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Ocean sandy beaches and coastal erosion

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Abstract

Saving our beaches and banning coastal real estate along fragile shorelines are very important issue that must be considered by the scientists. Many houses built on the beach lines, hit by waves, could be protected by building concrete walls, jetties and other appropriate barriers to prevent the action of waves on the properties. On the other hand, these structures would destroy the beach. Knowing how the beach system works, believing that one should not try to interfere with the natural processes that allow beaches to remain in dynamic equilibrium with waves and currents. Humans are upsetting this balance more and more by construction of huts on the coast; for paving parking lots on the beaches; and through the construction of jetties, jetties, piers and wave breakers. The consequence of these constructions carried out with little knowledge is the shrinking of the beaches in a place and expansion in another. The classic example is the containment tip built into the shore at right angles to the shore. In subsequent months and years, the beach sand disappears on one side of the point and the beach expands on the other. As landlords and builders sue each other and state governments, lawyers introduce the issue of "sand rights" into courts of law, that is, the beach's right to have the sand it would naturally contain.

Keywords: Sandy beach; Erosion; Wave.

1. Introduction

Beaches are the most familiar formations on the entire coast, attracting millions of visitors each year and providing the economic base for many communities. Depending on of the configuration of the coastline and the intensity of the wave, the beaches can be discontinuous, existing only as pocket beaches in protected areas such as a bay, or they may be continuous for long distances (Wicander and Monroe, 2015) as shown in Figure 1 and

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Figure 2. The sandy beaches, long and straight, they stretch for miles along the low coastal plains.

In contrast, the rocky cliffs limit to the high back (costões), and the few beaches that exist are formed, mainly by gravel. So, the tectonics, erosion and sedimentation create this variety of shapes and materials.

Figure 1. Gascony Gulf, pocket beach in Spain (Source: Author's archive.)

Figure 2. Straight beach with sandstone reef. Barra de São Miguel/AL (Source: Author's archive.)

Although the sandy ocean beaches occupy only a small portion of the total surface of the planet, assume considerable socio-economic and environmental importance in most of the tropical and temperate coasts of the world. They present themselves as highly dynamic and sensitive transitional systems and undergo reworking by wind, biological and hydraulic processes. They also cover a wide spectrum of movements, highlighting the waves generated by the wind, the coastal currents and the tides. Their main environmental function is to protect the coast from the direct action of ocean energy.

1.1. Beach definitions and limits

Although the definitions used for the term “beach” may differ considerably from each other, it is evident the non-cohesive character of the sediments that compose it and also the dominance in this system of hydrodynamic factors such as coastal currents, waves and tides, the latter being of secondary importance. In cases where the influence of the tides exceeds that of the waves, “tidal terraces” are established and not beaches per se (Short, 1985).

King (1957) conceptualizes a beach as a coastal sedimentary environment of varied composition, most commonly formed by sand, and conditioned by the interaction of incident wave systems on the coast. The external limits (towards the sea) and internal (towards the land) of a beach would be determined, respectively, by the depth from which the waves start to cause effective movement of sediment over the bottom, and by the upper limit of action of storm waves over the coast.

Komar (1976) defines the beach as an accumulation of unconsolidated sediments of different sizes, such as sand or gravel that extends towards the coast, from the mean level of low tide to some physiographic alteration such as a cliff, a field of dunes or simply to the point of permanent attachment of the vegetation. To include the subaqueous portion adjacent to this environment, the author uses the term littoral, whose external limit would be that depth at which the sediment is no longer actively transported by incident waves, generally less than 15 m.

More recent definitions seek, in the hydrodynamic processes acting on the coast, the delimitation of beach environments. Thus, Horikawa (1988) considers a beach to be that region of unconsolidated sediments, located in the coastal region, therefore easily deformable by wave action, which extends, towards the land, from the depth of effective sediment mobilization by waves, up to the maximum limit of storm wave action on the beach or up to the frontal dunes, if any.

