

Coastal Environments



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Synonyms

Coastal zones

Definition

Coastal environments are those bordering the shoreline on both the seaward and landward sides, which is the geometric place where land, sea, and atmosphere meet and therefore encompasses a variety of subenvironments.

Introduction

Shorelines extend along the five continents for approximately 440 million km, crossing the Equator, Tropics, and Arctic circles, but this only partially explains the variety of coastal environments. Postglacial sea level rise (approx. 120 m) submerged many continental landforms, with headlands, bays, and beaches, and then migrated landwards and either welded to the continent or formed barrier islands.

Further, rivers have long fed the coast with sediments produced by erosion within their watershed forming coastal plains and deltas; at the land/water interface beaches, accumulations of loose material varying in size from mud to

boulders are being continuously reshaped by waves, winds, and subject to tides.

Inherited from the eustatic rise and reshaped by wave erosion and by weathering, rock coasts (see “► [Rock Coasts](#)”) tremendously increase coastal variability, contributing to the scenic value of such environments. While cliff erosion is an irreversible process, rock coast formation is active in tropical areas, where fringing reefs, platform reefs, atolls, and barrier reefs can grow by several millimeters per year.

Waves

Waves and the energy contained within them are a pivotal factor characterizing and affecting coastal environments. They have a variety of terms and are caused by several independent generating forces (wind, tide, earthquakes, under water landslide, explosions, etc.).

- (a) Winds are the main originators (with a wave period shorter than 30 s (see elsewhere)) blowing on the sea surface, they accumulate transferred energy (E), which is proportional to deep sea wave height (H):

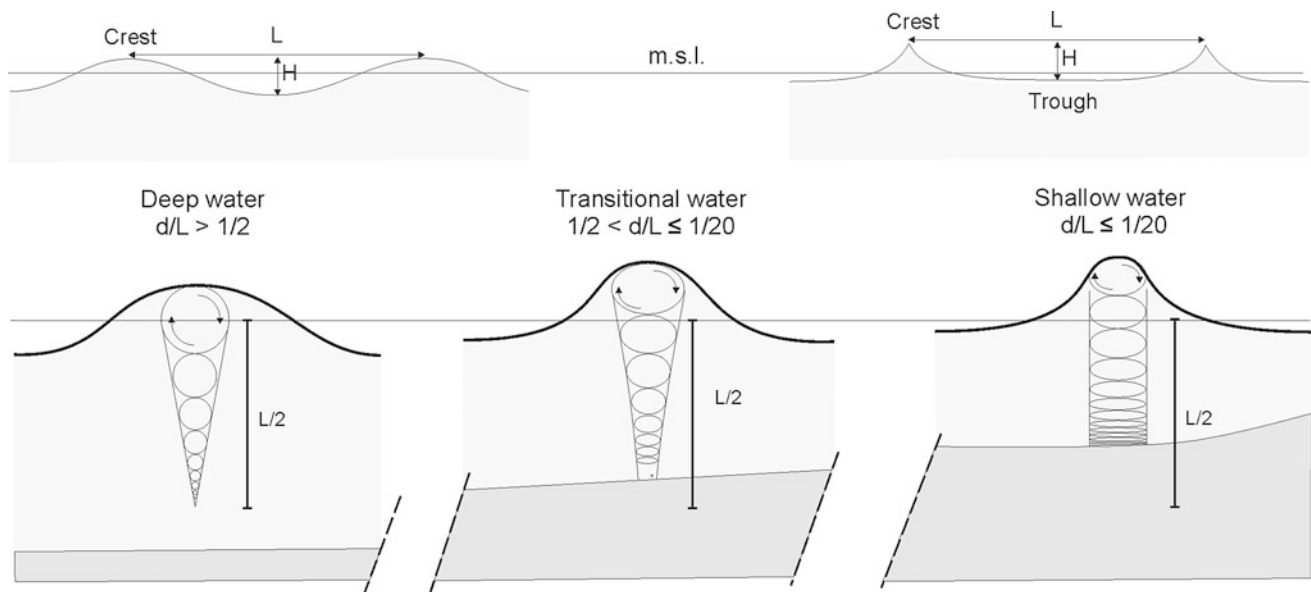
$$E = 1/8\rho gH^2$$

where ρ is the water density and g gravity acceleration.

