EROSION OF THE UNITED STATES SHORELINE

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ABSTRACT: Over 75 percent of the United States ocean shoreline is eroding (retreating landward). Shoreline progradation, where occurring, is generally assumed to be a temporary phenomenon. When affecting a developed area, shoreline retreat is usually termed *erosion*, but considerable confusion remains over the use of this term. *Retreat* and *progradation* refer to a change in shoreline position, whereas *erosion* and *accretion* refer to volumetric changes in the subaerial beach. As used in this paper, however, *erosion* refers to any form of shoreline retreat, consistent with common usage.

Coastal erosion is a fundamental and widespread process on U.S. and world shorelines. Evidence, particularly on barrier-island coasts, indicates that in the past few decades or millenia, erosion may have become a more widespread process. Possible causes of this change include the effect of humans, shoreface steepening, or an increase in the rate of eustatic sea-level rise.

Mechanisms responsible for shoreline erosion are highly variable, both temporally and geographically. In addition, our understanding of shoreline sediment-transport dynamics is incomplete. Consequently, we are presently unable to predict accurately future shoreline-retreat rates related to continued sea-level rise. The Bruun Rule, for example, predicts little shoreline retreat relative to using, as a predictive tool, the slope of the land surface over which sea level is expected to rise.

WHAT IS COASTAL EROSION?

Defining erosion in the coastal environment is difficult. Various terms are used to describe the process, including *drowning, coastal erosion, shoreline erosion, beach erosion, shoreline retreat, beach retreat,* and *shoreline recession*. Strictly speaking, *retreat* and *progradation* refer to a change in shoreline position; *erosion* and *accretion* refer to volumetric changes in the subaerial beach (Wood and others, 1988; Oertel and others, 1989). The term *beach erosion,* however, is deeply ingrained in the public lexicon to refer to any form of shoreline retreat (usually the change in position of the high-tide line); we shall here use it in the same broad sense as does the general public.

When dealing with shorelines and beaches, it is crucial to distinguish between *erosion* and an *erosion problem*. Many kilometers of undeveloped U.S. shoreline are eroding (retreating landward) and, as a rule, such locations are not considered to be societal problems. Erosion and retreat of the shoreline are, in fact, critically important processes in the evolution of Holocene coastal landforms. Estuaries, lagoons, spits, barrier islands, sea cliffs, and many other coastal landforms all owe their shape and depositional patterns to erosion, at least in part. It is only when humans interfere with or get in the way of shoreline erosion that it is recognized as a problem. A broad discussion of the U.S. coastal-erosion problem, along with methodology, political implications, and costs for mitigation is furnished by the National Research Council (1990).

U.S. SHORELINE-EROSION RATES

Erosion rates for the contiguous U.S. shoreline, based on data in the Coastal Erosion Information System (CEIS; May and others, 1982), have been compiled by May and others (1983) and Dolan and others (1985; Tables 1 and 2; Fig. 1). CEIS includes shoreline-change data for the Atlantic, Gulf of Mexico, Pacific and Great Lakes coasts, as well as for major bays and estuaries. The data in CEIS are drawn from a variety of sources, including published reports, historical shoreline-change maps, field surveys, and aerial-photograph analyses. However, the lack of a standard method among coastal scientists for analyzing shoreline changes has resulted in the inclusion of data utilizing a variety of reference features, measurement techniques, and rate-of-change calculations. Thus, whereas CEIS represents the best available data for the U.S. as a whole, much work is needed to document regional and local erosion rates accurately.

When examined in detail, such as on a state-by-state basis, the actual percentage of eroding shoreline is generally much higher than the coastwide averages shown in Figure 1 suggest. This discrepancy is likely due to the large amount of shoreline for which "no data" exist and the coarse resolution of CEIS. Dolan and others (1990b), for example, report that 78 percent of the Delaware shoreline is eroding; Maryland, 94 percent; Virginia, 72 percent; and North Carolina, 72 percent. Griggs (1987a) states that approximately 86 percent of the California shoreline is eroding.