Suguio (2010) considers a beach as a system orthogonal formed by a coastal accumulation of non-cohesive sediments whose shape and texture are controlled by wave-dominated processes. As internal and external limits, it defines the upper limit of the upwelling range and the depth at which effective transport of bottom sediments by waves ceases to occur.

According to Wicander and Monroe (2015), a beach is an unconsolidated sediment deposit extending inland from low tide to a change in topography, such as a line of sand dunes, a cliff of the sea, or the point where permanent vegetation begins.

2. Morphological zonation

Figure 3 illustrates the terminologies extracted from Albino (1999) based on the adaptation of the zonation proposed by Davies (1985).

The term upper shorefront is limited by the maximum height of high tide and the minimum height of low tide. In this portion is located the beach face, which is a sloping section of the beach where the swash occurs. On a very gentle slope, this location is best recognized by changes in sediment texture and composition, which is typically marked by a concentration of shell fragments or by coarser sediments.

The lower shorefront (nearshore) is characterized by a submerged part of the profile, which extends from the low tide level to the sandbanks. This zone is dominated by surf and surf zone processes. To designate the most distant portion of the coast (and also the flattest part of the profile), which extends from the final limit of the longitudinal bank to the margin of the continental shelf, Komar (1976) used the term offshore zone.

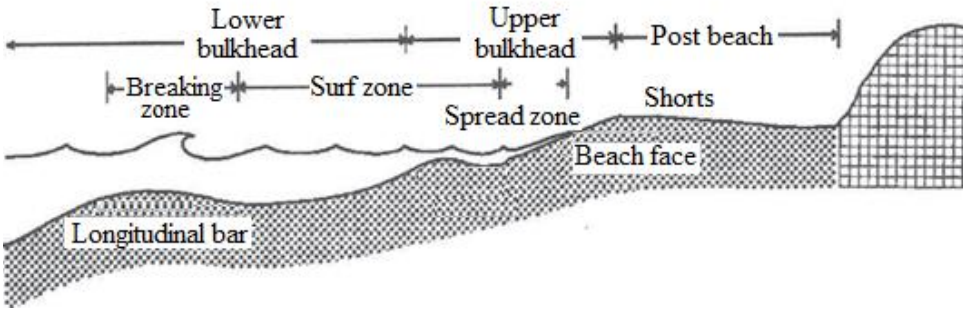

Figure 3. General diagram of the beach profile (Source: Albino, 1999, modified from Davies, 1985.)

2.1. Hydrodynamic Zonation

Hydrodynamically, the surf zone and the swash zone are distinguished on a beach, as can be seen in Figure 3.

- Breaking zone - when approaching progressively shallower waters, the incident waves tend to become unstable up to a point where they will break, showing the energy dissipation mode of the wave over the beach. How the wave breaks depend on the slope of the beach, the height and length of the wave?
- Surf zone - is primarily a function of the beach slope, and therefore is directly related to the type of break and, secondarily, to the tidal range. Low slope beaches are characterized by extensive surf zones. During this route, much of the energy is transferred to the generation of longitudinal and transverse currents to the beach as rip currents (Hoefel, 1998). In contrast, sloping beaches rarely have a surf zone and predominantly reflect wave energy.
- Swash zone - can be explained as that region of the beach delimited between the maximum and minimum excursion of the waves over the beach face. In this, longitudinal currents do not develop. The spreading processes are important in the transport of sediments from a beach, since the ebb and flow of the waves determine whether the sediment will be stored on the beach, or returned to the surf zone, and can then be transported. Commonly, rhythmic features of longitudinal expression to the coast are observed in this portion of the profile, such as beach cusps (Figure 4).

Figure 4. Beach cusps. Maracaipe Beach (PE), Brazil. (Source: Author's archive.)

3. Active factors in the characterization and beach mobility

3.1. waves

Wind-generated waves are one of the main energy sources that govern beach changes. When a wave breaks, depending on the slope of the beach, some energy may return to the sea (the smaller the angle of the beach slope, the less energy is reflected), but a good part is dissipated. Part of this is used to fracture rocks and minerals into smaller particles, but most of the energy must be used to move sediments and increase their height and hence the potential energy of the beach shape.

