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COASTAL TOPOGRAPHY, HUMAN IMPACT ON

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Introduction

The trademark of humans throughout time is the modification of the natural landscape. Topography has been modified from the earliest farming to the modern modifications of nature for transportation and commerce (e.g., roads, utilities, mining), and often for recreation, pleasure, and esthetics. While human modifications of the environment have affected vast areas of the continents, and small portions of the ocean floor, nowhere have human intentions met headlong with nature's forces as in the coastal zone.

A most significant change in human behavior since the 1950s has been the dramatic, rapid increase in population and nonessential development in the coastal zone (**Figure 1**). The associated density of development is in an area that is far more vulnerable and likely to be impacted by natural processes (e.g., wind, waves, storm-surge flooding, and coastal erosion) than most inland areas. Not only are more people and development in harm's way, but the human modifications of the coastal zone (e.g., dune removal) have increased the frequency and severity of the hazards. Finally, coastal engineering as a means to combat coastal erosion and management of waterways, ports, and harbors has had profound and often deleterious effects on coastal environments. The endproduct is a total interruption of sediment interchange between land and sea, and a heavily modified topography. Natural hazard mitigation is now moving with a more positive, albeit small, approach by restoring natural features, such as beaches and dunes, and their associated interchangeable sediment supply.

The Scope of Human Impact on the Coast

The natural coastal zone is highly dynamic, with geomorphic changes occurring over several time scales. Equally significant changes are made by humans. On Ocean Isle, NC, USA, an interior dune ridge, the only one on the island, was removed to make way for development. The lowered elevation put the entire development in a higher hazard zone, with a corresponding greater risk for property damage from flooding and other storm processes.

Another example of change, impacting on property damage risk, can be seen in Kitty Hawk, North Carolina. A large shorefront dune once extended in front of the entire community. The dune was constructed in the 1930s by the Civilian Conservation Corps to halt shoreline erosion, and provide a 'protected' area along which to build a road. The modification was done before barrier island migration was understood. Erosion was assumed to be permanent land loss. The artificial dune actually increased

Figure 1 The coastal population explosion has resulted in too many people and buildings crowded too close to the shoreline. As sea level rises, the shoreline naturally moves back and encounters the immovable structures of human development. In this example from San Juan, Puerto Rico, erosion in front of buildings has necessitated engineering of the shoreline.

erosion here by acting as a seawall in a long-term sense, blocking overwash sand which would have raised island elevation and brought sand to the backside of the island, although the dune did afford some protection for development. As a consequence, buildings by the hundreds were built in the lee of the dune. Fifty years on, however, the price is being paid. During the 1980s, the dune began to deteriorate due to storm penetration, and the 1991 Halloween northeaster finished the job by creating large gaps in the dune, resulting in flooding of portions of the community. The dune cannot be rebuilt in place because the old dune location is now occupied by the beach, backed up against the frontal road. Between the time of dune construction and 1991, the community had only experienced major flooding once, in the great 1962 Ash Wednesday storm. Between 1991 and 2000, the community was flooded four times.

The effect of shoreline engineering on a whole-island system is starkly portrayed by the contrast between Ocean City, MD and the next island to the south, Assateague Island, MD. It has taken several decades to be fully realized, but the impact of the jetties is now apparent. Assateague Island has moved back one entire island width due to sand trapping by an updrift jetty. Similar stories abound along the coast. The Charleston lighthouse, once on the backside of Morris Island, SC, now stands some 650 m at sea; a sentinel that watched Morris Island rapidly migrate away after the Charleston Harbor jetties, built in 1898, halted the supply of sand to the island (**Figure 2**).

Human alterations of the natural environment have direct and indirect effects. Some types of human modifications to the coastal environment include: (1) construction site modification, (2) building and infrastructure construction, (3) hard shoreline stabilization, (4) soft shoreline stabilization, and (5) major coastal engineering construction projects for waterway, port, and harbor management and inlet channel alteration. Each of the modification types impacts the coastal environment in a variety of ways and also has several direct and indirect effects. Some of the effects are obvious and intuitive, but many are surprising in that there can be a domino effect as one simple modification creates potential for damage and destruction by increasing the frequency and intensity of natural hazards at individual sites.

