Coastal Land Loss

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Coastal Land Loss

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CONTENTS

INTRODUCTION

Two major phenomena are making coastal land loss an immediate problem for society. The first of these is the "rush to the shore"--the intense development of coastal areas since World War II. Tens of thousands of vacation homes have been built, the closer to the sea the better (Figure 1). This intensified shorefront development is occurring worldwide, fueled by a combination of population pressures and, in some countries, unprecedented individual wealth and prosperity.

The increased production of carbon dioxide from burning fossil fuels has resulted in the second major cause of coastal land loss, the greenhouse effect. The dramatic rise in sea level expected within the next century will lead to serious land loss problems.

Fig. 1. Construction workers fishing in the surf zone on the day a condominium was topped off (roof put in place) in Garden City, South Carolina. The photograph was published on February 21, 1985. The seawall was destroyed on January 1, 1987 as the result of a northeaster.

Thus shorelines are retreating just when the number of shorefront buildings is increasing. Because of shorefront construction, the shoreline retreat problem has become a shoreline erosion problem. Shoreline retreat is a purely natural phenomenon while shoreline erosion is purely anthropogenic. Unfortunately, few societies are capable of generating much concern and particularly much funding for a phenomenon only vaguely defined and not entirely agreed upon by the ever-contentious scientific community. Making an immediate societal response even more unlikely is the fact that present models of the greenhouse effect indicate that the expected acceleration in sea level rise is still at least two decades away.

Geologists recognize that the cause of land loss is far more complex than sea level rise. For example, the sediment supply to the beaches on many of the more steeply dipping shorelines has been strongly affected by upstream dam construction, which cuts off the influx of fresh sand normally accompanying river floods. This effect is dramatically illustrated on the Mississippi River delta, which will be discussed in this volume. Numerous other factors cause land loss as well. For example, stream channelization, levee construction, various agricultural practices, and paving and urbanization all affect shoreline sediment supply. More directly, construction of seawalls, groins, offshore breakwaters, and perhaps most important of all, jetties, strongly affects the longshore distribution of sediment already in the beach system.

Coastal geology, a field almost unrecognized two decades ago, is coming to the forefront of environmental geology. The reasons for its increasing prominence are manifold, but the expected acceleration in sea level rise and the attendant increase in shoreline erosion rates is the major one. Coastal geology, coastal engineering, and coastal geography are interrelated fields. Depending on the local situation, professionals from any of these specialties may be called upon to devise a long-term shoreline management scheme, to design shoreline stabilization structures, to predict the long-term environmental effect of such structures, and to monitor the actual effects of shoreline management techniques.

Geologists are the best qualified to examine problems relating to the sand transport system. But the basic concepts regarding sand transportation, such as the Bagnold equations, were derived to explain the occurrence and characteristics of various types of sedimentary rocks. A quantitative description of the sedimentary processes leading to the formation of sedimentary rocks is set in a time frame very different from a description of sediment processes affecting shoreline position and beach width that would be of use to the political system of a shorefront community. In the first instance, answers need to be framed in a context of millions of years; in the second, the time span is at most a few decades long. Bridging the gap between these temporal requirements is a major chore facing coastal geologists.

Geographers are generally concerned with the coastal management implications of shoreline processes and with evaluating a broad range of economic, political, and environmental implications of various shoreline management alternatives. Engineers are presumed to be the best qualified to design various shoreline stabilization schemes, ranging from seawall construction to beach replenishment to building relocation. However, the distinction between these specialties has blurred considerably and probably will continue to do so. An understanding of shallow-water physical oceanography, the general principles of coastal engineering, the politics of shoreline management, the economics of shorefront development, and even a basic understanding of the biological system of nearshore waters must be in the repertoire of the next generation of coastal geologists.

This short course will not make an expert coastal geologist out of any participant. However, we do hope to introduce a wide range of coastal problems that the four of us have faced at one time or another. The home base of each of the instructors is on a different type of shoreline. One of the most solid (and one of the most frequently ignored) principles of coastal geology is that each coastal type is different. What works on a barrier island may not work on a rocky coast; what works on a New Jersey barrier island may not work on a Florida barrier island. Principles of shoreline behavior useful on one type of coast may have little application elsewhere.