In a deep water wave, water particles move in circular orbits, with a decreasing radius with depth, so that at a water depth 1/2 of the wavelength motion is practically insignificant (Fig. 1).

These waves move from the generation area at a speed defined as:

$$C_0 = \sqrt{1,56L_0}$$



Coastal Environments, Fig. 1 Water orbits and wave profile deformation while shoaling

where L_0 is the wave length in deep water; the longer the wave length the faster it moves.

Approaching the coast, water depth decreases and water particle motion is subject to friction, that is, the orbits flatten so that at the seabed they produce a forward and backward movement.

Waves slow down, but their period (the time taken for successive peaks/troughs to pass a stationary object) cannot change and reduced velocity implies shorter length waves. As waves enter shallow water, they “peak up” or increase in height together with a decreased wave length resulting in a steepened wave (steepness = H/L ; maximum 1:7). If the crest angle decreases, the wave becomes unstable with the crest moving more rapidly than the water beneath it, so it collapses and the wave breaks. The water depth at which this occurs (h_b) is generally considered proportional to the wave height at breaking (H_b), with $\gamma = 0.78$ and $H_b = \gamma h_b$ and $C = \sqrt{g \cdot d}$.

- (b) Tsunamis waves are generated by seismic activity or submarine landslides; they have very long wavelengths and periods and can be extremely destructive.
- (c) Tidal waves caused by astronomical forces are formed as a function of the periodic movement of the Moon around the Earth (the sun plays a very small part).

When waves approach obliquely with respect to the coast, the part nearest the coast slows down earlier than the remaining part due to bottom friction; in this manner waves rotate to fit the coast (wave refraction; Fig. 2 top). If the nearshore has a mild slope or waves are long, their rotation can complete otherwise they arrive at the shore with a certain angle. The longshore component of the energy, mostly near

the breaker zone, is responsible for sediment transport along the coast.

For the same process, headlands and bays receive different wave energy, due to concentration or dispersion while shoaling (Fig. 2 center). Waves passing through a straight, or through the gap between two detached breakwaters, generate circular waves (wave diffraction). After bypassing headlands and anthropogenic structures stretching into the sea (e.g., jetties and breakwaters), waves enter the sheltered area with a circular planform (Fig. 2 bottom).