WHY UBIQUITOUS EROSION?

Coastal erosion is a fundamental and widespread process not only on U.S. but also world shorelines. There is some evidence, however, that such has not always been the case. Examination of the U.S. barrier-island shoreline, for example, indicates that fundamental changes in depositional patterns have recently taken place. Many barrier islands are regressive, indicating that a seaward accretion or widening of the island occurred over the last 2 to 4 ka. Within the last several hundred years, however, a profound change has taken place and shoreline retreat has replaced shoreline progradation. In other words, barrier islands are becoming increasingly transgressive. Most regressive barrier islands (e.g., Bogue Banks, North Carolina, and Galveston Island, Texas) are now eroding on both the ocean and lagoon sides.

Possible explanations for increased worldwide erosion include the effects of humans—shoreline stabilization and river damming; sand supply reduction—shoreface steepening; and a recent increase in the rate of eustatic sea-level rise. However appealing, each of these possibilities leaves certain questions unanswered. For example, humans certainly contribute to coastal erosion in some locations, but completely undeveloped areas such as the barrier-island system on the Pacific coast of Colombia are also eroding at high rates.

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TABLE 1.—SHORELINE RATES OF CHANGE FOR REGIONS AND STATES

Region	Mean (m/yr)[1]	Standard Deviation	Range[1]
Atlantic Coast	−0.8	3.2	25.5/−24.6
Maine	−0.4	0.6	1.9/−0.5
New Hampshire	−0.5	—	−0.5/−0.5
Massachusetts	−0.9	1.9	4.5/−4.5
Rhode Island	−0.5	0.1	−0.3/−0.7
New York	0.1	3.2	18.8/−2.2
New Jersey	−1.0	5.4	25.5/−15.0
Delaware	0.1	2.4	5.0/−2.3
Maryland	−1.5	3.0	1.3/−8.8
Virginia	−4.2	5.5	0.9/−24.6
North Carolina	−0.6	2.1	9.4/−6.0
South Carolina	−2.0	3.8	5.9/−17.7
Georgia	0.7	2.8	5.0/−4.0
Florida	−0.1	1.2	5.0/−2.9
Gulf of Mexico	−1.8	2.7	8.8/−15.3
Florida	−0.4	1.6	8.8/−4.5
Alabama	−1.1	0.6	0.8/−3.1
Mississippi	−0.6	2.0	0.6/−6.4
Louisiana	−4.2	3.3	3.4/−15.3
Texas	−1.2	1.4	0.8/−5.0
Pacific Coast	0.0	1.5	10.0/−4.2
California	−0.1	1.3	10.0/−4.2
Oregon	−0.1	1.4	5.0/−5.0
Washington	−0.5	2.2	5.0/−3.9

[1]Positive values indicate accretion; negative values indicate erosion. (After Dolan and others, 1985.)

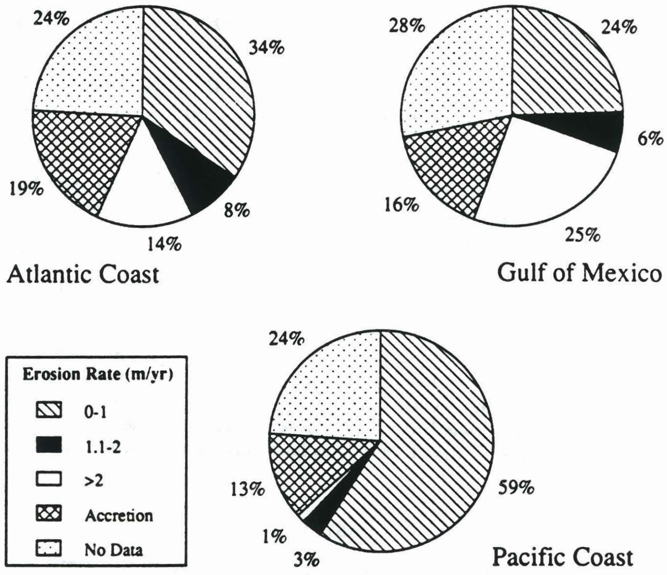

FIG. 1.—Pie charts of erosion rates on the U.S. open-ocean coastline. The large amount of shoreline classified as "no data" likely results in an artificially low figure for the total percentage of eroding shoreline (see text for discussion). (After Dolan and others, 1990a).

