STRUCTURE AND FUNCTION OF MARINE SHORELINE ECOSYSTEMS

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Summary

As the economic importance of coastal zones has been growing substantially, it is essential to understand the problems and processes operating in these zones. Coastal change along the mainland and island states is a common phenomenon due to erosion, accretion, sea level changes, hazards, and disasters. Anthropogenic activities like construction of ports/harbors, coastal engineering structures, sand mining, and reclamation adds to the complexity of coastal evolution. Retreat of the coastline causes many problems including displacement of settlements, destruction of agricultural and recreational lands, and damage to harbors, navigational structures, roads, and other infrastructures.

Management of vital/critical coastal habitats like corals and mangroves is an important need as they are productive ecosystems and nursery grounds for various biota. In addition, mangroves act as buffer zones between the land and the sea and offer protection to the coast from storms. Correlation of depositional features with erosional ones, reveal whether a particular coast is getting eroded or accreted. Knowledge of the sediment transport rate and direction is useful for selecting sites suitable for harbors/ports and coastal engineering projects.

The state of art of research on coastal aspects and new techniques is mentioned briefly. A broad perspective of shoreline ecosystems, their contribution to primary production, environmental stresses and strains, and the need to have a long-range coastal zone management are discussed. A few examples pertaining to impact of coastal engineering structures on shoreline changes are included.

1. Introduction

The coastlines of the world's oceans are the most dynamic environments and encompass a wide variety of geomorphic features. They include a gradient of highly variable habitats between the transient land–sea environment and the wave-dominated surf-zone. Coastal regions occupy 18% of the global surface, inhabited by 60% of human population. Two thirds of the world's largest cities are located on the coasts and the same proportion of population of developing nations were living along the coasts by the end of twentieth century. Coastal waters supply about 90% of the world's fish catch. Associated with this region several processes of interest take place: (a) 25% of global primary production, (b) 80% of global organic matter burial, (c) mineralization of 90% of 2×10^{11} ton y^{-1} global sediment load, (d) deposition of 75–90% of global river load and pollutants, and (e) deposition of 50% of global carbonate.

The shoreline combines the interests of the physicist because of the wave energy propagation, the geologist for the morphodynamics of the coastline, and the ecologist for the habitats and their fauna and flora. Because coastlines sustain a wide diversity of fauna and flora, including several commercially important species, humans are drawn to the shoreline for settlement and food and a symbiotic relationship existed until 1850. Coastal waters support ~90% of the world's biomass of fish and shellfish and 60% of the developing countries obtain their protein from fish. Most shoreline habitats serve as nursery grounds for a variety of biota. However, with modern industrialization,

urbanization, recreation, mariculture, strategic defense, and several other anthropocentric activities, ruination of the coastal environment ensued. US coastal areas are about 10% of the country but generate >33% of the gross national product and the international commerce moving through coastal waters were about US$5671 billion in 1994. Although it has been predicted that the human population will increase enormously in the coastal zone, it remains the least studied. The economic importance of the coastal zone is expected to grow in the years to come, leading to an increase in pressure for urbanization and development. The alarming decline in the habitat quality in the USA resulted in greater awareness and necessitated legislation known as Coastal Zone Management Act (CZMA) in 1972. Several developed and developing nations today have in place similar coastal zone management programs such as the United Nations Environmental Program (UNEP), Coastal Marine Project of UNESCO (COMAR), Coast and Beach Stability in the Eastern Caribbean Islands (COSALC), and Caribbean Coastal Marine Productivity (CARICOMP).

The interaction of antecedent geology, physical dynamic processes, and man-made intervention shapes the geomorphic forms and ecosystems. An understanding of the processes that shape the shore is crucial to the design of coastal structures and for prudent management of coastal resources and habitats. In this article we present information on coastal processes in tropical, sub-tropical, and temperate regions; engineered coastlines; Quaternary Sea level and shoreline changes; as well as coastal remote sensing. A broad perspective of the shoreline ecosystems, their contribution to production, environmental stresses and strains, and the need to have long-range coastal zone management in the new millennium before reaching a point of no return is also included.