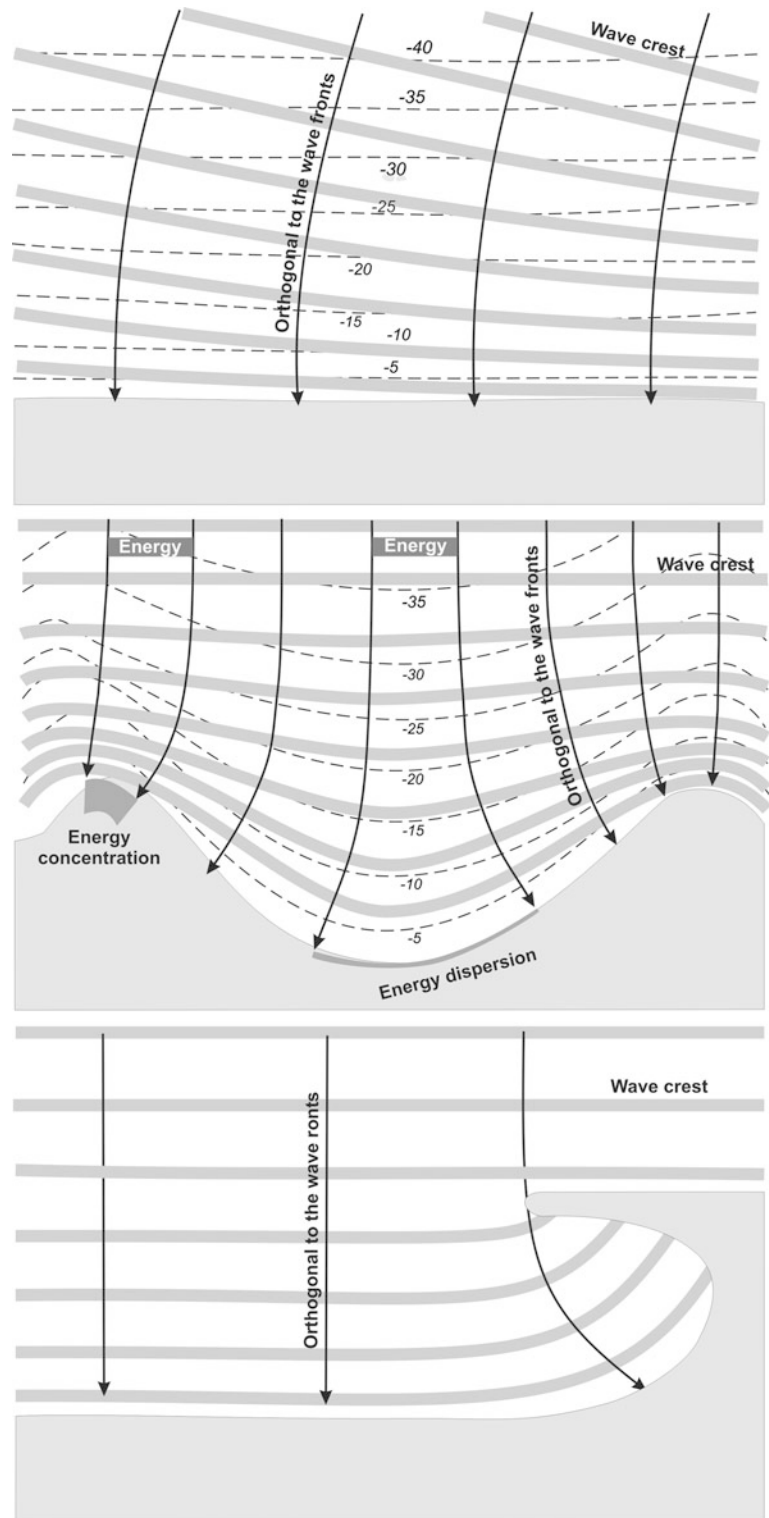
Beaches

The bulk of the world’s beaches consist of sediments delivered by rivers to their mouth and moved longshore by wave-induced currents. River input is modified by human activities (e.g., river dams, changing land use patterns, riverbed quarrying, land reclamation), all operating with different intensities, and sediments can be trapped by coastal structures in their longshore movement. With more than 70% of the world beaches eroding and 50% currently under threat because of excessive development (Pilkey and Cooper 2014), the interest of geoscience in this environment is pronounced.

Beach profile, in the emerged and submerged part, depends on grain size and wave energy. The coarser the sediments the steeper is the profile; high energy waves produce gentler slopes, that is, storm waves flatten the beach, whereas low energy waves build up the beach, or steepen the gradient. Following wave characteristic changes, beach profiles modify with cross-shore sediment displacement.