TABLE 2.—SHORELINE RATES OF CHANGE FOR COASTAL LANDFORM TYPES

Type/Region	Mean (m/yr)[1]	Standard Deviation	Range[1]
Barrier islands			
Atlantic Coast	−0.8	3.4	25.5/−24.6
Maine-New York	−0.3	2.6	4.5/−1.5
New York-North Carolina	−1.5	4.5	25.5/−24.6
North Carolina-Florida	−0.4	2.6	9.4/−17.7
Gulf of Mexico	−0.6	1.5	8.8/−4.3
Florida-Louisana	−0.5	1.7	8.8/−4.3
Louisiana-Texas	−0.8	1.2	0.8/−3.5
Sand beaches			
Atlantic Coast	−1.0	1.0	2.0/−4.5
Maine-Massachusetts	−0.7	0.5	−0.5/−2.5
Massachusetts-New Jersey	−1.3	1.3	2.0/−4.5
Gulf of Mexico	−0.4	1.6	8.8/−4.5
Pacific Coast	−0.3	1.0	0.7/−4.2
Sand beaches with rock headland	−0.3	1.9	10.0/−5.0
Pocket beaches			
Atlantic Coast	−0.5	—	−0.5/−0.5
Pacific Coast	−0.2	1.1	5.0/−1.1
Deltas	−2.5	3.5	8.8/−15.3
Mud flats			
Gulf of Mexico	−1.9	2.2	3.4/−8.1
Florida	−0.3	0.9	1.5/−1.5
Louisiana-Texas	−2.1	2.2	3.4/−8.1
Rock shorelines			
Atlantic Coast	1.0	1.2	1.9/−4.5
Pacific Coast	−0.5	—	−0.5/−0.5

[1]Positive values indicate accretion; negative values indicate erosion. (After Dolan and others, 1985.)

LOCAL FACTORS AFFECTING EROSION

On all types of sandy or unconsolidated coasts, beach erosion can be considered to be controlled by a dynamic equilibrium involving three major components: sediment supply, wave and tidal energy, and the position of, or changes in, sea level.

On barrier-island coasts, erosion rates must be examined in the context of the total barrier-island system. The concurrent development of transgressive and regressive barriers along the Texas coast, for example, is related to the longshore distribution of sediment sources and sinks (Morton, 1979; Nummedal, 1983).

Shoreline erosion on the Texas coast predominates at deltaic headlands, such as the Rio Grande and Brazos deltas. In the central portion of each embayment between the deltaic headlands, accretion or at least relatively slow erosion occurs (Morton, 1979). The eroding deltaic headlands are the source of sand for the accreting shoreline between river mouths.

Evolution of the Louisiana coast is similarly affected by regional-scale processes. Penland and others (1985) demonstrated a cyclic relation between Mississippi Delta lobe-switching events and barrier development and destruction. Extremely rapid shoreline-erosion rates prevail no matter what the stage of barrier development in this cycle. The high overall erosion rates are fundamentally due to subsidence-induced rapid rates of sea-level rise (0.50–1.00 cm/yr; Penland and others, 1985). However, the rates of shoreline recession, which vary from 5 to 15 m/yr (Penland and others, 1985), depend partly on the age of the individual barrier-island chains. Beaches on young barrier chains on the Mississippi Delta (e.g., Isles Dernieres) have relatively lower erosion rates because the sand supply (the eroding deltaic lobe) is close to sea level. As the lobe subsides, the sand source is effectively removed and shoreline-erosion rates increase.

