COASTAL EROSION AND DEFENSES AGAINST EROSION

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Summary

Coastal erosion is often thought of as an inevitable. The forces of winds, waves, and currents on the shore are uncontrollable. Tiny particles, like the sands that make up the great recreational beaches of the world, will move inexorably from place to place. As sediment moves, so does the coastline. But viewed in human timescales of decades to centuries, many beaches are moving imperceptibly. After all, they have had thousands of years to evolve into forms that are nearly in balance with the local wave and tide conditions. They may erode during storms, but often rebuild naturally in a continuing cycle. Human activities have exacerbated erosion in many areas, but so have large-scale phenomenon like channel avulsions or natural openings of inlets.

This article describes some of the causes of coastal erosion and tries to put into perspective their scales and consequences. There are no uniform causes, just as there are no uniform solutions. Erosion tends to be site-specific. Yet, with careful observation and measurement, a particular problem can be placed in context and draw from the experience of similar sites. Given the variety of the world's coastlines, many other "signatures of erosion" beyond those mentioned here are at work. The attraction for scientists seeking to understand these signatures is the same as the casual tourist's—the ever-changing image of the shore.

1. Introduction

All sedimentary coasts tend to erode at one time or another. This basic tenet of coastal science reflects the complex interactions that occur where air, sea, and land come together. Wherever shorelines are composed of discrete grains of sediment, the processes of winds, waves, currents, and changing water levels combine to mobilize the particles and move them around by varying degrees.

This article describes the physical processes and primary causes of coastal erosion and presents some commonly applied erosion defenses. To many observers, erosion is inevitable and a problem only because of human development at the coast. Yet, on closer examination, the problem and solutions have many facets. Not all coasts are alike, nor are they all eroding. Each has its own set of characteristics, including specific geologic history, sediment type, exposure to waves and tides, and relationship to everyday use by humans.

As long as people are drawn to the sea, the coast will remain a special place, having to adjust to storms, rising sea levels, and encroaching development. The question is not so much whether the coast is eroding. The question is how we can live with it and properly accommodate its changing shoreline conditions.

2. Sea Levels and Frames of Reference

Coasts evolve in relation to their tectonic setting, sediment supply, wind and wave climate, and water-level changes. Over long geologic timescales (>10^6 years), plate tectonics fundamentally control the evolution of the coast. Where the earth's plates are colliding, relief at the coast tends to be steep. This results in narrow coastal plains and continental shelves. On the other hand, where the earth's plates are separating or "trailing away" from each other, relief tends to be gentle, leaving wide continental shelves and coastal plains. The Pacific and Atlantic coasts of the United States are examples of (respectively) a "collision" coast and a "trailing-edge" coast. Most barrier island and estuarine shorelines are situated along trailing-edge coasts.

At much shorter geologic timescales (~10^5 years), sea-level movements control the position of the coast. Examination of sediments and fossils confirms that sea level has fluctuated by at least 100 meters (m) over the past 100 000 years (Figure 1). Cycles of glaciation (the most important sea-level position factor) release or remove huge volumes of water from the world ocean, causing seas to rise or fall across the coastal plain and continental shelf. Today, sea level is closer to its highest possible level than its lowest recorded level because the earth is between glacial periods.

At historical timescales (~10^4 years), the magnitude of sea-level change has been of the order 10^1 m. Carbon-14 dating confirms the last glacial stage ("Wisconsin") ended with a global warming trend around 20,000 years BP (before the present). Between 20,000 BP and 5,000 BP, melting ice sheets produced a rapid rise in sea level. Present sea level was nearly reached 5000 years ago; at which time its rate of rise slowed markedly. Since then, sea level has oscillated over a narrow range with some periods experiencing a lowering and others a rising ocean.

Our present coastline and its diversity of features (including river deltas, barrier islands, lagoons, and estuaries) all formed in the past few thousand years. In geologic terms, then, the coast is exceedingly young and relatively ephemeral.