The processes that cause morphological changes on the coast are those of sediment transport. These changes will continue indefinitely until eventually the energy input is dissipated without any sediment transport. Therefore, changes in morphology occur whenever there is a change in energy input and the function of the coastal zone is to dissipate this energy.

3.2. Refraction and diffraction of waves

As the wave moves towards shallower water, important transformations become more pronounced before it reaches the shoreline. Among these transformations, related to the bathymetric variation, the angle of incidence of the waves and the geomorphological irregularity of the coastal region, we can mention the refraction and diffraction of the waves.

The wave undergoes refraction when passing obliquely from deeper to shallower water, in which it propagates at different speeds. In this process, the wave crests are bent until they become parallel to the underwater and shoreline contours. For example, with the arrival of a wave train in a bay bordered by headlands, the waves first “touch” the bottom close to the headlands, where it is shallower, and this results in the convergence of wave rays, which indicate the direction of wave propagation. At the same time, over the bay, the rays diverge. Where wave rays converge, the energy of the wave crests is contained within a small area, which results in greater wave heights; and where the wave rays diverge the energy is scattered and the wave height decreases. The result of this process is that there will be a greater erosive force on the promontories, while on the bay there will be sediment deposition.

Diffraction is the property that the wave has to go around an obstacle when it is partially interrupted by it. This happens because the waves, when passing through a barrier, have the directions of their rays altered and go around the obstacle. When the wave propagates through a hole between two barriers, the diffraction will be more pronounced the smaller the width of the hole and the longer the wavelength.

3.3. Types of surf

Depending on the slope of the beach, the height and length of the wave, waves can break basically in four ways, according to Galvin's classification (Hoefel, 1998), although several intermediate types frequently occur and that more of a kind can be seen on the same beach and in the same location:

a) Sliding – is characterized by foam and turbulence at the crest of the wave, also known as “little sheep”. Usually this type of break starts at some distance from the beach, being a characteristic of a coastline with a gentle slope, so the wave energy is gradually dissipated (Figure 5).

Figure 5. Maracaipe beach. Ipojuca, Brazil (Source: Author's archive.)

b) Diving – this is the classic form much preferred by surfers (Figure 6). The ridges curl, spiral and dip with considerable force, dissipating their energy in a small area and therefore can have a large erosive effect. This type of surf occurs on moderately steep beaches and is usually associated with long swells generated by distant storms.

Figure 6. Cacimba do Padre Beach. Fernando de Noronha/PE (Source: Author's archive.)

c) Frontal, similar to plunging, except the waves are less steep and instead of the crests spiraling, the front face collapses. This type occurs on beaches with moderate to high slopes and under moderate wind conditions. They represent the transition between plunging and rising types.

d) Ascendant, found on very steep beaches, typically formed by small and long waves. The front faces and crests resist without breaking as the wave slides over the beach face.

4. Currents generated by waves

4.1. Longitudinal current

Longitudinal currents run parallel to the coast and transport sediments suspended by incident waves, potentially moving them over several kilometers through the mesoscale temporal process known as littoral drift. Typically, these currents increase in intensity from the coast towards the sea, reaching a maximum approximately in the middle of the surf zone, from where they begin to decrease. On beaches interrupted by natural or artificial obstacles, the effects of littoral drift are visibly noticeable, although they are equally important for the sediment balance of continuous beaches. On semi-enclosed beaches, such as pocket beaches, littoral drift tends to be weak or negligible compared to normal coastal transport.

The direction of the longitudinal current is associated with that of the winds that are responsible for the wave climate in the region.

4.2. Rip currents

Rip currents are characterized by narrow flows, positioned normal or obliquely in relation to the coast, which cross the surf zone towards the sea. Its origin may be associated with longitudinal currents that converge near the beach and tend to disappear shortly after the surf zone towards the sea, forming circulation cells, or may be caused by longitudinal variations in the height of the surf.