Construction Site Modification

Building sites are often flattened and vegetation is removed for ease of construction. Activities such as grading of the natural coastal topography include dune and forest removal. Furthermore, paving of large areas is common, as roads, parking lots, and driveways are constructed. Direct effects of building site modification, in addition to changes in the natural landform configuration, include demobilization of sediment in some places by paving and building footpaths, but also sediment mobilization by removal of vegetation. In either case, rates of onshore–offshore sediment transport and storm-recovery capabilities are changed, which can increase or decrease erosion rates as sediment supply changes.

Other common site modifications include excavating through dunes (dune notching) to improve beach access or sea views. This is particularly common at the ends of streets running toward the beach. After Hurricane Hugo in South Carolina in 1989, shore-perpendicular streets where dunes were notched at their ocean termini were seen to have acted as storm-surge ebb conduits, funneling water back to the sea and increasing scour and property damage. The same effect was noted after Hurricane Gilbert along the northern coast of the Yucatán Peninsula of Mexico in 1988.

Building and Infrastructure Construction

A variety of buildings are constructed in the coastal zone, ranging from single-family homes to high-rise hotels and commercial structures. Some of the common direct effects of building construction are alteration of wind patterns as the buildings themselves interact with natural wind flow, obstruction of sediment movement, marking the landward limit of the beach or dune, channelizing storm surge and

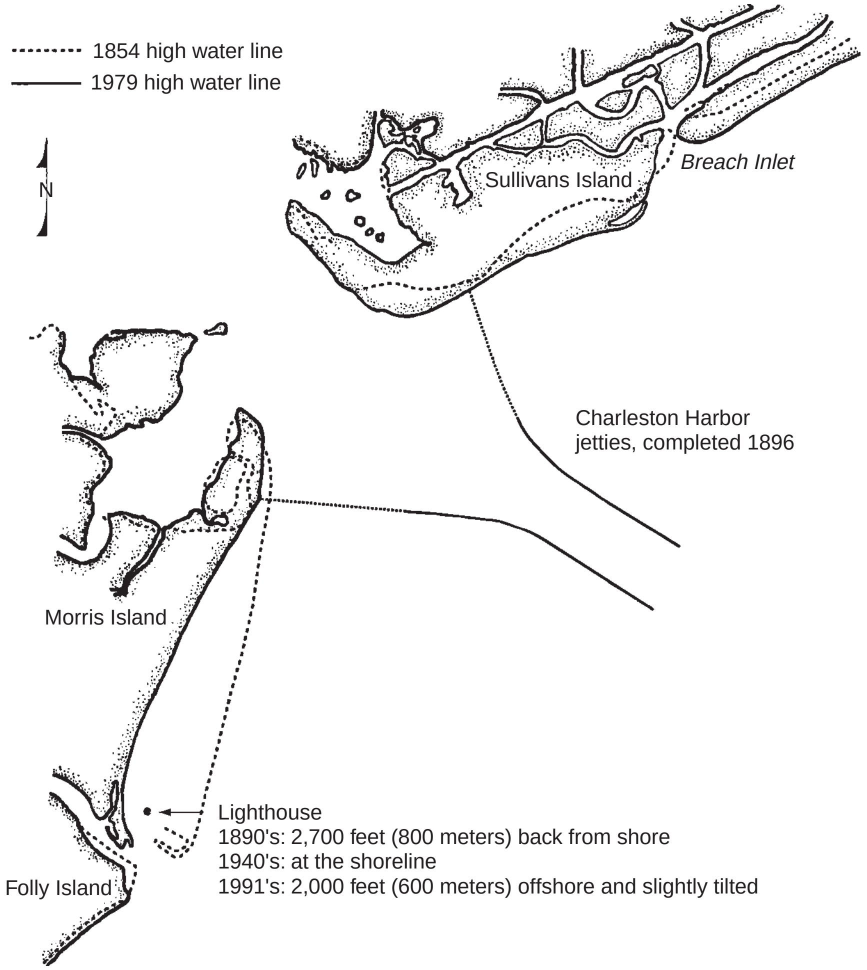

Figure 2 The jetties that stabilize Charleston Harbor, South Carolina, were completed in 1896. The jetties block the southward transport sediment along the beach. As a result, the islands to the north of the jetties have grown seaward slightly, but the islands to the south of the inlet have eroded back more than 1400 m. The Morris Island lighthouse, once on the back side of the island, is now 650 m offshore.

storm-surge ebb flow, and reflection of wave energy. Indirect effects result from the simple fact that once there is construction in an area, people tend to want to add more construction, and to increase and improve infrastructure and services. As buildings become threatened by shoreline erosion, coastal engineering endeavors begin.