For thousands of years, the continental shelf has been used mainly for landing various valuable sea products, including fish. The concept of plate tectonics provided an opportunity of exploration for oil from the continental shelf and hence, at the end of the twentieth century, it became a place for oil and gas production. Promising oil and gas bearing areas are found on about 90% of Russian shelves covering 5.2 to 6.2 million km^2 with an estimated recoverable hydrocarbon resources of 90 to 100 billion tons. The affinity between the offshore petroleum-bearing provinces and corresponding geological structures of the adjoining inland areas is found practically everywhere on the Russian shelf. Global experience indicates that in such cases, the oil and gas potential of the shelf fields is higher than that of the onshore accumulations. The recoverable hydrocarbon resources of the shallow shelf of the Caspian Sea are estimated to reach up to 2–3 billion tons. The exploration and drilling activities here are complicated due to the very deep location of petroleum deposits (over 4 km), high reservoir drive, and large amounts of aggressive sulfurous gases. Two giant oil and gas bearing basins found in the west Arctic cover a total area of 2 million km^2. They contain potential resources of at least 50–60 billion tons of conventional fuel. The shelves of the Far East and eastern Siberia have especially good prospects for large-scale and long-term development of the offshore oil and gas fields. The promising regions are principally the Sea of Okhotsk and the Bering, Chukchi, and east Siberian seas covering an area of about 1.5 million km^2. Here, more than 20 oil and gas bearing basins of different geotectonic nature have been discovered. The discovery of hydrocarbons in the offshore waters surrounding the world's largest island continent (Australia) came relatively late in the mid 1960s when

Esso and BHP struck oil in the Gippsland Basin in the Bass Strait, off the coast of Victoria. Over the next 20 years the Bass Strait area proved highly prospective, with many major oil strikes recorded, putting Australia on the map as an oil producer.

India's offshore exploration started with seismic surveys in the western shelf in 1964. Within a decade, the giant oil field, Bombay High, was discovered and put into production. The western continental margin is typically a passive margin and like other divergent margins has a favorable habitat for hydrocarbon generation and accumulation. Of the 1.78 million km^2 of sedimentary basins of India, 0.38 million km^2 are in the continental shelf region (within 200 meter isobath). Some indications of hydrocarbon (mainly gas) were obtained in the wells drilled in the offshore of the Andaman and Nicobar and Bengal basins in the Bay of Bengal. A well on the Porto Novo structure off Pondicherry coast produced gas from fractured basement and Eocene limestone in 1980. Later in 1981, oil was struck in a well drilled in North Palk Bay. In the offshore, three prospects have produced hydrocarbons so far and have added considerably to the production potential and reserves of the Cauvery basin.

The most important exploration tool for oil and gas is common depth point (CDP) seismic profiling. In recent years satellite altimetry has emerged as an efficient alternative much too expensive and hazardous ship borne gravity surveys. It is found to be quite useful as a quick and inexpensive reconnaissance tool for mapping the megastructures in the poorly explored offshore regions.

2. Shoreline Environments

The width of the coastal zone varies in different regions. Compared to countries with continental shelves, island countries such as the Maldives and Kiribati have a larger coastal area than the dry land. Coastal zones with a broad shelf usually retain a larger sediment load than those with no shelf zone. Unique to the shoreline environment is the constant interaction between the atmosphere, hydrosphere, and biosphere where the scale of spatio–temporal events range between < 1 second to 10^{10}s, and from 1cm to >10^6 m. Time scales of events which vary widely are as follows:

- Waves – few seconds
- Tides – daily
- El-Nino Southern Oscillation (ENSO) events – interannual
- Sea level changes, global climate – long term

Common to all shoreline habitats are extremes of climatic conditions, wave action, exposure, desiccation, littoral and longshore currents, and impacts due to shipping activities, eutrophication, pollution, and urbanization. In 1988, Carter discussed at length various classifications of the coastal environment and, based on a first order scale, recognized six categories (Table 1).