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SOCIAL IMPLICATIONS OF LAND LOSS

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Introduction

The National Research Council (NRC) [1987] and the U.S. Environmental Protection Agency (EPA) [Hoffman et al., 1983; Barth and Titus, 1984; Titus, 1988a] have predicted that the shores of the United States will be subjected to an increase in sea level of over 2 m by the year 2100 (Figure 2). This dramatic rise in sea level will drastically affect coastal areas and put inhabitants at extreme risk. Since World War II, a tremendous portion of the U.S. population has moved to the coast, and this migration continues today. An enormous infrastructure supporting the socioeconomic and environmental foundation of the nation is tied to current sea level conditions. Much of this newly developed coastal zone lies below the 2-m contour line; as a consequence, a 1-m rise in sea level will result in the loss of about 36,260 km^2 of dry and wet land (J. G. Titus, U.S. Environmental Protection Agency, unpublished report, 1988). EPA estimates that it will cost $140,000 per acre to protect just the developed areas, which account for 7% of the total predicted area of loss or about $1,960 million. This paper reviews some of the potential socioeconomic and environmental impacts of the forecast sea level rise.

Socioeconomic Impacts

Flood Control and Drainage

Low-lying coastal areas will be subject to increased flooding as sea level rises. The 50- to 100-year flood zones will be pushed landward, to communities not previously affected by these conditions. Zoning and flood-hazard codes will have to be constantly revised. More important from the public safety standpoint is that flood protection structures built for a specific flood elevation will provide less and less protection. This will hold true for drainage systems as well; they will have to be overhauled and new ones built.

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Water Supply

Saltwater intrusion will cause the quality of the drinking water to deteriorate in low-lying coastal areas that rely on surface drainage for drinking water. In some cases the high sodium content will make the water hazardous to drink. This has already occurred in parts of Louisiana where the current relative sea level rise rates exceed 1 m per century. In Terrebonne Parish, which draws its drinking water from tidal bayous, the EPA has notified the local government that drinking the water is dangerous for citizens suffering from hypertension and heart diseases. Saltwater intrusion will also damage estuarine habitats, and some shallow aquifers may be recharged by salt water.

Urban-Suburban Infrastructure

The coastal cities and towns of the U.S. Atlantic and Gulf coasts have built a vast infrastructure of industrial, residential, and commercial facilities. Most of this development lies below the 2-m contour. Airports of many coastal cities are constructed on landfill in bays with levees. A 1-m rise in sea level would severely disrupt air service and will eventually force costly relocation of the airports. Breakwaters, seawalls, jetties, piers, wharves, dry docks, and wet docks will face increasing storm impacts and flooding. Maintenance costs will increase and eventually economics will dictate abandonment of the structures and construction of new ones. Other considerations include the impacts of rising sea level on power plants, hotels, malls, residential centers, and urban centers.

Landfills and Waste Disposal Sites

Landfills and waste disposal sites pose a public health and safety hazard in low-lying areas. If sea level rises, these areas face direct overtopping and erosion. Changes in the hydrology of groundwater movement could result in the dispersal of potentially harmful and hazardous waste into the coastal zone. In Louisiana, for example, most of the coastal area lies below the 2-m contour, and unfortunately, it is also in this environment that some of the highest concentrations of hazard waste sites occur. Coastal Louisianians already face health risks associated with the extensive industry tied to the oil and gas infrastructure; the forecast sea level rise will exacerbate and spread these risks.

Environmental Impacts

The major environmental impact of the forecast sea level rise is the destruction of the nation's wetlands and barrier island systems. EPA predicts that from 22% to 56% of the nation's wetlands and barrier islands will be lost, depending on the amount of increase in sea level (Table 1). These