Roads, streets, water lines, and other utilities are often laid out in the standard grid pattern used inland, cutting through interior and frontal dunes instead of over and around coastal topography (**Figure 3**). Buildings block natural sediment flow (e.g., overwash) while the ends of streets and gaps between rigid buildings funnel and concentrate flow, accentuating the erosive power of flood waters. As noted above, during Hurricane Hugo, water, sand, and debris were carried inland along shore-perpendicular roads in several South Carolina communities. Storm-surge ebb along the shore-perpendicular roads caused scour channels, which undermined roadways and damaged adjacent houses and property. Even something as seemingly harmless as buried utilities may cause a problem as the excavation disrupts the substrate, resulting in a less stable topography after post-construction restorations.

Plugging dune gaps can be a part of nourishment and sand conservation projects. Because dunes are critical coastal geomorphic features with respect to property damage mitigation, they are now often protected, right down to vegetation types that are critical to dune growth. Prior to strict coastal-zone management regulations, however, frontal dunes were often excavated for ocean views or building sites, or notched at road termini for beach access. These artificially created dune gaps are exploited by waves and storm-surge, and by storm surge ebb flows. Wherever dune removal for development has occurred, the probability is increased for the

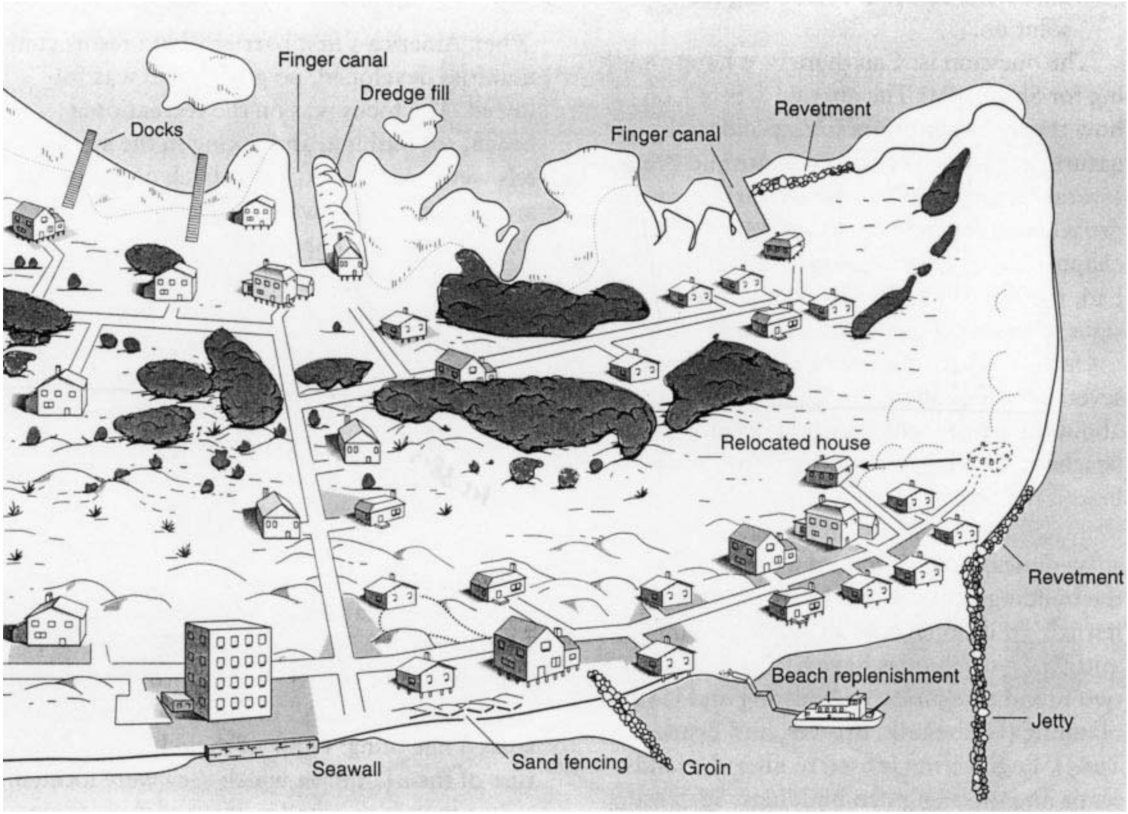

Figure 3 A compilation of many of the impacts humans have on the coastal topography. In this fictional barrier island, roads have been cut through excavated dunes, maritime forest removed for building sites, finger canals dredged, structures built too close to the water, and several types of coastal engineering projects undertaken.

likelihood of complete overwash and possible inlet formation.