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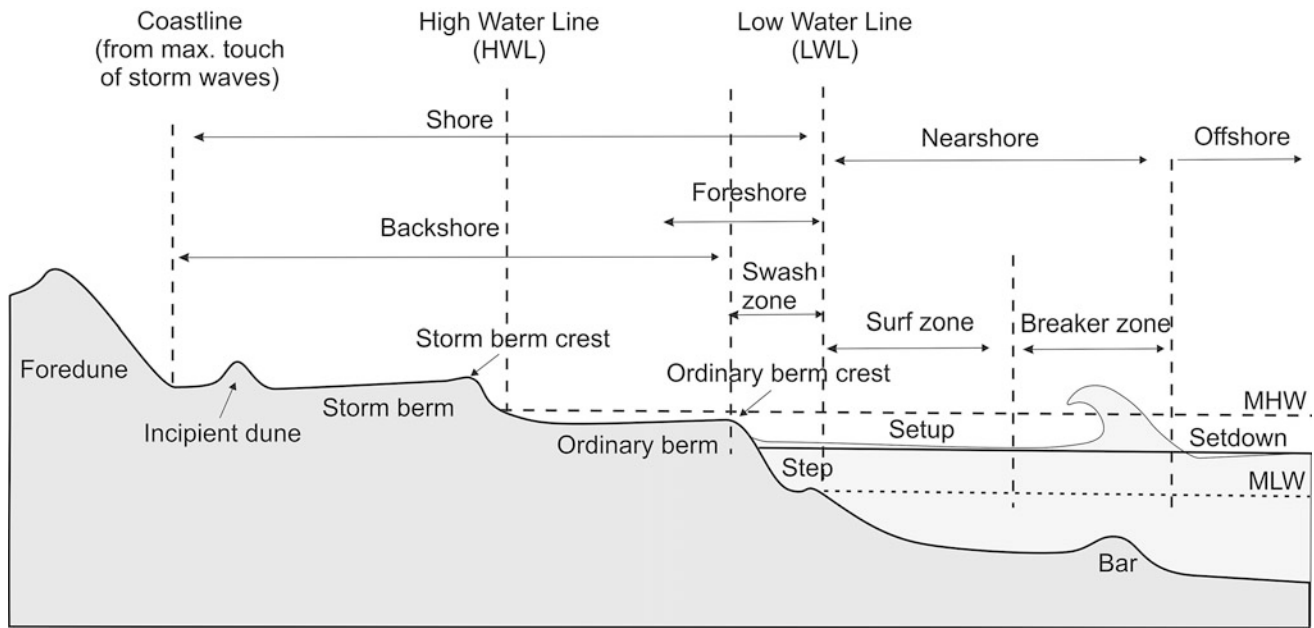
Fig. 2 Offshore oblique waves refracting while shoaling in a linear (top) and in an embayed coast (center); wave refraction on the leeside of an obstacle (bottom)



After breaking, water in the upper layers moves towards the beach and a return flux runs near the bottom, which moves sediment offshore and these tend to accumulate beneath the breaker line forming a bar (Fig. 3).

During storms, when higher waves break in deeper water, bars form far from the beach, but this material returns onshore with milder constructive waves.

In the swash zone, wave uprush transports grains, a part of which is abandoned on a ridge because backwash is less rapid



Coastal Environments, Fig. 3 Beach profile and terminology

and part of the water infiltrates into the sediments. The higher the waves, the higher is the ridge; milder storms produce lower ridges welding to the former. In this manner, the beach develops a stepped profile, with each step slowly deepening landward, but steepening seawards.

In a prograding beach, storm berm crests can grow intercepting wind-driven sediments forming foredunes; flanking one another these linear and parallel rises form beach-ridge or foredune-ridge plains, where interdune swales and ponds can be present. On river deltas, they converge to the apex and the innermost trace the old coastlines. The proposed beach profile model is valid for microtidal environments, but when tidal range is significant, wave-induced processes shift cross shore; the most evident result being a low-tide terrace and the absence of features such as berm crests and steps.

The basic framework for the morpho-dynamic states of a beach is inherited from earlier states (Short and Wright 1983), each state distinguished by a different association of morphology, circulation, and behavior. Different morphological types relate to stages in erosional or accretional sequences and the two extreme types are: *Dissipative* (flat, shallow beaches with relatively large subaqueous sand storage) and *Reflective* beaches (steep beaches, with small subaqueous sand storage).

The surf scaling parameter (ε) divides them:

$$\varepsilon = 2\pi a/gT \cdot \tan^2 \beta$$

where a = wave amplitude, T = wave period, g = gravity component, β = beach slope.

Reflection dominates when $\varepsilon < 2.5$, and for $\varepsilon > 2.5$ waves begin to plunge dissipating energy, and at $\varepsilon > 20$ spilling

breakers occur, surf zone widens, and turbulent dissipation of incident wave energy increases.

The dissipative extreme has high ε values across the surf zone and beach face (30 to >100), spilling breakers, and surf zones across which bores decay progressively to become smaller and smaller.