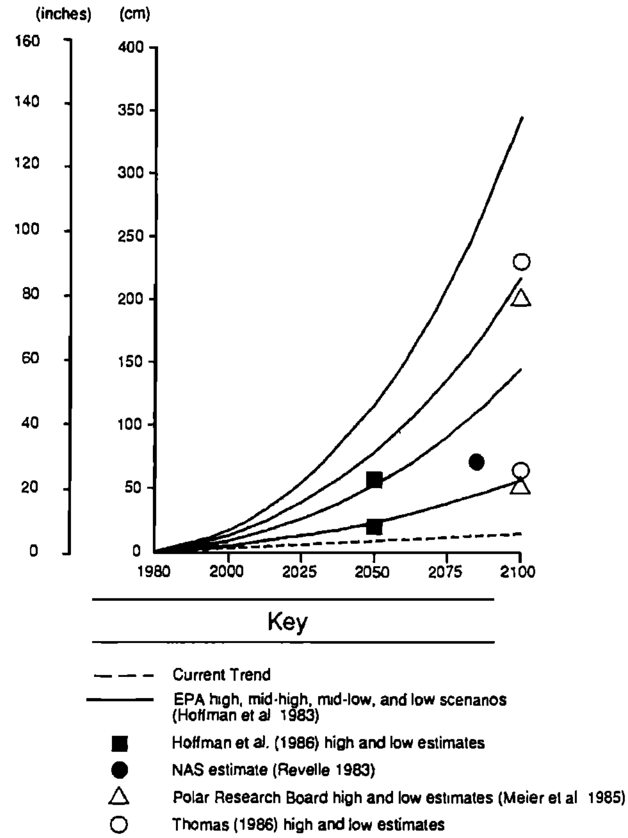

Fig. 2. Global sea level rise scenarios [Titus 1988].

coastal environments are critical to the environmental quality of the nation's coastal zone. They are barriers to hurricane storm surges and saltwater intrusion, and they act as filters that improve water quality in the coastal zone. These wetlands and barrier systems are renewable estuarine resources that support a diverse fishing industry. The state hardest hit by the predicted sea level rise may be Louisiana, where 80%-97% of the wetlands and barriers are predicted to be destroyed by the year 2100. As sea level rises, the marshes will gradually disappear, or, if the barrier island systems protecting them disappear, the marshes will decline precipitously.

Discussion

The United States and other countries will face dramatic physical alterations in their coastal areas if projected increases in future sea level are realized. The implication of these changes is that the quality of life in coastal areas will seriously decline over the next century. In addition, damages to infrastructure, residential and commercial development, and renewable estuarine resources of the coastal zone will have economic impacts that will reverberate through the national and global economics. How do we protect our society from these changes? Do we back off now from coastal areas? Do we retreat strategically? Or do we defend our current coastline as much as possible? Recent studies have concluded that we must evaluate and develop well-managed responses to the forecast conditions. The EPA [Titus, 1988] makes the following conclusions:

1. Along undeveloped coasts, a rise in sea level drowns the seaward wetlands and allows new wetlands to be created inland as formerly dry land is flooded. However, . . . the area . . . available for wetland creation is generally far smaller than the area of wetlands that would be lost.
2. Sea level rise could become a major cause of wetland loss throughout the coastal zone of the United States.
3. The coastal wetlands of Louisiana appear to be the most vulnerable to a rise in sea level.
4. The impact of sea level rise on coastal wetlands will depend in large measure on whether developed areas immediately inland of the marsh are protected from rising sea level by levees and bulkheads.
5. [Other] factors . . . could increase or decrease the vulnerability of wetlands to a rise in sea level.
6. Federal and state agencies responsible for wetland protection should now begin to determine how to mitigate the loss of wetlands from sea level rise.

TABLE 1. Changes in wetland areas between 1975 and 2100 (all areas in 10^3 hectares).

Region	1975 Marsh Area	Low Scenario Lost	Low Scenario Gained	Low Scenario Net	High Scenario Lost	High Scenario Gained	High Scenario Net
New England	6.0	0.2	0	-0.2	3.8	0	-3.8
Mid-Atlantic	45.4	17.7	8.9	-8.8	45.5	6.7	-38.8
South Atlantic	91.3	26.1	30.2	4.1	70.5	21.2	-49.3
Florida (subtropical)	59.8	0.2	17.4	17.2	24.1	16.0	-8.1
NE Gulf Coast	73.6	6.4	1.3	-5.1	21.6	2.4	-19.2
Mississippi Delta	150.9	121.1	0	-121.1	146.0	0	-146.0
Chenier Plain TX	29.9	10.9	6.8	-4.1	31.5	6.5	-25.0
Californian Prov.	26.5	9.1	8.9	-0.2	9.5	10.2	4.7
Columbian Prov.	1.2	0.1	11.6	11.5	0.3	12.4	12.1
TOTAL IN SAMPLE	484.6	191.8	85.1	-106.7	352.8	76.4	-272.4

SOURCE: Titus [1988].

7. The prospect of accelerated sea level rise does not decrease the need to implement existing wetland protection policies. [Titus, 1988, p. iii]

The National Research Council [1987] has convened a "Committee on Engineering Implications of Changes in Relative Mean Sea Level," which has made the following recommendations about coping with predictions of future sea level rise.