Hard Shoreline Stabilization

Hard shoreline stabilization includes various fixed, immovable structures designed to hold an eroding shoreline in place. Hard stabilization is one of the most common modifiers of topography in the coastal zone and is discussed in more detail below. Seawalls, jetties, groins, and offshore breakwaters interrupt sediment exchange and reduce shoreline flexibility to respond to wave and tidal actions. Armoring the shoreline changes the location and intensity of erosion and deposition. Indirectly, hard shoreline stabilization gives a false sense of security and encourages increased development landward of the walls, placing more and more people and property at risk from coastal hazards including waves, storm surge, and wind. Eventual loss of the recreational beach as shoreline erosion continues and catches up with the static line of stabilization is almost a certainty. In addition, structures beget more structures as small walls or groins are replaced by larger and larger walls and groins.

Soft Shoreline Stabilization

The most common forms of soft shoreline stabilization are beach nourishment, dune building, sand fencing, beach bulldozing (beach scraping), and planting of vegetation to grow or stabilize dunes. Direct effects of such manipulations are changes in sedimentation rates and severity of erosion, and interruption of the onshore–offshore sediment transfer, similar in that respect to hard shoreline stabilization. Indirectly, soft shoreline stabilization may make it more difficult to recognize the severity of an erosion problem, i.e., ‘masking’ the erosion problem. Moreover, as with hard shoreline stabilization, development is actually encouraged in the high-hazard zone behind the beach.

Coastal Engineering Construction Projects

The construction of harbors, port facilities, waterways (e.g., shipping channels, canals) and inlet channel alterations significantly change the coastal outline as well as eliminating land topographic features or erecting artificial shorelines and dredge spoil banks. The Intracoastal Waterway of the Atlantic and Gulf Coasts is one of the longest artificial coastal modifications in the world. Large harbors in many places around the world represent significant alteration of the landscape. Many examples of coastal fill or artificial shorelines exist, but one of the best examples of such a managed shoreline is Chicago's 18 miles of continuous public waterfront. Major canals such as the Suez, Panama, Cape Cod, or Great Dismal Swamp Canal also represent major modifications in the coastal zone. The Houston Ship Channel made the city of Houston, Texas, a major port some 40 miles from the Gulf of Mexico.

Tidal inlets, either on the mainland or between barrier islands, can be altered by dredging, relocation, or artificial closure. Direct effects of dredging tidal inlets are changes in current patterns, which may change the location and degree of erosion and deposition events, and prevention of sand transfer across inlets. In either case, additional shoreline hardening is a common response.

The Scope of Coastal Engineering Impacts

Between 80 and 90% of the American open-ocean shoreline is retreating in a landward direction because of sea-level rise and coastal erosion. Because more static buildings are being sited next to this moving and constantly changing coastline, our society faces major problems. Various coastal engineering approaches to dealing with the coastal erosion problem have been developed (**Figure 3**). More than a century of experience with seawalls and other engineering structures in New Jersey and other coastal developments shows that the process of holding the shoreline in place leads to the loss of the beach, dunes, and other coastal landforms. The real societal issue is how to save both buildings and beaches. The action taken often leads to modifications to the coast that limit the natural flexibility of the coastal zone to respond to storms, that inhibit the natural onshore–offshore exchange of sand, and that interrupt the natural alongshore flow of sand.

Seawalls

Seawalls include a family of coastal engineering structures built either on land at the back of the beach or on the beach, parallel to the shoreline. Strictly defined, seawalls are free-standing structures near the surf-zone edge. The best examples are the giant walls of the northern New Jersey coast, the end result of more than a century of armoring the shoreline (**Figure 4**). If such walls are filled in behind with soil or sand, they are referred to as bulkheads.

Figure 4 Cape May, New Jersey has been a popular seaside resort since 1800. Several generations of larger and larger seawalls have been built as coastal erosion caught up with the older structures. Today in many places there is no beach left in front of the seawall.