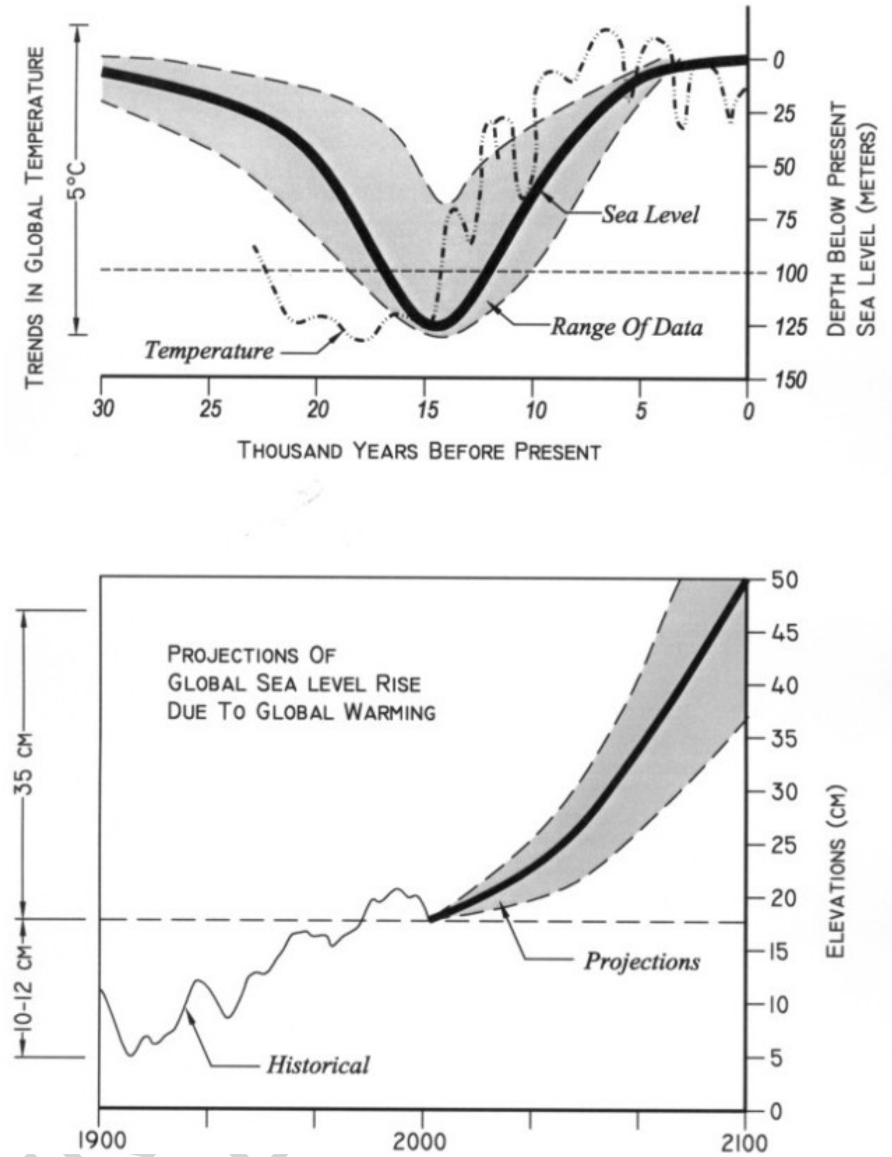

Figure 1. Trends in sea level and temperature over the past 30 000 years (upper), measured trends and projections 1900 to 2100 (lower)
(*Sources*: Based on R.W. Fairbridge, Eustatic changes in sea level, *Physics and Chemistry of the Earth*, Vol. 4, ed. L. Ahrens et al. (London: Pergamon, 1961), pp. 99–185; M.C. Barth and J.G. Titus, eds., *Greenhouse Effect and Sea Level Rise: A Challenge for This Generation* (New York: Van Nostrand Reinhold, 1984); NRC, *Responding to Changes in Sea Level* (Washington, D.C.: NRC, National Academy Press, 1987))

It may persist in more or less its present shape for several thousand more years, or it may migrate seaward or landward if the global climate destabilizes, triggering a new glacial stage or a warmer cycle. Glaciation removes volume from the ocean and leads to lower sea levels. Global warming, of course, does the opposite, melting the ice caps and raising sea levels.

In the last decades of the twentieth century, attention was focused on global warming because of evidence that the industrial age and human activities are producing a measurable impact on climate. The burning of fossil fuels and other anthropogenic effects have increased carbon dioxide (CO_2) concentrations in the atmosphere and, through the greenhouse effect, contributed to global warming of the order 0.5 degrees Celsius (°C) in the twentieth century. Evidence suggests that the mean global temperature has fluctuated no more than ~1°C over the past 1000 years and about 5°C in the past 25 000 years. Climate change models presently project a probable ~2°C temperature rise over the twenty-first century. Global warming of this magnitude could lead to sea levels ~35 cm higher than 2000 levels by 2100. This compares with a global rise of 10–12 cm during the twentieth century.