1. The prognosis for sea level rise should not be a cause for alarm or complacency. Long-term planning and policy development should explicitly consider the high probability of increased rates of sea level rise.
2. The . . . scenarios of sea level rise provide a useful range of possible future sea level changes for design calculations.
3. Practitioners can more readily incorporate the implications of sea level rise if probabilities reflecting uncertainties are attached to the projections.
4. Feasibility studies for coastal projects . . . should consider the high probability of accelerated sea level rise.
5. The federal government should acquire long-term reliable accurate data from a water-level measuring system for open-ocean stations at scientifically important locations throughout the world.
6. The important decision for maintaining or abandoning coastal facilities in the face of rising sea levels should be well documented by scientific knowledge. [NRC, 1987, p. 124-125]

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FACTORS AFFECTING LAND LOSS

It is difficult, if not impossible, to isolate and quantify all the specific causes of coastal land loss because of the great number of interacting variables (Figure 3). But despite these inherent limitations and uncertainties, investigators need to analyze both the major and minor influences at a given site to properly evaluate the potential factors and their interrelationships. The basis for future prediction comes from such evaluation.

Physical Agents

Waves, Currents, and Storms

Coastal land loss is largely a response to marine erosion, which is driven by the combined forces of waves and currents. Breaking waves weaken the shoreline by entraining sediments or dislodging rocks, while the longshore currents (wave-generated, wind-generated, tidal) transport the material from the site and deposit it elsewhere. In some areas, chemical solution and mechanical abrasion are important in the retreat of rocky headlands and some sea cliffs.

Intense storms (hurricanes, typhoons, northeasters) are not the only agents of coastal land loss, but they do represent the highest and most concentrated levels of energy affecting the coast. Furthermore, they are clearly responsible for the greatest short-term losses and perhaps most of the long-term losses on a global scale. During storms, high-velocity winds generate powerful waves and exceptionally strong nearshore currents that scour and transport enormous volumes of sediment during storm approach and landfall. Attendant land losses along the beach and adjacent areas depend on a number of variables, including distance from the storm center, angle wind velocities, forward speed of the storm, stage of astronomical tide, decrease in barometric pressure, and longevity of the storm [Morton, 1977].

Sediment Budget

Another important factor affecting land loss on sandy shores in the sediment budget. Quantitative estimates of all sediment sources and sinks are required to determine the sediment budget of a coastal compartment. Surpluses in sediment budget are expressed as land gains, whereas deficits are manifested as land loss. Sediment sources include major rivers and coastal-plain streams, onshore transport of shelf sand, and littoral drift. Updrift shoreline and shoreface erosion are

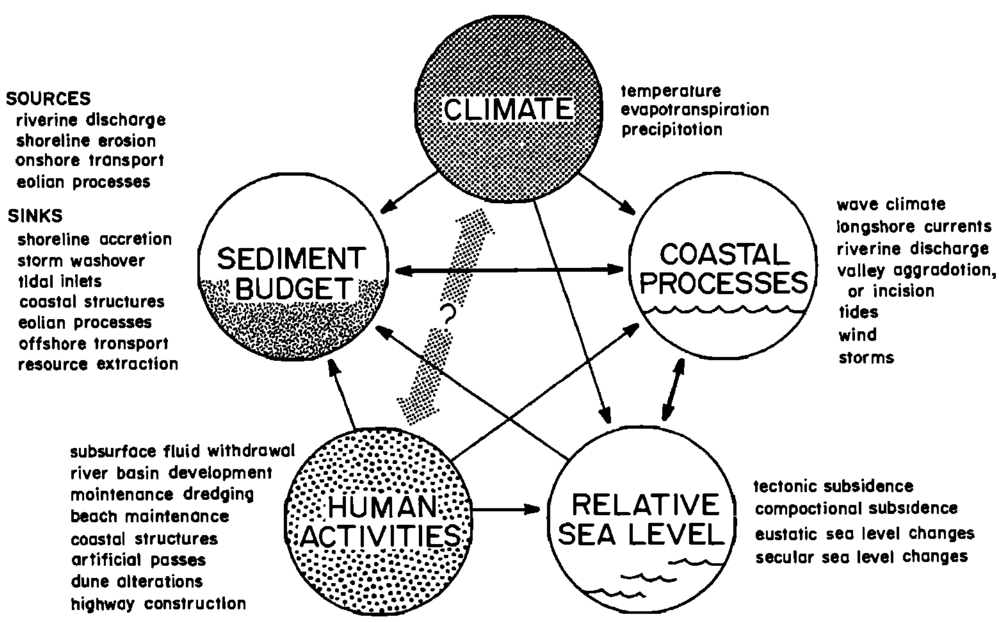

Fig. 3. Interaction of agents affecting land loss. Arrows point toward the dependent variables. The number of arrows originating from or terminating at a particular agent indicates the relative degree of independence or interaction. For example, human activities are independent of other agents, but they affect sediment budget, coastal processes, relative sea level conditions, and perhaps climate (from Morton [1977]).

probably the largest extant sources of sediment, but volumetric estimates must be reduced for those areas where the quantities of sand contributed by eroding clay substrates are not substantial in relation to the area eroded.