Revetments, commonly made of piled loose rock, are walls built up against the lower dune-face or land at the back of the beach. For the purpose of considering their alteration of topography both at their construction site and laterally, the distinction between the types of walls is gradational and unimportant, and the general term seawall is used here for all structures on the beach that parallel the shoreline.

Seawalls are usually built to protect the property, not to protect the beach. Sometimes low seawalls are intended only to prevent shoreline retreat, rather than to block wave attack on buildings. Seawalls are successful in preventing property damage if built strongly, high enough to avoid being overtopped, and kept in good repair. The problem is that a very high societal price is paid for such protection. That price is the eventual loss of the recreational beach and steepening of the shoreface or outer beach. This is why several states in the USA (e.g. Maine, Rhode Island, North Carolina, South Carolina, Texas, and Oregon) prohibit or place strict limits on shoreline armoring.

Three mechanisms account for beach degradation by seawalls. Passive loss is the most important. Whatever is causing the shoreline to retreat is unaffected by the wall, and the beach eventually retreats up against the wall. Placement loss refers to the emplacement of walls on the beach seaward of the high-tide line, thus removing part or all of the beach when the wall is constructed (**Figure 5**). Seawall placement was responsible for much of the beach loss in Miami Beach, Florida, necessitating a major beach nourishment project, completed in 1981. Active loss is the least understood of the beach

Figure 5 An example of placement loss in Virginia Beach, Virginia. The seawall was built out on the recreational beach, instantaneously narrowing the beach in front of the wall.

degradation mechanisms. Seawalls are assumed to interact with the surf during storms, which enhances the rate of beach loss. This interaction can occur in a number of ways including seaward reflection of waves, refraction of waves toward the end of the wall, and intensification of surf-zone currents.

By the year 2000, 50% of the developed shoreline on Florida's western (Gulf of Mexico) coast was armored, the same as the New Jersey coast. Similarly 45% of developed shoreline on Florida's eastern (Atlantic Ocean) coast was armored, in contrast to 27% for South Carolina, and only 6% of the developed North Carolina open-ocean shoreline. These figures represent the armored percentage of developed shorelines and do not include protected areas such as parks and National Seashores.

Shoreline stabilization is a difficult political issue because seawalls take as long as five or six decades to destroy beaches, although the usual time range for the beach to be entirely eroded at mid-to-high tide may be only one to three decades. Thus it takes a politician of some foresight to vote for prohibition of armoring. Another issue of political difficulty is that there is no room for compromise. Once a seawall is in place, it is rarely removed. The economic reasoning is that the wall must be maintained and even itself protected, so most walls grow higher and longer.

Groins and Jetties

Groins and jetties are walls or barriers built perpendicular to the shoreline. A jetty, often very long (thousands of feet), is intended to keep sand from flowing into a ship channel within an inlet and to reduce the cost of channel maintenance by dredging. Groins are much shorter structures built on straight stretches of beach away from inlets. Groins are intended to trap sand moving in longshore currents. They can be made of wood, stone, concrete, steel, or fabric bags filled with sand. Some designs are referred to as T-groins because the end of the structure terminates in a short shore-parallel segment.

Both groins and jetties are very successful sand traps. If a groin is working correctly, more sand should be piled up on one side of the groin than on the other. The problem with groins is that they trap sand that is flowing to a neighboring beach. Thus, if a groin is growing the topographic beach updrift, it must be causing downdrift beach loss. Per Bruun, past director of the Coastal Engineering program at the University of Florida, has observed that, on a worldwide basis, groins may be a losing proposition, i.e. more beach may be lost than gained by the use of groins. After one groin is built, the increased rate of erosion effect on adjacent beaches has to be addressed. So other groins are constructed, in self-defense. The result is a series of groins sometimes extending for miles (**Figure 6**). The resulting groin field is a saw-toothed beach in plan view.

Groins fail when continued erosion at their landward end causes the groin to become detached, allowing water and sand to pass behind the groin. When detachment occurs, beach retreat is renewed and additional alteration of the topography occurs.

Jetties, because of their length, can cause major topographic changes. After jetty emplacement, massive tidal deltas at most barrier island inlents will be dispersed by wave activity. In addition, major build-out of the updrift and retreat of the downdrift shorelines may occur. In the case of the Charleston, SC, jetties noted earlier, beach accretion occurred on the updrift Sullivans Island and Isle of Palms.