The presence of these currents can be noticed by the rhythmic topographical variations on the face of the beach, called cusps. The intensity, size and spacing of rip currents and, consequently, of the cusps, vary as a function of the incident wave climate.

Like longitudinal currents, rip currents are effective in transporting sediments and play an important role in the surf zones in which they occur, although they are not necessarily erosive.

5. Sediment

Beach sediment can be composed of any material that is available in significant quantities and has appropriate characteristics (such as size and durability) to withstand the hydrodynamic conditions of the beach. Quartz grains, derived from weathering, mainly from continental rocks transported through rivers, are widespread in relation to other materials due to their physical and chemical durability. Carbonate sediments composed of fragments of molluscs, calcareous algae, foraminifera and other organisms with a carbonate structure are important, especially in the tropics, where biological productivity is intense. In addition to the sediments brought by the rivers and biological production, there are other sources of sediment for the beach, such as the formation of chemical precipitates, the erosion of cliffs and rocky shores and material from volcanic activities, which can make up almost all the sediment on the coast. of volcanic islands.

5.1. *Modal state of a beach*

The studies developed by the Australian school culminated in the development of an evolutionary model based on the description of six states or morphodynamic types of sandy beaches. These states, described by Short and Wright (1983), are dependent on two main factors: the wave energy level (which controls the swash zone boundary) and the grain size (which influences sediment transport). According to the authors, beaches can be classified as: dissipative, reflective and 4 intermediate types (Figure 7).

5.2. *Dissipative state*

Dissipative state is the combination of high waves (>2.5 m) with fine sand (Md<0.2 mm), which results in a beach characterized by a gentle slope and a fairly extensive surf zone (220 to 500 m), where two to five discrete bars may be present. The surf is sliding and the progressive dissipation of wave energy along a large portion of the profile promotes stationary oscillations.

The following four types represent the intermediate state, i.e. the transition between dissipative and reflective. The characteristics of intermediate types are medium sand and moderate wave height. When the modal wave height exceeds 2 m, the persistent type is the Longitudinal Ditch; when the waves are between 1.5 and 2 m, rhythmic beach benches predominate; between 1.5 and 1 m appears the Transversal and Rip Bench type; and, under low energy with waves less than 1m, the Low Tide Channel/Terrace Ridge type prevails. Because waves are rarely stable at levels above, beaches change from one state to another in response to changing wave conditions. These are beaches with greater temporal variability, due to energetic and spatial variations, due to the shape of beach cusps and banks.

5.3. *Longitudinal Bank and Pit*

In this stage, the bench-pit relief is much more pronounced than in the dissipative stage. The incident waves initially break progressively on the bank to reform in the trough and advance over the beach until a new break, this time in a very abrupt and turbulent way, of the plunging type. Thus, the proximal portion of the profile exhibits localized reflectivity. Large scale beach cusps (100-300 m) are commonly observed on the beach face, as well as incipient rip currents.

Rhythmic Bench and Beach–morphologically this stage is distinguished by the rhythmic character of the bench (in crescent) and also of the beach face. As the crescent banks migrate towards the sea, they become highly rhythmic and form banks alternately with rip current channels. Beach mega-cusps occur, whose spacing can reach 500 m on the most exposed beaches.

5.3.1. *Transversal Bank and Rip*

The accretion cycles make the protuberances of the crescent banks weld to the beach, forming transversal banks regularly interrupted by very developed rip currents, which pose a danger to bathers.

