beach profile changes. These recover even after severe storms suggesting that the sedimentary system is a closed one with sediments moving from the beach to the foreshore and vice-versa without introduction of new sediments. Longshore transport is driven to east and west according the wave incidence without a net transport direction.

Foredunes, when present, play an important role in the stabilization of the barrier. In their absence wave overwash and the small width of the barrier indicate their transgressive trend.
An exceptional strong storm occurred in May 2001 (MUEHE and FERNANDEZ, 1999; MUEHE et al., 2001), impinging severe destruction of houses, mainly eastward from the Guanabara Bay in the county of Maricá and Saquarema (BARROS et al., 2003). There, as frequently occurs, constructions where located very close to the backshore and damage occurred widespread (Figure 10). But, what could be considered a response to an exceptional storm, is in reality a trend of backshore retrogradation, as indicated by the gradual retreat of up to 11 m of a segment of foredunes, five kilometers westward from Arraial do (Cabo Frio), at the Massambamba beach, monitored during almost eight years.

The Multiple Beach Barrier Coast of Rio Grande do Sul

From Torres to Chui an almost continuous beach of about 640 km length, with a Northeast-Southwest orientation, represents the ocean-side of the very large coastal plain of Rio Grande do Sul. Three important interruptions are due to the stabilization of river inlets through jetties, at the outlets of the Mampituba and Tramandá lagoon in the North and the Patos lagoon in the South. Four sets of beach barriers gradually enlarged the plain since the Pleistocene, forming a sequence of barriers and lagoons, each barrier representing the landward reach of a transgressive episode (VILLWOCK, 1984; TOMAZELLI and VILLWOCK, 1996). The third barrier, Patos and Mirim lagoons, originated during the last Pleistocene transgression, while the forth barrier associated to the ocean beach, developed during the Holocene.

Climate is temperate humid. Swell waves from Southeast are responsible for the net longshore sediment transport to the North, while sea waves from East and Northeast and episodic storm waves from East and Southeast trigger the erosional and depositional processes along the coast (TOMAZELLI and VILLWOCK, 1992, 1996). Mean tidal range is about 0.5 m.

Occupation of the coastline is low, mainly concentrated in small villages principally in the northern coast where the distance to the metropolitan area of Porto Alegre is short (ESTEVES et al., 2003).

Comparison of aerial photographs with DGPS mapping of the whole coastline, covering a time span of 22 years, indicated that erosion widely dominated affecting about 528 km of the shoreline, with only 50 km of progradation and 52 km of stable segments (ESTEVES et al., 2003; TOLDO et al., 2003).

A different approach, based on wave refraction, identified two segments with permanent erosion due to convergence of wave rays called stable focus of beach erosion (CALLIARI et al., 1998, SPERANSKI and CALLIARI, 2000, CALLIARI and SPERANSKI, 2003). These segments, with about 30 to 50 km length are located near the Conceição lighthouse (about 70 km North of Rio Grande) and in the eastern South between the Fronteira Aberta lighthouse and arroio Chui, at the border with Uruguay.

The influence of the sediment retention at both sides of the previously mentioned jetties were investigated by LÉLIS and CALLIARI (2003), indicating the occurrence of high rates of progradation at the South side of the jetties and low rates of erosion at the North side, indicating that although the net sediment transport is to the North there is also an important transport in the opposite direction reflection the bidirectional character of wave incidence.

CONCLUSIONS

Coastal erosion is widespread along the whole coastline, although effectively endangered coastal segments are limited to some restricted areas. In these the intervention in the sediment budget trough construction of rigid structures in order to protect the coast or harbors triggered or increased the erosive process resulting in the building of new structures like groins, seawalls or jetties with the down drift spreading of the erosion. The most critical sites are found in Fortaleza and Recife - Olinda but also occur in several other places along the coast and in the vicinity of river mouths.

Problems always arise as houses are constructed too close to the beach. This problem has already been recognized and specific guidelines to left a buffer zone between the beach and the front of the urbanized area has been recommended by governmental agencies. Nevertheless these guidelines have not yet been largely adopted. Also the already urbanized areas cannot be removed.

The lack of long-term monitoring of shoreline mobilities, wave climate and sea level makes difficult to distinguish between short-term events and long-term trends. An occasional contradictory classification between highly endangered or stable for a same coastal segment is a consequence of this absence of information.

Considering that, as a whole, the coastline is not seriously endangered there are although aspects of concern. Large areas, like in part of the Northeast, already show a negative sediment budget due to the transfer of sediments to the dune field. Beach-barriers along the Northeast and South coast migrated backward during the Holocene transgressive sea level oscillations and present actually a transgressive trend with wave overwash and localized erosion. Shoreface and inner-shelf declivity is very low in the North and Northeast region resulting in very large shore recession in case of a sealevel rise (MUEHE, 2002; 2001). Under such scenario beach rock outcrops in front of wide stretches along the Northeast coast will have reduced their protection of the beaches as wave height will increase due to the increase in water depth resulting in large adaptation of the beach profile through localized erosion and progradation. The sedimentary cliffs of the North, Northeast and part of the Southeast regions represent a good protection as their recession although increasing will still be slow.

Recent trends of sea level for different places along the coast are not known. A forty-two year tide record from the port of Recife indicated for the period of 1946 to 1988 a sea-level rise of 5.6 mm/year (HARARI and CAMARGO, 1994 in NEVES and MUEHE, 1995). For the port of Rio de Janeiro the analysis of a record from 1965 to 1986 indicated a very strong rise of 12.6 mm/yr (SILVA 1992 in MUEHE and NEVES, 1995). Subsequent analysis of more recent data indicated that this trend dropped (personal communication by Dr. Claudio Neves) but the results have not been published yet. For the coast of São Paulo (Cananéia) a rise of sea level, starting in the early 1970's was also reported by MESQUITA and HARARI, (1983 in MUEHE and NEVES, 1995). Another process variable is a modification in wave climate. Continuous record of wave height is few and discontinuous. Only in the last years a network of wave gauges is beginning to be established. An increase in storminess was inferred by NEVES Fo. (1992) based on the increase of deviations between predicted and measured tides in Rio de Janeiro (Ilha Fiscal) and São Paulo (Cananéia) during the period from 1965 to 1986. This could explain the erosion at the barrier coast of Rio de Janeiro but is in disagreement with the suggested
trend of decrease in the advance of cold fronts.

Concluding, in spite of the sometimes-contradictory interpretations for the actual trend of shoreline mobility as also the difficulty to recognize reliable trends for wave climate and sea level rise, the establishment of buffer zones in urbanized areas together with the monitoring of representative coastal segments as also the expansion and maintenance of networks for long term measurements of tides and waves.

LITERATURE CITED