Offshore Breakwaters

Offshore breakwaters are walls built parallel to the shoreline but at some distance offshore, typically a few tens of meters seaward of the normal surf zone. These structures dampen the wave energy on the 'protected' shoreline behind the breakwater, interrupting the longshore current and causing sand to be deposited and a beach to form. Sometimes these deposits will accumulate out to the breakwater, creating a feature like a natural tombolo. As in the case of groins, the sand trapped behind breakwaters causes a shortage of sediment downdrift in the directions of dominant longshore transport, leading to additional shoreline retreat (e.g. beach and dune loss, scarping of the fastland, accelerated mass wasting).

Figure 6 A groin field along Pawleys Island, South Carolina. Trapping of sand on the updrift side of a groin, and erosion of the beach on the downdrift side usually results in a sawtooth pattern to the beach. Note that in this example the beach is the same width on both sides of each groin, indicating little or no longshore transport of sand.

Beach Nourishment

Beach nourishment consists of pumping or trucking sand onto the beach. The goal of most communities is to improve their recreational beach, to halt shoreline erosion, and to afford storm protection for beachfront buildings. Many famous beaches in developed areas, in fact, are now artificial!

The beach or zone of active sand movement actually extends out to a water depth of 9–12 m below the low-tide line. This surface is referred to as the shoreface. With nourishment, only the upper beach is covered with new sand so that a steeper beach is created, i.e. the topographic profile is modified on land and offshore. This new steepened profile often increases the rate of erosion; in general, replenished beaches almost always disappear at a faster rate than their natural predecessors.

Beach scraping (bulldozing) should not be confused with beach nourishment. Beach sand is moved from the low-tide beach to the upper back beach (independent of building artificial dunes) as an erosion-mitigation technique. In effect this is beach erosion! A relatively thin layer of sand ($\leq 30\,\mathrm{cm}$) is removed from over the entire lower beach using a variety of heavy machinery (drag, grader, bulldozer, front-end loader) and spread over the upper beach. The objectives are to build a wider, higher, high-tide dry beach; to fill in any trough-like lows that drain across the beach; and to encourage additional sand to accrete to the lower beach.

The newly accreted sand in turn, can be scraped, leading to a net gain of sand on the manicured beach. An enhanced recreational beach may be achieved for the short term, but no new sand has been added to the system. Ideally, scraping is intended to encourage onshore transport of sand, but most of the sand ‘trapped’ on the lower beach is brought in by the longshore transport. Removal of this lower beach sand deprives downdrift beaches of their natural nourishment, steepens the beach topographic profile, and destroys beach organisms.

Dune building is often an important part of beach nourishment design, or it may be carried out independently of beach nourishment. Coastal dunes are a common landform at the back of the beach and part of the dynamic equilibrium of barrier beach systems. Although extensive literature exists about dunes, their protective role often is unknown or misunderstood. Frontal dunes are the last line of defense against ocean storm wave attack and flooding from overwash, but interior dunes may provide high ground and protection against penetration of overwash, and against the damaging effects of storm-surge ebb scour.

Human Impact on Sand Supply

In most of the preceding discussion the impact of humans on beaches and shoreline shape and position was emphasized. The beach plays a major role in supplying sand to barrier islands and, in fact, is important in supplying sand and gravel to any kind of upland, mainland, or island. In this sense, any topographic modification, however small, that affects the sand supply of the beach will affect the topography. In beach communities, sand is routinely removed from the streets and driveways after storms or when sand deposited by wind has accumulated to an uncomfortable level for the community. This sand would have been part of the island or coastal evolution process. Often, dunes are replaced by flat, well-manicured lawns. Sand-trapping dune vegetation is often removed altogether.

The previously mentioned Civilian Conservation Corps construction of the large dune line along almost the entire length of the Outer Banks of North Carolina is an example of a major topographic modification that had unexpected ramifications, namely the increased rate of erosion on the beach as well as on the backside of the islands. Prior to dune construction, the surf zone, especially during storms, expended its energy across a wide band of island surface which was overwashed several times a year. After construction of the frontal dune, wave energy was expended in a much narrower zone, leading to increased rates of shoreline retreat, and overwash no longer nourished the backside of the island. Now that the frontal dune is deteriorating, North Carolina Highway-12 is buried by overwash sand in a least a dozen places 1–4 times each year. Overwash sand is an important part of the island migration process, because these deposits raise the elevation of islands, and when sediment extends entirely across an island, widening occurs. If not for human activities, much of the Outer Banks would be migrating at this point in time, but because preservation of the highway is deemed essential to connect the eight villages of the southern Outer Banks, the NC Department of Transportation removes sand and places it back on the beach. As a result, the island fails to gain elevation.