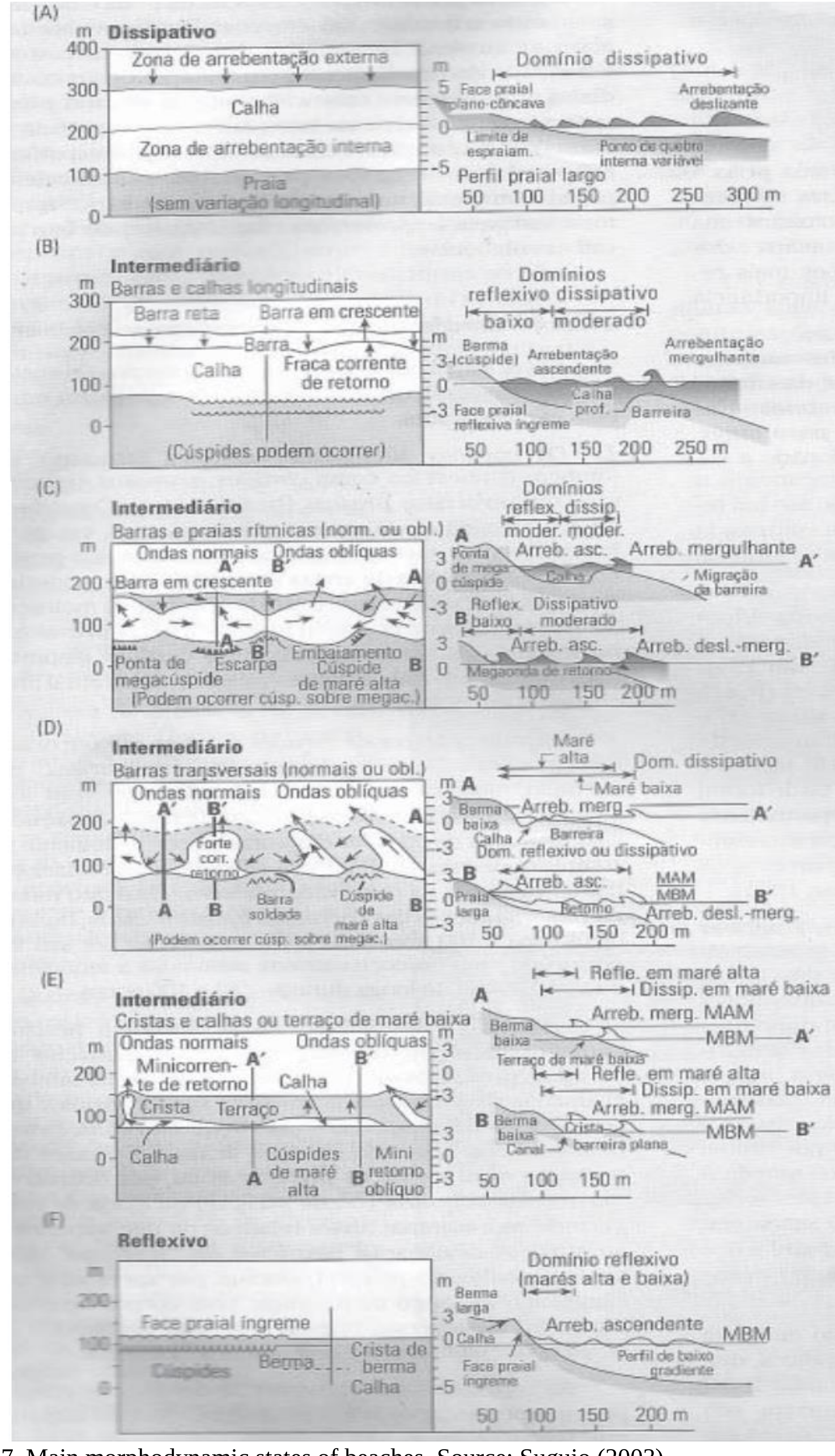

Figure 7. Main morphodynamic states of beaches. Source: Suguio (2003).

5.3.2. Low Tide Channel/Terraço Ridge

A relatively flat profile at low tide, preceded by a rather steep beach face at high tide. Thus, at high tide the beach is typically reflective while at low tide it assumes a dissipative character. Return currents can still be observed, even if weak, despite the large deposition of sediments near the proximal portion of the profile.

5.3.3. Reflective beaches

Reflective beaches are normally formed in areas of low energy (wave height < 1 m), often sheltered, and with very coarse sand (Md > 0.6 mm = 0.75), and can also be found in more exposed areas, high energy, where the sediment is composed of gravel. The beach is relatively high, normally containing a well-developed berm and cusps, while the beach face is steeply sloped. The surf is up or down, there is no surf zone or sandy banks and the flow is predominantly normal to the coast.