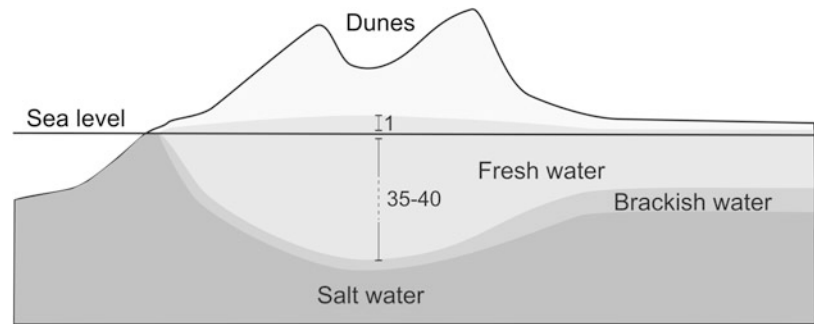
Coastal Dunes

Offshore winds take the finer sand fractions from backshore surfaces and deposit them against obstacles or vegetation, forming incipient dunes, which can further evolve into foredunes (Fig. 3). Since vegetation lives at a specific distance from the shoreline, dunes form parallel to the coast, independent from the prevailing wind direction. Dune growth is a feedback-regulated process, since the higher the dune the stronger the wind on the crest, which in turn erodes its own deposits. In arid environments, or where sand accumulates faster than vegetation grows, dunes can move landward, possibly losing their linear disposition and forming barchans or seifs. They can climb cliffs (cliff-top dunes) and overpass promontories.

Dunes are inherent to any natural sand beach, but high dune formation needs strong offshore winds, fine sand sources, and a high tidal range; in middle latitudes, dunes are better developed on coasts that are exposed to westerly winds. Along Arctic coasts, dune formation is limited given coarse glacial deposits, wet soil, and land-based winds. In the Tropics, it is the vegetation growing on the beach that opposes wind ablation.

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Fig. 4 Dunes as fresh water reservoirs (Ghyben-Herzberg relation)



Unvegetated dunes can move inland, obstructing communication lines and burying villages, as occurred during the Middle Ages when Via Julia, in Wales, was abandoned. Wind fences are often built to stabilize the sand, generally constructed with wood lathes. Planting, when possible, is a more effective way of dune stabilization and marram (*Ammophila arenaria* or *brevigulata*) grass is frequently used.

Dunes act as water reserves since freshwater is lighter than saltwater: for each meter of water table elevation above sea level 40 m of water will be present in the aquifer below; per the Ghyben-Herzberg relation (Fig. 4). Coastal development negatively impacts dunes, especially flattening or cutting, thus reducing this fresh water resource.

Coastal Plains and River Deltas

When rivers enter the sea, they deposit their bedload, which is reworked by waves and distributed longshore to form beaches and coastal plains. The latter can grow due to alluvial deposits because of floods and river course migration. Uneven sedimentation can give rise to coastal lakes and marshes, whose formation is favored by subsidence (see “► Subsidence”) characterizing recently deposited materials.

If sediment supply is greater than what waves can move longshore, part of it will remain to construct a delta that protrudes into the sea. Delta shape depends on river input, wave energy, and tidal processes, and given these three parameters, a classification is proposed by Galloway (1975) (Fig. 5): wave dominated, fluvial dominated, and tide dominated. The first have cusped shapes, more or less prominent as a function of the ratio river input versus longshore transport; the second shows several branches cut by distributaries; and the latter are funnel-shaped with elongated sand islands continuously reshaped by ebb and flood tides.

Given an almost constant wave energy and direction over the last few centuries, delta accretion and erosion has been mostly modulated by changing river input and, consequently, by changing soil erosion rates. Providing that most deltas began to form only after sea level stabilization (approx. 6,000 year BP), human impact on their evolution is evident.

Delta progradation accompanied socio-economic development, since humans started to cut forests to expand pasture and agriculture including use of the timber. Furthermore, dam construction, hill slope stabilization, riverbed quarrying, and river diversion have filled coastal lagoons reducing overall coastal sediment input. Consequently, beach erosion first started at river mouths, especially at deltas. Forest cutting in developing countries, which triggers additional soil erosion, reduces coastal accretion or stability since reservoirs built along a river course prevents coarse sediments from reaching the coast (Syvitski et al. 2005).