Category	Features	Examples

1. Mountain coast	Rocky shores, pebbly shores in high latitudes, shingle cobble shores. Algal mats, extremes of climatic conditions, wave impact, exposure, sea cliffs, wave cut platforms, rock pools	California, Peru, Chile
2. Narrow shelf a) Headlands and bays b) Coastal plain	Sandy shores most common in tropics, rocky shores/beaches, anthropogenic perturbations, seaweeds Diversity of intertidal biota, seaweeds, tidal flats, meiofauna, cyclicity of erosion and deposition, tidal currents, ebb and flood currents, transport of sediments	S. Arabia and west coast of Red Sea Western Bay of Bengal
3. Wide shelf a) Headlands and bays b) Coastal plain	Sandy and rocky beaches, mangroves, anthropogenic perturbations, seaweeds, diversity of intertidal biota and meiofauna	West coast of India South Africa US east coast, west coast of Australia
4. Deltaic coast	Estuarine, heavy sediment load, lagoon formation, mangroves, erosion, burrowing benthic fauna, meiofana	Most river mouths like Ganges, Godavari
5. Reef coast	Coral reefs, seagrasses	Great Barrier Reef, West Indies
6. Glaciated coast	Impacted by coastal sea ice, erosion	Hudson Bay, Greenland

Table 1. Classification of shoreline environments

2.1. Tropical Coastal Environments

On a global basis, a very large fraction (>50%) of the mass flux from land to the marine environment enters from tropical rivers. Coastal–ocean processes in the wet tropics are globally important, fundamentally different than at higher latitudes, and diverse in operation.

The coastal region of East Africa and the western Indian Ocean has 12 000 km long coastline and a rapidly growing population of about 55 million. The usual causes of coastal change in this region include coastal erosion, sediment accretion, and coastal reclamation. The latter is commonly carried out in the island states where land is at a premium. The response to coastal change in the region has been the construction of shoreline structures. Shoreline structures have performed poorly and, in several cases, they have aggravated the problems by accelerating shoreline change.

India has a coastline of 7516 km and its exclusive economic zone covers 2.02 million km^2. About 20% of India's population inhabits coastal areas. Like a majority of the coasts of the world, the west coast of India experiences an annual cycle of storm and swell conditions. The entire coast is exposed to seasonally changing winds—the monsoons. The reversal of these winds takes place predominantly from the southwest (May–September) to northeast (December–March) direction. The storm condition prevails during the southwest monsoon as a result of differential heating of the Indian peninsula. Numerous west flowing rivers form estuaries, bays, mud flats, creeks, and tidal marshes, while east flowing rivers form deltas.

Most of the beaches on the west coast of India exhibit cyclic episodes of erosion and accretion in response to the monsoon and fair weather seasons. Unique to the central part of the Kerala coast is the appearance of mud banks in the nearshore regions during the southwest monsoon. Beaches of south Karnataka are long, narrow, and straight with spectacular spits, whereas in north Karnataka they are mainly the crescent-shaped pocket type lying between rocky headlands. In contrast, the presence of rock outcrops and small offshore islands are common along the coast of Gao. The shoreline of Maharashtra is very irregular and associated with features like cliffs, notches, promontories, sea caves, embayments, submerged shoals, and offshore islands. The northern part is known for exceptionally wide and thick mud flats. These flats are associated with muddy beaches and high tidal range, >3m. The coast between Ratnagiri and Vengurla is narrow, hilly, highly dissected with transverse ridges, which extend as promontories into the Arabian Sea.