Antecedent geology has also been shown to affect barrier development and hence shoreline-erosion rates. Barrier islands grounded on antecedent topographic features (e.g., Evans and others, 1985) may, at least temporarily, experience reduced erosion rates. In addition, the Holocene/Pleistocene stratigraphy underlying the barrier islands may play a major role in determining shoreline-erosion rates. Thick sequences of lagoonal or salt-marsh mud are responsible for the rapid shoreline-erosion rates of some islands along the Delmarva Peninsula (Demarest and Leatherman, 1985). The high beach-erosion rates are due to a combination of (1) ease of erosion of a muddy shoreface, and (2) a lack of sand contribution from the eroding shoreface (Demarest and Leatherman, 1985).

Waves associated with extratropical and tropical storms cause the most visible and obvious shoreline erosion, but often storm-caused erosion is substantially "repaired" by post-storm onshore and longshore sediment transport. Shoreline retreat may occur under both fairweather and storm conditions. The relative proportion of fairweather and storm retreat is not well documented, but it probably varies widely from beach to beach. In addition, different shorelines are adjusted to different wave climates. New England and Mid-Atlantic shorelines, for example, frequently retreat on an annual basis in response to "northeaster" storms. Erosion of Florida's Gulf of Mexico beaches, on the other hand, is most affected by hurricanes, often spaced decades apart.

The role of humans in causing coastal retreat ranges in scope from global to local. Global production of excess CO_2 is widely assumed to be leading to "greenhouse effect"-related sea-level rise and accelerated erosion. Locally, the damming of rivers is cutting off a major source of sand for many beaches, which accelerates erosion. This problem is acute for California beaches (Griggs, 1987b). Flood prevention on rivers by the armoring of channel banks and construction of artificial levees accelerates erosion by inhibiting vertial accretion of river deltas and further reducing beach sediment supply.

The myriad sea walls, breakwaters, groins, and jetties that line developed shorelines divert offshore, slow down, trap, and otherwise reduce the regional beach sediment supplied by longshore currents, and thereby increase erosion rates. Seawall construction along formerly glaciated coasts has cut off the supply of sand normally contributed to the beaches by eroding bluffs. This phenomenon has led the state governments of Massachusetts and Maine to prohibit the construction of sea walls in front of bluffs.

A spectacular example of the role of jetties in affecting beach sand supply, and also a spectacular example of beach erosion and barrier-island migration, are afforded by the northern end of Assateague Island, Maryland (Leatherman, 1984). After the Ocean City Inlet opened during a hurricane in 1933, jetties were constructed to stabilize the inlet. Since that time, sand that would have been transported across the inlet to Assateague has been accumulating updrift of the jetties in front of Ocean City, or offshore at the end of the jetties. This diversion of sediment has caused the Assateague shoreline to retreat and the island itself to migrate landward. Today, the open-ocean surf zone of Assateague Island is landward of the island's 1933 lagoon shoreline.

The causes and mechanics of erosion are more complex on rocky coasts than on unconsolidated coasts. Processes involved in the erosion of rocky coasts are summarized in Trenhaile (1987). Factors controlling erosion on the California coast are addressed by Griggs and Savoy (1985).

The degree of cliff retreat in California depends on (1) orientation or exposure, (2) local wave climate, and (3) the physical properties of the cliff. Important rock properties include hardness, consolidation, and the presence or absence of internal weaknesses such as joints, fractures, and faults. Crystalline rocks such as granite tend to erode irregularly and very slowly, producing a highly irregular coastline. Sedimentary rock, broadly speaking, tends to erode somewhat more regularly and rapidly, producing relatively straight coasts.