Inlet formation also is an important part of barrier island evolution. Each barrier island system is different, but inlets form, evolve, and close in a manner to allow the most efficient means of moving water in and out of estuaries and lagoons. Humans interfere by preventing inlets from forming, by closing them after they open naturally (usually during storms), or by preventing their natural migration by construction of jetties. The net result is clogging of navigation channels by construction of huge tidal deltas and reduced water circulation and exchange between the sea and estuaries.

Globally shoreline change is being affected by human activity that causes subsidence and loss of sand supply. The Mississippi River delta is a classic example. The sediment discharge from the Mississippi River has been substantially reduced by upstream dam construction on the river and its tributaries. Large flood-control levees constructed along the lower Mississippi River prevent sediment from reaching the marshes and barrier islands along the rim of the delta in the Gulf of Mexico. Natural land subsidence caused by compaction of muds has added to the problem by creating a rapid (1–2 m per century) relative sea-level rise. Finally, maintaining the river channel south of New Orleans has extended the river mouth to the edge of the continental shelf, causing most remaining sediment to be deposited in the deep sea rather than on the delta. The end result is an extraordinary loss rate of salt marshes and very rapid island migration. The face of the Mississippi River delta is changing with remarkable rapidity.

Other deltas around the world have similar problems that accelerate changes in the shape of associated marshes and barrier islands. The Niger and Nile deltas have lost a significant part of their sediment supply because of trapping sand behind dams. Land loss on the Nile delta is permanent and not just migration of the outermost barrier islands. On the Niger delta the lost sediment supply is compounded by the subsidence caused by oil, gas, and water extraction. The barrier islands there are rapidly thinning.

Sand mining is a worldwide phenomenon whose quantitative importance is difficult to guage. Mining dunes, beaches, and river mouths for sand has reduced the sand supply to the shoreface, beaches, and barrier islands. In developing countries beach-sand mining is ubiquitous, while in developed countries beach and dune mining often is illegal and certainly less extensive, although still a problem. For example, sand mining has adversely affected the beaches of many West Indies nations going through the growing pains of development. Dune mining has been going on for so long that many current residents cannot remember sand dunes ever being present on the beaches, although they must have been there at one time, given the sand supply and the strong winds. For example, on the dual-island nation of Antigua and Barbuda, beach ridges – evidence of accumulating sand – can be observed on Barbuda, but are missing on Antigua. The beach ridges of Barbuda have survived to date only because it is much less heavily developed and populated. Sadly, Barbuda's beach ridges are being actively mined.

Puerto Rico is a heavily developed Caribbean island, much larger than Antigua or Barbuda, and with a more diversified economy. Many of Puerto Rico's dunes have been trucked away (**Figure 7**). East of the capital city of San Juan, large sand dunes were mined to construct the International Airport at Isla Verde by filling in coastal wetlands. As a result of removing the dunes, the highway was regularly overwashed and flooded during even moderate winter storms. First an attempt was made to rebuild the dune, then a major seawall was built to protect the lone coastal road.

Figure 7 The dunes here near Camuy, Puerto Rico, used to be over 20 m high. After mining for construction purposes, all that remains is a thin veneer of sand over a rock outcrop.

Dredging or pumping sand from offshore seems like a quick and simple solution to replace lost beach sand; however, such operations must be considered with great care. The offshore dredge hole may allow larger waves to attack the adjacent beach. Offshore sand may be finer in grain size, or it may be composed of calcium carbonate, which breaks up quickly under wave abrasion. In all of these cases, the new beach will erode faster than the original beach. Dredging also may create turbidity that can kill bottom organisms. Offshore, protective reefs may be damaged by increased turbidity. Loss of reefs will mean faster beach erosion, as well as the obvious loss to the fishery habitat.

Sand can also be brought in from land sources by dump truck, but this may prove to be more expensive. Sand is a scarce resource, and beaches/dunes have been regarded as a source for mining rather than areas that need artificial replenishment. Past beach and dune mining may well be a principal cause of present beach erosion. In some cases, gravel may be better for nourishment than sand, but the recreational value of beaches declines when gravel is substituted.