In the Nile delta, the Rosetta promontory retreated more than 70 m/year following the Aswan dam construction. Elsewhere, over the past 60 years, construction of large reservoirs and soil-conservation practices within the Yellow River basin have reduced sediment flux to the sea by some 90%. The Niger delta is severely eroding with subsidence induced by oil extraction a relevant factor. In Colombia, coastal erosion was approximately 80 m/year on the western side of the Magdalena river delta after the construction of a jetty in 1936, which delivered sediments at the head of a submarine canyon (Correa et al. 2005).

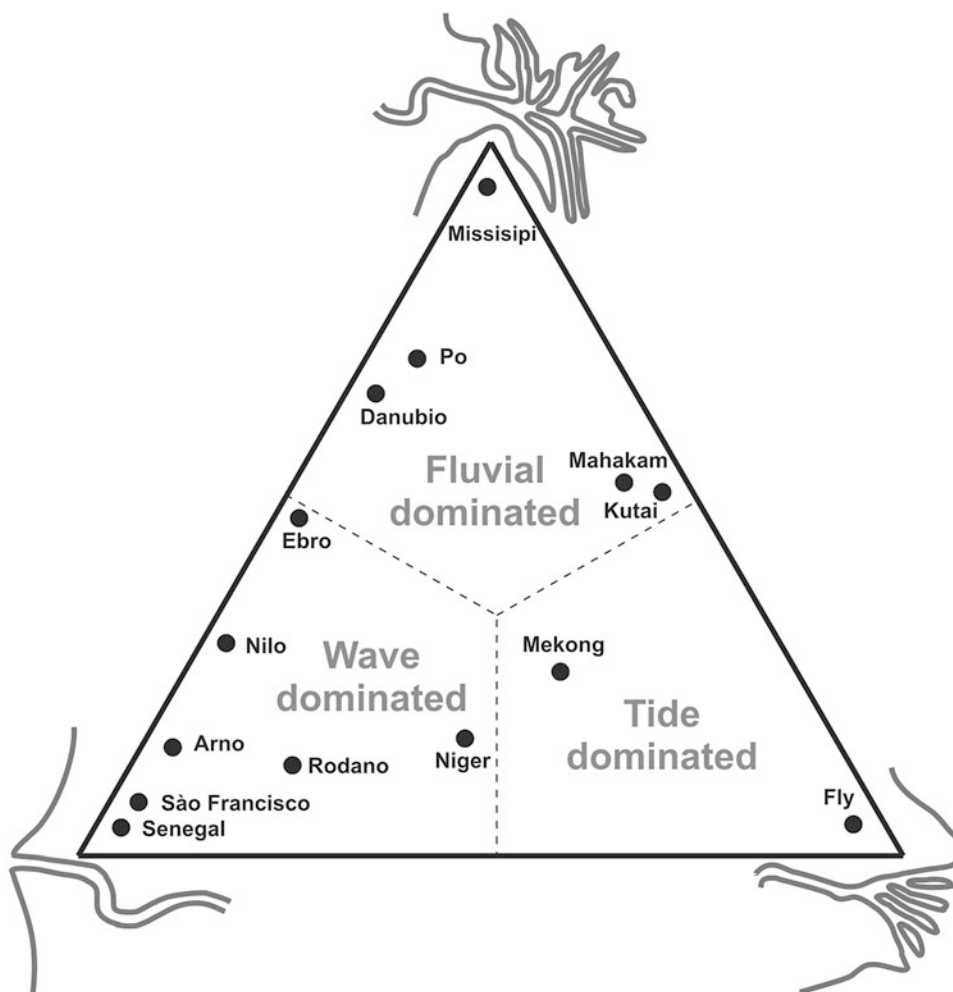
Estuaries are not immune from similar processes: from 1921 to 1965, the average cumulative subsidence in Shanghai (Yellow River estuary) was 1.76 m; through water extraction limitations and artificial recharge, this process has slowed down, but large building construction made subsidence rates jump over 10 cm/year in the city (Wang et al. 2012).

River deltas host a relevant part of the world population, e.g., Ganges, Indo Brahmaputra, Nile, and coastal erosion, increased by land subsidence, severely threatens their future.

Barrier Islands, Spits, and Lagoons

Sediments (sand and/or gravel) bypassing headlands can settle downcoast to form emerged bars connected to the mainland; their tip is frequently bent due to wave diffraction. If the bar geomorphologically welds to the coast, a lagoon forms. Bay barriers close embayments.