Sea level is such a fundamental parameter that coastal erosion tends to be closely linked to any rising or falling trend. The degree to which a changing sea level will alter the shoreline depends on the slope of the land at the coast. Gently sloping, low coastal plains, such as the shoreline around the Brahma-Putra River in Bangladesh, will tend to fluctuate much more than high-relief coasts such as Baha, California. However, a close examination of world shorelines reveals great complexity in their response to changing sea levels. Some coastlines retreated much further than expected during the twentieth century (in the face of a 10–12 cm global sea-level rise), whereas others actually grew seaward. But before outlining why such variability occurs, it is necessary to establish a common frame of reference because coastal erosion is a time-dependent process.

Scales of coastal change generally increase the longer one looks backward or forward in time. In long geologic timescales, tectonic activity, volcanism, glaciation, and even biogenic processes (such as reef building) will fundamentally control the shape and position of the coast. Where broad continental shelves occur, such as the U.S. east coast, shoreline position will fluctuate 50–100 km or more in the cross-shore direction. However, geologic timescales are well beyond the period of concern for global habitation and planning. At the opposite extreme from geologic timescales are instantaneous events such as those associated with a single breaking wave at the shoreline or perhaps landfall of a major storm. Certainly, it is important to understand these microscale processes but, by their very nature, it is difficult to extrapolate from isolated events. Human timescales are generally of most concern because our investments parallel our life spans. These middle, or “meso,” timescales are a practical frame of reference because they can be linked to recorded history and personal experience. They allow averaging of many microscale events while avoiding the unpredictability and interminable pace of major tectonic activity.

For the remainder of this article, coastal erosion will be considered in the context of a mesoscale frame of reference; that is, shoreline fluctuations experienced over decades to centuries. The U.S. government establishes minimum building elevations based on the 100-year flood (defined as the expected flood elevation for a particular coastal or riverine site that has a 1% probability of occurrence in any given year, that is, a 100% probability over a 100-year period). Some states, such as South Carolina, base coastal development on “40-year” setback lines. In that case, development must be placed landward of the anticipated maximum point of erosion over the next 40 years, using historical shoreline data for the previous 40 years. Setback lines are political jurisdiction lines that establish the seaward-most limit for human development along a particular coast based on any number of criteria depending on the locality, governing authority, and available shoreline data; they may prescribe an arbitrary distance landward of the present shoreline or be linked to site-specific erosion rates. Although there is nothing unique about either of these time periods, they provide for consistency in the application of laws and building codes. Longer planning periods are often desirable but too costly to implement compared with the economy at risk. However, in places like The Netherlands, where large populations and much of a country's wealth is at stake along the coast, planning horizons tend to expand well beyond 100 years.

Conflicting views regarding coastal erosion stem largely from different frames of reference. Since the late 1970s, there has been heated debate among geologists, coastal engineers, environmentalists, and the media over the problem of coastal erosion and what to do about it. Such debates can only be tempered if common time frames and scales are adopted. In the meantime, those who live, work, and play at the coast need to understand that coastal erosion is site specific and so must be accommodated based on local conditions.

3. Coastal Processes and Erosion

Unconsolidated sediments at the coast move in response to winds, waves, currents, and changing water levels. As we saw in the previous section, global effects control sea level. However, at mesoscales, the magnitude of sea level change is relatively small, on the order of 10 cm to 60 cm over a century. A much greater change in water levels is experienced daily along most ocean coasts in the form of tides.

3.1. Tides and Surges

About one-third of the world's shorelines experience 0 m to 2 m tides (microtides), the next third experience 2 m to 4 m tides (mesotides), while the remaining third have tides > 4 m. Tides themselves do not move significant amounts of sediment but the currents they generate in constricted bodies of water (such as confined inlets, straits, or narrow embayments) can scour the bottom and cause slumping along channel banks. Tides on open coasts control the water level at which waves strike the shore.

Where tides are absent (such as in the U.S. Great Lakes), other factors can affect water levels at the shore. Rainfall and runoff change ground and surface water levels episodically. Winds moving across open bodies of water have the potential to push water up lee shores. These *wind tides* can be many times higher than astronomic tides at the downwind ends of shallow lagoons such as Laguna Madre (Texas). Winds tilting the surface of a lake can trigger back-and-forth oscillations, called *seiches,* which for a short time resemble the tides along ocean coasts. Lake Erie (U.S.) experiences water-level gradients upward of 4 m between Toledo, Ohio (west end), and Buffalo, New York (east end), when strong west winds blow parallel to the lake's long axis.