In exposed coastal regions, reflective beaches are highly sensitive to erosion. Therefore, these beaches can only exist as a modal state in sheltered areas where the sediment is of greater diameter.

The low temporal variability of both the beach face and the surf zone can be associated with extreme morphodynamic states (reflective and dissipative). In the reflective state, it is common for alterations to occur, such as variation in the height of the berm and the depth of the step, while in the dissipative state, expansion and contraction of the surf zone is observed due to increases in the height of the surf, without, however, changing the position of the surf. coastline or vertical variation of the volume of sand over the beach in either case. In the intermediate stages, small changes in the height of the breaking wave are sufficient to generate morphological changes on the beaches.

6. Models of meso/macro tidal beaches

Short (1985) carried out a review of the morphodynamics of meso/macro-tidal sandy beaches and identified three groups of beaches:

Group 1. Occurs in high energy environments dominated by waves. It is characterized by beaches with relatively smooth gradients (1-3º), with a concave profile and a surface free of banks. Beach cusps occur at high tide in the upwelling zone, while dissipative conditions dominate the lower parts of the beach.

Group 2. Consists of multiple bank systems, with low intertidal gradients (0.5º), which occur in lower energy environments exposed to episodic wave activity. The high tide beach must contain beach cusps and thicker material, while the intertidal banks are composed of finer material and are often covered by undulations generated by waves and tides, mainly in the troughs.

Group 3. Represents transition environments between beaches and tidal flats. They occur in systems dominated by low waves, with a beach face composed of relatively thick sediments forming a planar and steep profile that abruptly grades to a tidal flat of fine granulometry, with very gentle slope (0.1-0.3º).

Common to all meso/macro-tidal beaches is the display of a reflective pattern at high tide and a more dissipative pattern at low and intermediate tides. With the occurrence of high waves, the upper parts of the beach profile suffer escarpment, become dominated by more dissipative conditions and become more spatially and temporally stable.

6.1. Coastal erosion

The beaches, because they are located in the narrow range of contact between the land and the sea, react to any energetic and/or eustatic variation. Thus, they have the ability to adapt, protecting the coast from the erosive action of the sea. However, not all beaches have a sufficient sediment stock to respond morphologically to sea level rise by transferring sediment from the berm to the lower shorefront. The destruction of coastal vegetation and the construction of buildings on the coastline, especially the exposed one, can interfere in the process of sedimentary, wind and marine transport, causing imbalances in the sediment balance and, consequently, in the stability of the coastline.

The relationship between sediment losses and gains on a beach is called sedimentary balance (Table1), which is quite complex and depends on a number of factors. When the sediment balance on the beach is negative, that is, when there is more sediment loss than gain, erosion will predominate. Figure 8 illustrates a beach sand balance – the removal and addition of material by erosion and sedimentation.

Table 1. Sedimentary balance of a beach

Sediment supply to the beach	**Beach sediment loss**	**Balance**
From rivers and tidal channels	Transported towards the continent, to rivers and tidal channels	Depositional and erosive processes in the beach system, in balance
From rocky shores, beaches and frontal marine deposits	Transported along the beach (shore drift currents)	
From the continental shelf (currents generated by waves and tides)	Transported to platform (rip and offshore currents)	
From the dunes (carried by wind and storm waves)	Removed to the dunes (winds and waves from storms)	
Artificial beach food (anthropic contribution)	Extraction/mining of sand from the beach and outfalls	
Increase in the volume of sediments produced on the continent on the continental shelf (natural and anthropogenic causes)	Reduction in the volume of sediments produced on the continent and on the continental shelf (natural and anthropogenic causes)	