2.1.1. Mangroves

Between 30°N and 30°S latitudes mangroves or mangals occur. These comprise of about 60 halophyte species of which 20% are in the Atlantic and the rest in Southeast Asia and Micronesia. Six genera *Rhizophora, Avicennia, Excoecaria, Sonneratia, Languncularia,* and *Conocarpus* are dominant. In mangals there is more aerial biomass than underwater. The leaves that fall contribute to 95% of the organic matter that enters the detritus cycle. Besides supporting a variety of heterotrophs including fish, crustaceans, birds, small mammals, and invertebrates, mangals act as nursery areas for commercially important shrimp. They also act as a buffer zone between the land and the sea, and offer protection to the coast from natural disasters such as storms. Due to human activities such as reclamation for aquaculture, agriculture, or development, mangrove habitats are lost; for example 25% are lost due to urbanization in India and 40–70% are lost due to prawn and shrimp culture in Kenya (Table 2).

Region	Total ha in thousands	Loss
Indonesian archipelago	4250	45%
South Sulawesi	100	100%
Malaysia	641	12%
Thailand	360	50%
India	665	25%
African countries	198 373	40-70%

Table 2. Status of mangroves (modified from IOC, 1997, Workshop Report no. 131) Mangroves efficiently retain dissolved inorganic nutrients such as nitrate, ammonium, and phosphate with inconspicuous effect on seagrass.

2.1.2. Corals

Shallow, clear waters with normal salinity are a natural habitat for coral since these conditions determine the phenomenon of photosynthesis and set the tolerance limit for living coral. Rapid sedimentation from rivers and sea waves has a deleterious effect on

the survival of coral. It is for this reason that stretches of tropical coasts are devoid of coral reefs.

Coral reefs cover ~2 x 10^6 km^2 worldwide and are mostly located between $3°$N and $30°$S. However, they are best developed in the Indo-Pacific province. There are 9000 species of corals and a majority of them are hard with skeletons made of calcium carbonate. The hard corals form fringing reefs along the shorelines of continents and the South Pacific Islands, Hawaii and the Caribbean, and barrier reefs in the Indo-Pacific and Australia. Corals grow extremely slowly and harbor symbiotic photosynthetic algae—the zooxanthellae. They offer shelter to diverse biota belonging to most taxonomic groups. Marine fish reach their greatest diversity in the coral reef ecosystem. Coral reef communities dominated by zooxanthellae deplete 35% of the algal biomass measured as chlorophyll, 15% particulate organic carbon, and 23% particulate phosphorus. That sponges, tunicates, bivalves, and hard corals remove only <20% of particulate carbon suggests soft corals were the primary sink of suspended particulate carbon.

Besides starfish and fishes—the main predators on corals—oil slicks, heavy metals, dumping of garbage, sediment load that reduces light essential for algal photosynthesis, blast fishing with dynamite, over use of resources, anchoring, speed boat traffic, and discarded ghost nets devastate corals. Approximately 10% of corals are seriously degraded and nearly 30% may decline in the next 20 years. For example between 1986 and 1991, 50% of Philippine coral reefs were destroyed due to dynamite blasting and they are most seriously degraded due to the large deposition of mud in the Gulf of Kachchh, India. Globally coral reefs are at risk; 80% in Southeast Asia, 66% in Caribbean waters and in the United States off Florida, Hawaii, and Puerto Rico. Besides viral diseases, changes in sea level, storms, hurricanes, floods, and unusual high temperatures associated with El-Nino-Southern-Oscillation (ENSO), also have a serious impact on coral reefs.

2.2. Mid- and High-latitudinal Coasts

Cohesive shorelines have been described on a number of mid- and high-latitudinal marine coasts and they are particularly significant in the Great Lakes where they make up about 40% of the shoreline of the lower lakes (Lake Ontario, Lake Erie, and southern halves of Huron and Michigan) in Canada and the United States. Steep, sub-aerial cliffs (slope $45°$), narrow beaches (<10m) with thin sediment cover and a steep concave nearshore profile characterize these shorelines. Recent damage due to the flooding and erosion of cliffs has led to a major study of all aspects of flooding and erosion of cohesive shorelines. These coasts are developed in Quaternary and Holocene sediments, including glacial till. Erosion and recession rates are often 0.5 to 1.0 m/yr., and, in places, exceeding 1.5 m. The distribution of wave energy is a main control of cliff recession, which in turn supplies most of the sediment to the littoral system. Sediment availability for beach building has a negative correlation with shoreline recession, indicating that recession is generally lower where there is more sediment available to form a protective beach. Another factor influencing shoreline recession is isostatic adjustment in the Great Lakes, which has occurred over the last 14 000 years following deglaciation.