The degree to which winds *set up* water levels at the coast is directly proportional to wind speed. A descriptive term for this is *surge,* technically defined as the "excess water" level above the astronomic tide. Because winds also blow toward the offshore direction, they can produce a negative surge, lowering the water level at the windward shoreline. Highest surges are associated with tropical storms.

Researchers have made great strides in predicting the tide and surge levels associated with storms of particular magnitudes. Sophisticated computer models inventory historical storms for a given region, prepare a suite of statistical storms having a certain probability of occurrence over standard periods (such as once in 10 years, 25 years, or 100 years), then determine the effect of each synthetic storm on water levels (surges) and waves along the coast. These remarkable models are updated and recalibrated as more storm data and historical surge levels are obtained. A practical product of this research is a set of storm-inundation maps that governments use to set minimum building elevations, flood insurance premiums, and related controls on development at the coast. Elevated structures with improved pile foundations constitute perhaps the single most important defense against coastal erosion.

3.2. Waves and Wave-Generated Currents

While tides and surges are the principal controls on water levels at the coast, waves do most of the work of moving sediments. Waves arriving at the shore are transformed in shallow water, becoming steeper in the crest and flatter in the trough. As waves approach depths of water similar to their height (measured from crest to trough), they break. The form of the breaker varies from a gradual spilling over at the crest to a gentle up-and-down sloshing. An intermediate breaker type is the familiar plunging, or surfers', wave. Breaking waves form a bore of water that is propelled toward the shore, running up the slope in proportion to the wave's size and period. The uprush is followed by a return flow (backrush) toward the next incoming wave. A common name for this process is "undertow."

Wave breaking generates oscillating currents such as the uprush and backrush, as well as littoral circulation currents parallel and perpendicular to the shore. If waves arrive straight to a shoreline, the principal motion is onshore-offshore. However, when waves arrive at an angle to the shore, the motion becomes saw-toothed. Wave-generated currents can be resolved into longshore components as well as cross-shore components. The current associated with the shore-parallel component is simply the *longshore current.* It gains its momentum during the process of breaking so, characteristically, it tends to be strongest between the initial wave breakpoint and the point where the backrush meets the next incoming wave. The bibliography at the back of this section includes several texts that provide a comprehensive description of wave processes.

3.3. Littoral Zone

By now, it should be apparent that the shore can actually extend over a broad zone at the coast. At any point in time, the *still-water level* (i.e. the level in the absence of waves) can equal the average global sea level, be well below it at low tide, or be well above it at high tide. It can actually penetrate inland over the coastal plain for brief periods during storms. To understand the basic processes of coastal erosion, one must consider a set of boundaries. At mesoscales, the coastal width of interest is referred to as the *littoral zone* (Figure 2). This zone is generally defined as the area over which waves in the presence of changing water levels dissipate most of their energy. In common practice, the littoral zone extends from the point of maximum yearly uprush of waves to some small distance seaward of the breakpoint of the largest yearly wave. Along sedimentary coasts, the continual exposure to wave breaking and fluctuating water levels rearranges sediment particles. This leads to development of slopes and morphologic features balanced for the particular waves striking the beach.

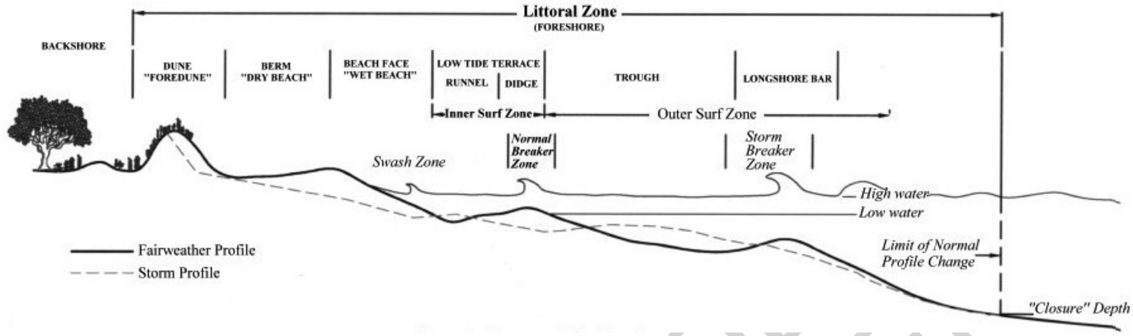

Figure 2. Features of the littoral zone
(*Source*: P.D. Komar, *Beach Processes and Sedimentation* (Englewood Cliffs: Prentice Hall, 1998))

Viewed in cross-section (as in Figure 2), the littoral zone at a site develops a *profile* that is related primarily to sediment texture, wave climate, tide range, sediment supply, and prevailing winds. Key elements of a profile include the following (viewed from a wave's perspective).