Sediment supplied by coastal rivers was undoubtedly important in the past, but natural decreases in sediment supply, river containment or diversion, and dam construction on many streams have drastically reduced peak discharge and sediment loads delivered to deltas and beaches. Landward transport of shelf sediment was also more important in the geological past and has probably diminished because of equilibration of the inner-shelf profile.

The most common sediment sinks include coastal dunes, tidal inlets, and storm washovers. Furthermore, during major storms some sand is transported to the continental shelf and deposited below fair-weather wave base or funneled into submarine canyons, where it is lost from the littoral drift system.

Relative Sea Level Rise

Land loss is commonly related to a rise in sea level because a minor vertical rise in sea level can cause considerable landward displacement of the shoreline. Of the four factors relevant to land-sea relationships (Figure 3), only two are of major importance. Tectonic forces are significant in some coastal areas, but in general sediment supply has greatly exceeded tectonic subsidence. Although eustatic rise has been documented [Lisitzin, 1974; Gornitz and Lebedeff, 1987], it is probably a moderate contributor to land loss, not only because it is difficult to define [Morner, 1980], but also because compactional subsidence and secular sea level variations are of greater magnitude. There is growing concern, however, that global warming of the atmosphere will cause thermal expansion of the oceans and possibly melting or disintegration of the West Antarctic ice sheet, which would cause a substantial rise in sea level [National Research Council, 1987].

Slope Failure

Landslides and active faults cause land loss in some coastal regions. Landslides occur where unstable slopes fail catastrophically and land is both lost and displaced downslope. Deep-water storm swells commonly undermine the toes of slopes and cause them to become oversteepened and eventually to slump in a retrogressive pattern. Where sea cliffs are prominent, land loss is largely attributable to landslides or rockfalls. On developed hills in coastal California, landslides are commonly triggered by overwatering, which increases the hydrostatic head and lubricates the detachment surfaces.

Coastlines submerged in conjunction with faulting occur in most of the active tectonic regions of the world, such as Japan, the Mediterranean Sea, the west coast of the United States, Australia, and some Pacific islands. Landslides and tsunamis associated with strong earthquakes also contribute to land loss in these areas.

Climate

Average annual temperatures and precipitation can indirectly influence land loss. For example, deep chemical weathering in humid tropical regions causes rapid decomposition of rocks and makes them more susceptible to erosion. In the colder climates of higher latitudes, repeated freezing and thawing along fractures and bedding planes contribute to mechanical weathering of exposed sea cliffs, and thawing of permafrost promotes loss of the tundra.

Because temperature was lower and precipitation was greater at the end of the Pleistocene than at present, the warmer and drier conditions that now prevail control other factors such as vegetal cover, upland runoff, sediment concentration, and sediment yield. Dury [1965] estimated that discharge for many early Holocene rivers was five to ten times greater than for the same rivers today. This greater discharge of mid- to low-latitude rivers supplied additional sediment to the littoral drift system. Droughts may indirectly affect land loss through their adverse impacts on vegetation and their influence on relative sea level. Vegetation weakened by droughts is less resistant to wave attack, and without healthy vegetation, sand is more easily removed from beaches by eolian processes. Many authors have described land loss accompanying relative sea-level rise, but little is known about the short-term effects of slightly lower water levels that occur periodically and are known as secular variations [Hicks, 1972]. White et al. [1978] demonstrated that water levels lowered by droughts can cause apparent gains in land where nearshore slopes are low.

Coastline Properties

Composition and Induration

Composition and induration of the coast are two of the most significant factors controlling land loss because they largely determine the erodibility of the coast. Erosion of unconsolidated sediments depends on their cohesiveness. For example, loose sand is more easily eroded than stiff marsh mud, and an exposed clay bluff that is weathered and spalls when moisture causes clay minerals to expand is more easily eroded than water-saturated mud near sea level. Obviously, hard crystalline rocks are extremely durable, and studies worldwide show that rocky coastlines at mid to high latitudes have not changed appreciably in recorded history [Shepard and Wanless, 1971; Bird and Schwartz, 1985].