3. Coastal Depositional Features

Coastal depositional features include beaches, spits, bars, deltas, barrier beaches, barrier islands, beach ridges, organic reefs, coastal lagoons, mud flats, tidal marshes, and salt marshes.

3.1. Beaches

A beach is a widespread coastal feature that extends between the uppermost limit of wave action and the low tide mark. Some beaches are narrow and steep while others are broad and flat. As shown in Figure 1 a beach may be classified into backshore, foreshore, and a part of the nearshore zone. The nature of a beach, whether narrow or wide and steep or gently sloping, depends on grain size, wave length, and wave steepness. Beaches comprise a wide range of sediment composition.

They may be classified into two broad groups as sandy beaches and non-sandy beaches. Sandy beaches are most common and consist of rounded and well-sorted grains in which quartz and feldspar, the two more resistant minerals, dominate. Non-sandy beaches are of several types. They include the uncommon muddy beaches, the more common shingle cobble beaches, and biogenic beaches. Muddy beaches are associated with the seaward margin of deltaic sediment.

They develop in an environment of low wave and current energy where coastal erosion has exposed the former deltaic material. Shingle and cobble beaches result from the erosion of bedrock or of stony glacial drift. Pebble beaches are more common in higher latitudes than in the tropics where sandy beaches are a rule. The former is associated with high-energy wave environment and the latter with a swell environment. The Lebanese coast—measuring 225km—consists 61% of sandy beaches and 14% of gravel and pebbly beaches. Carbonate bedrocks cover the remaining 25% of the coast, where sea cliffs are frequent.
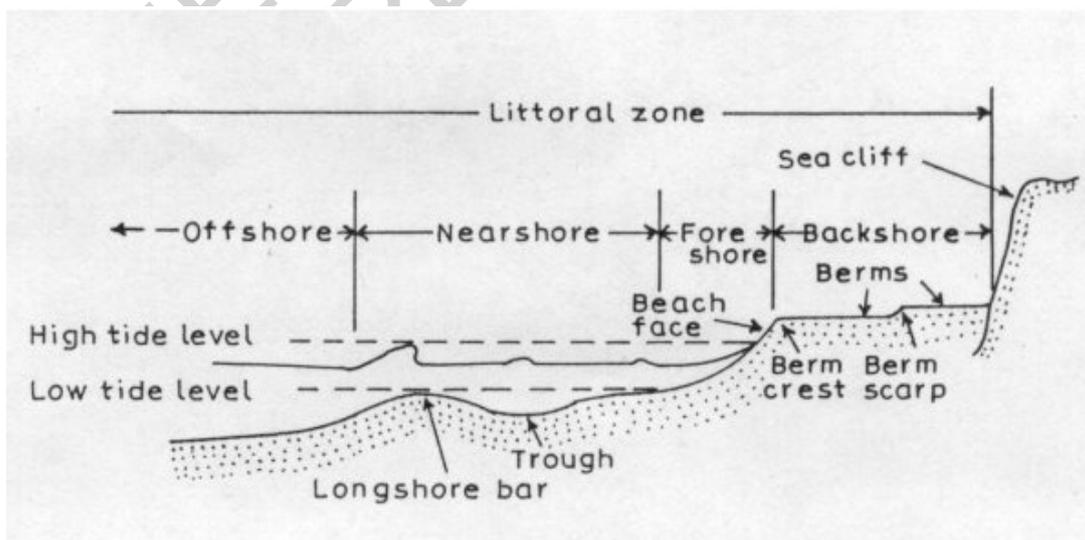

Figure 1. Terminologies used to describe beach and nearshore profiles

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