Sand mining of beaches and dunes accounts for many of Puerto Rico's problem erosion areas. Such sand removal is now illegal, but permits are given to remove sand for highway construction and emergency repair purposes. However, the extraction limits of such permits are often exceeded – and illegal removal of sand for construction aggregate continues. In all cases, the sand removal eliminates natural shore protection in the area of mining, and robs from the sand budget of downdrift beaches, accelerating erosion. Even a small removal operation can set off a sequence of major shoreline changes.

The Caribe Playa Seabeach Resort along the south-eastern coast illustrates just such a chain reaction. Located west of Cabo Mala Pascua, the resort has lost nearly 15 m of beach in recent years according to the owner. The problem dates to the days before permits and regulation, when an updrift property owner sold beach sand for 50 cents per dump truck load; a bargain by anyone's standards but a swindle to downdrift property owners. Where the sand was removed the beach eroded, resulting in shoreline retreat and tree kills. In an effort to restabilize the shore, and ultimately protect the highway, a rip-rap groin and seawall were constructed. Today, only a narrow gravel beach remains. Undoubtedly much of the aggregate in the concrete making up the buildings lining the shore, and now endangered by beach erosion, was beach sand. What extreme irony: taking sand from the beach to build structures that were subsequently endangered by the loss of beach sand.

Conclusion

The majority of the world's population lives in the coastal zone, and the percentage is growing. As this trend continues, the coastal zone will see increased impact of humans as more loss of habitats, more inlet dredging and jetties, continued sand removal, topography modification for building, sand starvation from groins and jetties, and the increased tourism and industrial use of coasts and estuaries. Our society's history illustrates the impact of humans as geomorphic agents, and nowhere is that fact borne out as it is in the coastal zone. The ultimate irony is that many of the human modifications on coastal topography actually decrease the esthetics of the area or increase the potential hazards.

See also

Beaches, Physical Processes Affecting. Coastal Zone Management. Sandy Beaches, Biology of. Viral and Bacterial Contamination of Beaches.

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COASTAL TRAPPED WAVES

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Introduction

Many shelf seas are dominated by shelf-wide motions that vary from day to day. Oceanic tides contribute large coastal sea-level variations and (on broad shelves) large currents. Atmospheric pressure and (especially) winds generate storm surges; strong currents and large changes of sea level. Other phenomena on these scales are wind-forced upwelling, along-slope currents and poleward undercurrents common on the eastern sides of oceans, responses to oceanic eddies, and alongshore pressure gradients.

All these responses depend on natural waves that travel along or across the continental shelf and slope. These waves, which have scales of about one to several days and tens to hundreds of kilometers according to the width of the continental shelf and slope, are the subject of this article. Also included are 'Kelvin' waves, also coastally trapped, that travel cyclonically around ocean basins but with typical scales of thousands of kilometers both alongshore and for offshore decrease of properties.

The waves have been widely observed through their association with the above phenomena. In fact they have been identified along coastlines of various orientations and all continents in both the Northern and Southern Hemispheres. Typically, the identification involves separating forced motion from the accompanying free waves. The 'lowest' mode with simplest structure (see below) has been most often identified; its peak coastal elevation is relatively easily measured. More complex forms need additional offshore measurements (usually of currents) for identification. This has been done (for example) off Oregon, the Middle Atlantic Bight and New South Wales (Australia). Observations substantiate many of the features described in the following sections.

Formulation

Analysis is based on Boussinesq momentum and continuity equations for an incompressible sea of near-uniform density between a gently-sloping seafloor $z = -h(\mathbf{x})$ and a free surface $z = \eta(\mathbf{x}, t)$ where the surface elevation $\eta = 0$ for the sea at rest. Cartesian coordinates $\mathbf{x} \equiv (x, y), z$ (vertically up) rotate with a vertical component $f/2$. The motion, velocity components (u, v, w), is assumed to be nearly horizontal and in hydrostatic balance. (These assumptions are almost always made for analysis on these scales; they are probably not necessary but certainly simplify the analysis.) At the surface, pressure and stress match atmospheric forcing (for free waves). There is no component of flow into the seabed (generalizing to zero onshore transport uh at the coast); $u \to 0$ far from the coast (the trapping condition) or is specified by forcing.