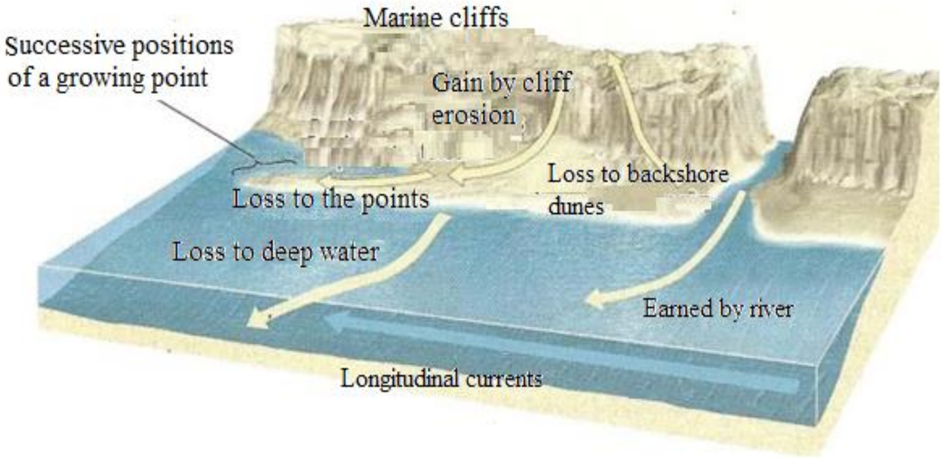

Figure 8. Sand balance – input and output of sand by erosion, transport and sedimentation. (Source: Press *et al*., 2006.)

About 20% of the coastlines of the entire planet are formed by sandy beaches, of which 70% are in a predominant process of erosion, 20% in pro-gradation and the remaining 10% are in relative equilibrium. However, most authors believe that the main cause is related to sea level rise during the last century.

In Brazil, although coastal erosion has become a growing risk and drawing a lot of attention, especially from the 1970s onwards, more detailed investigations into its causes gained momentum in the 1990s. erosion and relates the phenomenon to natural and/or anthropic causes. Table 2 shows a summary of the main coastal erosion indicators found in Brazil.

Table 2. Coastal erosion indicators in Brazil

1	Very narrow or non-existent backshore due to permanent flooding during high spring tides (urbanized beaches or not).
2	General retro-gradation of the coastline in recent decades, with a decrease in the width of the beach along its entire length, or more markedly in certain parts of it (urbanized beaches or not).
3	Progressive erosion of Pleistocene to current marine and/or wind deposits that border the beaches, without the development of cliffs or escarpments on dunes and marine terraces (urbanized beaches or not).
4	Presence of cliffs with heights of up to tens of meters in Mesozoic sedimentary rocks, Tertiary sediments (Barreiras Formation) and Pleistocene and Holocene beach rocks, and presence of escarpments in marine and/or Aeolian deposits from Pleistocene to current that border the beaches (urbanized beaches or not).
5	Destruction of front strips of "restinga" or mangrove vegetation and/or the presence of roots and trunks in a life position buried on the beach, due to erosion and burial caused by retro-gradation/migration of the coastline, or by processes over-washing (islands and barrier beaches).
6	Exhumation and erosion of paleolagunal deposits, peat bogs, beach sandstones or Holocene and Pleistocene marine terraces, on current foreshore and/or coastal face, due to the removal of beach sands by coastal erosion and extremely negative sedimentary deficit (urbanized beaches or not).

7	Frequent exhibition of "artificial terraces or cliffs", presenting packages of up to metric thickness, formed by successive layers of embankments buried by lenses of beach sand/dunes (contact between the beach and the urbanized area).
8	Construction and destruction of artificial structures erected on marine or Holocene wind deposits that border the beach, post-beach, foreshore, coastal face and/or surf zone.
9	Construction and destruction of artificial structures erected on marine or Holocene wind deposits that border the beach, post-beach, foreshore, coastal face and/or surf zone.
10	Erosive resumption of old marine abrasion platforms, +2 to +6 m high, formed on Precambrian and Mesozoic igneous-metamorphic basement rocks, or Mesozoic sedimentary rocks, or Tertiary sediments (Barrier Formation) or Pleistocene beach sandstones, in periods in which the sea level was above the current level, during the end of the Pleistocene and the Holocene (urbanized beaches or not).
11	Presence of concentrations of heavy minerals in certain stretches of the beach, in association with other evidence of erosion (urbanized beaches or not).
12	Presence of basements formed by the action of concentrated rip currents associated with shoreline zones or centers of divergence of a littoral drift cell located in a more or less fixed location on the beach, and over-washing processes (islands and barrier beaches) may also occur.