Morphology

Vulnerability to marine erosion also depends on both profile and planar shape of the coastline. Tall sea cliffs exhibit the greatest disequilibrium with extant marine processes and therefore may be highly susceptible to wave attack and undercutting. On the other hand, depending on their composition, they can also be the most resistant to erosion.

Because wave refraction focuses wave energy on promontories, rocky headlands of highly irregular glaciated coasts are attacked more vigorously than long stretches of smooth sandy beaches. Orientation fetch and nearshore water depths are components of shoreline morphology that control the wave energy reaching the coast. Long fetches, steep nearshore profiles (relatively deep water), and an orientation normal to wave approach promote rapid land loss.

Vegetation

Some common coastal vegetation habitats are salt marshes, dunes, upland prairies, mangrove swamps, freshwater swamps, scrub thickets, and forests. The density and type of vegetative cover can influence land loss by dissipating the energy reaching the shoreline, encouraging the accumulation of sediment, or acting as a sediment binder that resists erosion.

Dense stands of salt marsh and mangrove pneumatophores commonly trap sediment or offer resistance to waves and currents so that land loss is prevented or mitigated. Dune grasses help stabilize blowing sand and can assist in dune enlargement, but the roots of grasses are generally too shallow to reduce erosion from large storm waves that lower the backbeach and undercut the dunes or uplands.

Human Activities

Coastal land losses indirectly caused by humans are difficult to quantify because human activities promote alterations and imbalances in the sediment budget, coastal processes, and relative sea level (Figure 3). Field data from around the world indicate that the three activities causing most anthropogenic land losses are coastal construction, fluid production, and resource extraction. Coastal construction includes a broad range of projects, such as freshwater reservoirs, navigation channels, erosion-control structures, and economic development involving dredge-and-fill activities. Dams, seawalls, groins, and jetties can act as partial or complete sediment traps that contribute to changes in quantity and type of beach material. Even beach scraping and vehicular traffic can contribute to overall changes though they are not controlling factors. Impermeable structures, navigation channels, and river basin development are responsible for the largest volumes of impounded sand along most coasts. These activities generally result in permanent losses to the sediment budget.

Except in Japan, Italy, Venezuela, the Gulf of Mexico, and southern California, extant land losses associated with subsurface fluid withdrawal appear to be minor. But continued withdrawal and concomitant decline in fluid pressure from hydrocarbon production and groundwater pumping could eventually cause more substantial decreases in surface elevations. This would augment the effects of relative sea level rise and lead to future land loss at or near the shoreline.

At present, resource extraction also appears to cause only minor land loss. Resource extraction in coastal areas includes mining beaches and barriers for heavy minerals and construction material (sand and gravel), mining peat for horticultural uses, and dredging reefs and bay-margin deposits for shell that is used as road material or in the manufacture of cement.

Building impermeable barriers, dredging canals and mosquito ditches, and mining sediments are all known to cause both immediate and long-term land loss, but it will be many years before the effects of other activities, such as dam construction, fluid production, and salt water intrusion, can be fully evaluated.

Discussion

Judging from relict river morphology and the widespread occurrence of beach ridges, sediment supply was abundant and accretion dominant in many coastal areas as sea level approached its present position. But the natural conditions that promoted shoreline accretion have ceased to be effective in the face of recent reductions in shelf supplies of sediment and marked decreases in riverine discharge, and as a result. many beach-ridge complexes are now eroding.

It seems highly improbable that human activities could be solely responsible for the erosion that is occurring on so many shorelines throughout the world. The uncertainty regarding human effects on regional shoreline changes stems from a lack of precise quantitative data for sediment budget and relative sea level conditions preceding human alterations. Furthermore, the hysteresis following human activities is poorly defined.

Available data suggest that long-term land loss in most coastal areas is largely due to natural (nonhuman) processes and conditions. The most recent historical changes, however, appear to be greatly influenced by human activities. The most evident human-induced coastal changes are the unpredictable but rapid local responses to engineering modifications. For example, the maximum sustained rates of accretion (+75 m/yr) and erosion (-55 m/yr) documented for the Texas coast were associated with jetty construction and subsequent channel diversion at the mouth of the Brazos River. Rates of coastal change at other sites altered by humans are less spectacular, but they are still well above average.

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