Barrier islands are similar deposits, but detached from the coast to which they run almost parallel in a sequence of

Coastal Environments,**Fig. 5** River delta classification after Galloway (1975, modified)

elongated islands. They border 13% of the world coast and are present in all the continents except Antarctica. In the United States, they run for more than 4,300 km from Maine to Texas, in the North Sea they protect the coast of Germany and The Netherlands, and in the Arctic they occur in the Hudson Bay and on the Barents Sea; others are found in Nigeria, Gabon, Ceylon, Vietnam, and Australia; in the latter where Young-husband Peninsula stretches for 130 km.

Two conceptual models have been proposed for their formation: onshore sediment migration following Holocene sea level rise, with bar emergence (Shepard 1963), and detachment of one or more spits which migrated longshore (Otvos 1970).

Gaps separating islands guarantee water exchange through tidal inlets, where submerged ebb (offshore) and flood (inshore) deltas forms, the latter with a wave dominated shape and the former a tide dominated one. Being flat and narrow overwash can occur during severe storms and hurricanes, as along the US Atlantic coast, this process being part of barrier landward translation.

Coastal Erosion

Most of the world beaches are eroding, and many of these were accreting until the late nineteenth and early twentieth century. Natural and anthropogenic causes join in this process, the latter being dominant. Those factors mentioned for river delta erosion add to the interventions on the coast, which further alter the beach sediment budget. Harbors and jetties interrupting longshore transport are responsible for downdrift erosion. Sand quarrying on the beach to obtain cheap building material is an additional cause of the sedimentary deficit, and this generally illegal activity occurs due to the continuous development of the coastal zone.

Although most beaches are fed by rivers, soft cliff erosion makes sediment available for beach construction; in this case, cliff protection can trigger down coast beach erosion.

Coastal erosion works both on the dry beach, i.e., shoreline retreat, and on the nearshore, with profile lowering to the depth of closure, thus producing a milder sloping profile. When river deltas are involved, their deeper parts do not

erode and isobaths often trace the old landforms even when the shoreline is rectified.

Sea level rise is a natural factor contributing to beach erosion, even if produced by human-induced global warming. Bruun (1962) proposed a rule – still under revision – for which the beach profile adapts to sea level rise elevating the same amount within the depth of closure; if sediments are not available (e.g., from the river input), they are eroded from the upper part of the profile, inducing a more severe erosion than that produced by mere flooding. With recent sea level rise (approximately 20 cm in the last century), this component of beach erosion is minor, except on low lying areas, but under the future 2100 year scenario (IPCC 2014), with up to 1 m in sea level rise, this will be the dominant process in many coastal sectors.

Considering that most coastal plains are subsiding and that this process extends offshore, especially where oil and gas extraction is carried out, relative sea level rise will be more harmful.

Severe beach erosion is documented in most countries, except where tectonic uplift is intense and/or isostatic rebound is high. Boulder clay cliffs at Holderness, UK, for example, have been retreating about 2 m/year, and since the eleventh century, 26 villages have disappeared (Sheppard 1913). US Atlantic beaches are eroding mainly because of inlet stabilization via jetty construction. Climate change has been noticeably contributing to beach erosion, for instance, glacier retreat in Iceland deposited outwash sediments inside a moraine dammed lake instead of reaching the coast and thus is indirectly responsible for beach erosion of some 8 m/year (Jóhannesson and Sigurðarson 2005).

Conclusions

The areas bordering shorelines are very dynamic environments that are subject to waves, tides, sea level changes, cliff instability, river sediment input, and increasingly human intervention. Since humans preferentially gather along most shorelines through community settlements, industries, communication, and transportation corridors, etc., a sound knowledge base of the processes affecting coastlines is imperative to ensure prolonged and effective sustainable development.

Cross-References

- Alluvial Environments
- Beach Replenishment
- Dams
- Erosion
- Flooding
- Fluvial Environments
- Groundwater
- Marine Environments
- Reservoirs
- Rock Coasts
- Sea Level
- Sediments
- Subsidence

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