3.3.1. Outer Surf Zone

This is the gently sloping inshore area over which waves of all sizes begin to break and measurably redistribute sediment. It sometimes includes breakpoint or "longshore bars," which trigger wave breaking in storms, and troughs between bars. Typical water depths are 1 m to 6 m below sea level. Sediments tend to be finer than the beach but rarely muddy because of the degree of turbulence and mixing that occurs in this zone.

3.3.2. Inner Surf Zone

This is the area of complex topography between the normal point of wave breaking and usual limit of wave uprush along the beach face, sometimes encompassing an inner bar ("ridge") and trough ("runnel") that are exposed at low tide. This zone experiences the greatest vertical change and irregular bottom topography from day to day.

3.3.3. Beach Face

The beach face is that portion of the inner surf zone over which wave uprush and backrush occur. It is generally an area of constant slope that is balanced according to the local sediment grain size and wave climate. This is the final zone of wave energy dissipation and is sometimes referred to as the wet-sand beach over which tides migrate.

Coarsest sediments in the littoral zone generally occur at the lower beach face where the plunging action of breaking waves produces the greatest turbulence.

3.3.4. Berm

The berm is a nearly horizontal portion of the profile beginning at the upper beach face and extending landward to the base of the dune or backshore environment. Situated at the highest wave uprush level, the berm is dry for most of the tidal cycle and therefore is often referred to as the “dry-beach” zone. Typical elevations of the berm are equal to local mean high water plus twice the local mean wave height.

3.3.5. Foredunes and Washovers

Foredunes are windblown deposits having relatively steep slopes beginning at the landward edge of the berm where finer (noncohesive) sediments accumulate by onshore winds. Terrestrial vegetation establishes itself beginning at elevations that are infrequently flooded, often at a uniform minimum elevation. This offers a distinct demarcation between the “active” littoral zone and adjacent “highland.” Coastal erosion is often measured in relation to movement of the seaward vegetation line because it is a convenient, visible point along the profile. Where foredunes are missing and backshore elevations are similar to those of the berm, “washovers” extend inland some distance, receiving new sheets of sediment with each storm surge. Washovers remove an amount of sediment from the active littoral zone, forming a base for a possible new dune line along the backshore. Narrow peninsulas, such as barrier islands, may have washovers fanning landward all the way across them to the interior body of water. Where backshore elevations are much higher than the berm, washovers can’t form. Instead, wave swash cuts away the land, leaving near-vertical escarpments, and transporting new sediment into the littoral zone. Scarps at the edge of the vegetation line mark an abrupt transition between the highland and littoral zone. Vertical scarps in dunes are an indicator of very recent coastal erosion.

There are many smaller scale features within the littoral zone, including ripples, beach cusps, berm runnels, rip channels, and wrack lines that can change day to day, but are of less importance at mesoscales. Interested readers should consult some of the texts listed in the bibliography for a complete description of beach morphologic features.

Proper assessment of coastal erosion requires study of how the entire littoral zone responds to waves, tides, and currents over a period of time. Most studies through the twentieth century evaluated coastal erosion in terms of linear shoreline changes; that is, the displacement of the shoreline at a single contour elevation. However, it should be evident that many parts of the littoral zone could be used as reference points. Indeed, historical studies have used the seaward vegetation line, the toe of the foredune, storm debris lines, local mean high water, the berm crest, mean low water, and of course, mean sea level. As long as the comparisons are done rigorously, a reasonable estimate of change is possible. In practice, however, using only one contour can bias the result. This is because the littoral zone is continually adjusting to changes in wave energy.

Measurement of coastal erosion is most problematic using contours on the gently sloping portions of the littoral profile because minor changes in slope lead to large horizontal displacement of the contour. As we will see in the next section, adjustments in the slope of a beach can produce landward movement of the dune line and seaward movement of the low-tide line—at the same time.

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Biographical Sketch

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