Sources: Souza and Suguio (2003).

Areas with erosion problems can be considered those that have at least one of the following characteristics:

- High rates of erosion or significant recent erosion;
- Low or moderate erosion rates on beaches with a narrow strip of sand and located in highly urbanized areas;
- Beaches that were artificially reconstructed and that follow a maintenance schedule; and
- Beaches that need or already have protection or containment works.

6.2. Sea level rise

The relative rise in sea level is a variable to be considered in erosion, given the freezing of glaciers during the 1990s and the historical trend of rising atmospheric temperature (Muehe and Lins-de-Barros, 1998). Examining sea level fluctuations at the beginning of the last century (between 1900 and 1950) an average increase of 2 m was recorded, equivalent to 1.2 mm per year, however, this increase is not distributed equally in all regions of the world. The most affected countries have been those in the northern hemisphere, including Canada, the Scandinavian countries, the USA and Russia. With regard to a rise in sea level over the next few hundred years, there is generally a consensus of opinion among the world's scientists that the Earth is heading towards another interglacial period, which will affect the world's hydrological balance. Sea level changes can endanger coastal areas that are generally the most densely populated in the world.

The dominance of sandy oceanic beaches prevails along the Brazilian coast, with different degrees of exposure. In general, the Brazilian continental shelf is quite wide and has gentle slopes, but localized narrowing and widening are responsible for significant changes in the climate of waves incident on the beaches. In the vicinity of Cabo de Santa Marta (SC), Macaé (RJ) and in the strip between the north coast of Bahia and Sergipe, especially in this last stretch, the smaller extensions of the continental shelf suggest a greater influence of the incident wave climate. The reef formations located in the northeast region should also change the climate of incident waves, protecting the adjacent beach line.

7. Coastal erosion protection and containment methods and beach recovery

The current trend of areas at risk of coastal erosion, resulting from mainly from the disorderly occupation of the coastal zone, makes three types of actions to be adopted in response to the problem of erosion:

a) Leaving the threatened area–consists of letting erosion take its course, without adopting containment or recovery measures in areas whose values at risk are lower than the costs of protecting them. There is damage from loss of land and destruction of man-made structures.

b) Restricting the occupation of areas at risk – implies regulating how the types of use can be implemented in areas subject to erosion, especially on the less urbanized coasts, as it prevents occupation in critical areas. Among the most adopted measures are: establishing lines of retreat for the occupation; create zoning of risk areas where the types of permitted occupation are defined; and encourage the relocation of structures at risk and the redirection of land use and occupation.

c) Implement coastal protection measures–this is an option chosen when the area and the values or activities at risk are significant. Protection techniques can be grouped into two categories: rigid or flexible engineering works and passive engineering works that include structures parallel to the coast, such as containment/protection walls and bulkheads, gabions, breakwaters and artificial reefs, which use materials such as rock, concrete, tires, steel, etc., and structures perpendicular or transversal to the coast, such as spikes, ripraps, jetties and current guides, which use materials such as rock, concrete, sand bags, etc. Passive engineering methods consist of artificially rebuilding dunes and beaches (artificial feeding with sand).

Conclusion

The beaches, which are anchored in the coastal plains, are characterized by frequent morphological changes, which act dissipating the incident energy and protecting the land against the erosive action of the sea. When in this environment the sediment transport process is altered, imbalances occur in the sedimentary balance of the beaches and, consequently, in the stability of the coastline, generating losses by erosion. The morphodynamic criterion considers the ability of seabed sediments to be mobilized by wave action, their displacement along a profile perpendicular to the coast, and the morphological response of the onshore portion of the coast.

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