Both marine and nonmarine processes are involved in cliff retreat (Norris, 1990; Emery and Kuhn, 1982). Marine erosion includes direct wave attack, a variety of chemical-solution processes, and flaking by salt-crystal expansion. Nonmarine cliff erosion is accomplished by chemical and mechanical processes usually involving rain water. Groundwater seepage along contacts and joints is often a critical part of cliff retreat. Along the California coast, the effects of seepage have been increased by lawn watering and septic-tank emplacement (Norris, 1990).

Mass movement in the form of slumps and various types of landslides is frequently the major process of retreat and is responsible for the very uneven spatial and temporal retreat rates of cliffs. Emery and Kuhn (1982) present a classification of coastal cliffs based in part on the relative importance of marine and nonmarine processes.

According to Griggs and Savoy (1985), erosion rates along the rocky coast of California are highly variable, ranging from negligible to 3 to 4 m/yr. Typically, shoreline-retreat rates are on the order of 10 to 20 cm/yr. Griggs and Savoy also note that the highly episodic nature of erosion rates here is strongly dependent on storminess. Frequent storms translate to high-erosion rates, and the degree of storminess itself is episodic.

PREDICTING FUTURE SHORELINE CHANGES

One of the most critical research problems in coastal geology today is predicting the effect of sea-level rise on shoreline-retreat rates. Coastal communities need accurate predictions of shoreline position on a time frame of decades, an impossibility at present.

Were sea level to rise catastrophically 10 m in the next year, there is no question that the shoreline would be inland at what is now the 10-m contour. Predicting shoreline behavior at a slower rate of sea-level rise, however, is much more difficult. The problem is complex, and standard engineering models such as the Bruun Rule (Bruun, 1962) are too rigid and are based on too many narrow assumptions to have wide application (Kraft and others, 1987; Orford, 1987; SCOR Working Group 89, 1991).

Methods of predicting future shoreline changes include extrapolation of present erosion rates, application of predictive models, and use of numerical models. Present erosion rates are often used by states to determine building setbacks (e.g., in North Carolina and South Carolina). The basic problem with this method, however, is that recent trends and their underlying causes may not in any way reflect the future. Dolan and others (1991) provide a review of the methods used to calculate rates of shoreline change using historical data.

A number of fairly simple predictive models are used to project future shoreline positions, including the Bruun Rule (Bruun, 1962; 1983), the Generalized Bruun Rule (Dean and Maurmeyer, 1983), the Edelman method (Edelman, 1970), and various others (e.g., Everts, 1987). The basis for these models is the assumption that the shoreface will retreat landward and upward due to a rise in sea level. Most of the models assume: (1) a constant wave climate, (2) a purely sandy shoreface, (3) no longshore loss of sand, (4) sand transport by incident waves only, and (5) no sand transport seaward beyond the shoreface by storms. These assumptions are never completely valid. Clearly, the slope of the surface over which a shoreline will retreat must also be a factor; this consideration, however, is not a part of any current models.

Pilkey and Davis (1987) applied several of these models to the barrier-island coast of North Carolina. South of Cape Lookout, the Bruun Rule, Generalized Bruun Rule and a model incorporating the slope of the migration surface all predicted similar recession for a given rise in sea level. North of Cape Lookout, consideration of the slope of the migration surface predicted a much greater recession than did Bruun-related models, perhaps because the islands are in an "out-of-equilibrium position" with respect to present sea level. That is, the recent (since about 4.5 ka) near-stillstand of relative sea level combined with a large sediment supply has permitted these islands to remain in place, while the back-barrier lagoons (Albemarle and Pamlico Sounds) have widened.

Numerical models of the coastal environment have become important tools for studying shoreline changes. Several approaches to modeling the coastal environment are given by Fox (1985) and Lakhan and Trenhaile (1989). It is important to note, however, that the coastal system consists of many poorly understood components (e.g., shoreface, tidal-inlet, and so forth) that cannot yet be modeled realistically. Wright and others (1991), for example, demonstrate that much more is involved in shoreface sediment transport than just the incident wave field considered in most models. It is doubtful that any existing models can predict shoreline-erosion rates with an accuracy useful to coastal communities.

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