The Coastal Challenge

Fragile ribbons which border our land require more understanding, new technology, and resolute planning.

Douglas L. Inman and Birchard M. Brush

The shoreline is the unique boundary separating the earth's three domains: the land, the sea, and the atmosphere. It is one of man's oldest frontiers and one of his most informative paleo-oceanographical tablets. The nearshore and estuarine waters exert a predominate influence in the everyday affairs of man. Although the continental shelves and nearshore waters comprise only about 5 percent of the area of the world, about two-thirds of the world's population lives near the coast. This imbalance has its roots in antiquity for mankind's first freeways were the seas which, once oars and sails appeared, became the means of bypassing the rigors of overland travel. Sailors traditionally have sought the comparative safety of the open sea in preference to the hostility of the shores' dangerous shoals, strong and unexpected currents, and destructive breaking waves.

To the casual observer, the coastlines of the world look craggy and indomitable, the rocky stretches seem tough, and the beaches appear to be permanent. But the sand on the beaches is easily moved and is in increasingly short supply. In reality, then, the beaches are fragile ribbons of sand that are frequently broken by acts of nature and man. The waters that bathe them have a limited flushing capacity, and yet they have become the most common depository for mankind's wastes (Fig. 1).

Pictorially and esthetically diverse as they may be, the coastal and nearshore zones of the world all share common dynamic experiences (Fig. 2). Here, shore processes begin the mixing, sorting, and transportation of sediments and of runoff from land. Waves, winds, and currents mold the shorelines of the world, and their interaction with the land and its runoff determines the configuration of coastlines and the adjacent bathymetry.

Man's rapidly expanding use of the ocean and his increasing incursion into it commonly involve processes that take place in shallow water. These same shallow waters are experiencing the bulk of the impact of waste discharges, thermal and radioactive pollution, dredging, coastal construction, mining, and poaching.

The Coastal Zone

The oceans and seas have a profound effect on the continents, exerting the controlling influence on weather and climate. Indeed, the sea completely dominates the environmental aspects of the land bordering it. In this connection it is useful to describe coastal areas in terms of a "coastal zone" and a "shore zone" (Fig. 3).

The coastal zone may be defined in terms of the large-scale tectonic and erosional-depositional features which have lengths along the coastline of the order of 1000 kilometers and widths extending from the coastal plain out into the water of an order of magnitude less. The coastal zone is composed of the coastal plain, the continental shelf, and the waters that cover the shelf; it also includes other major features such as large bays, estuaries, lagoons, coastal dune fields, river estuaries, and deltas.

The shore zone is the sedimentary and solid surface associated directly with the interaction of waves and wave-induced currents on the land and on the runoff products from the land. The shore zone includes the beach, the surf zone, and the nearshore waters where wave action moves bottom sediments. The shore zone extends landward to the sea cliffs that border the backshore of a beach, and, where wave-deposited structures such as barrier islands and spits are narrow, across these features to the cliff or coastal plains bordering shallow lagoons. All bodies of water have "shore zones," the extent and configuration of which depend upon the length and height of the waves, the range of the tide, the degree of exposure to winds, and the size of the wave-deposited structures. As a practical concept, the waters involved in the coastal zone may be considered to include the shallow seas and waters covering all the continental shelves of the world which total an area of 29×10^6 km^2, or about 8 percent of the surface area of the world oceans. The nearshore waters are bounded on the landward side by shorelines that total about 440,000 km in length (*1*) and on the seaward side by the break in slope at the shelf edge, which marks the change from the relatively horizontal shelf to the steeper continental slope. The continental slope marks the topographical and structured edge of the continents and is the boundary between relatively shallow water covering the shelf and the great depths of the true oceans. The continental slopes, one of the striking geographic features of the earth, have a combined length of about 150,000 km (*1*).

Conventionally, the depth of the shelf edge is taken as about 200 meters (100 fathoms), although in some localities the depth may be as great as 400 m. On a worldwide basis, the average depth of the shelf edge is about 130 m. The width of the shelf ranges from nearly zero to more than 1300 km and averages about 74 km (*2*).

Because of the mutual interdependence of processes in the coastal and nearshore zones, it is difficult to decide where to begin a discussion of the processes that affect the shore. One can break into this circle by asking: What are the important shore processes, and what coastal factors affect them? In a very general sense, the important factors are: (i) the degree of exposure to waves and currents, (ii) the supply of sediment and runoff to the coast, (iii) the topography of the continental shelf and the adjacent coast, (iv) the tidal range and intensity of the current, and (v) the coastal climate.

Dr. Inman is professor of oceanography and Mr. Brush is a senior development engineer; both authors are affiliated with Scripps Institution of Oceanography, University of California, La Jolla 92037. This article is based on a talk entitled "Degradation of the coastal environment" that was presented 9 December 1970 at the San Francisco meeting of the American Geophysical Union.

Coastal climate is principally dependent upon latitude and the location of the major ocean current and wind systems; the topography of the shelves and coast are closely associated with the geologic setting of the coasts and the origin of the adjacent ocean basins (*1*). The potential of man's intervention becomes apparent when one compares the physical processes operative in nearshore waters and the natural balance of energy that drives them with man's requirements in terms of usage and waste disposal.

Physical Processes in Nearshore Waters

The important processes that operate in the nearshore waters of oceans, bays, and lakes are similar. They differ in intensity and scale, variables which are determined by the energy in the waves and in the physical dimensions of the surf zone. Moreover, it is becoming increasingly clear that processes in nearshore waters are driven by basic, interrelated forces that are systematic and essentially regular in form. These systematic driving forces lead in turn to the development of coherent processes such as the nearshore circulation cells (Fig. 2) and the longshore transport of sand that are basically similar the world over.

Most of the energy for these processes comes from the sea (Fig. 4). It is translated by the stress from winds which blow over the ocean and generate waves of many sizes and frequencies. It is produced by the gravitational attraction of the moon and sun acting on the mass of the ocean. It is transmitted by various, sometimes impulsive, disturbances at the boundaries of the ocean with the atmosphere and with the sea bottom, which generate additional waves of other sizes and frequencies. These waves travel across the ocean with little loss of energy, until the configuration of the landmass and of the adjacent shelves and the slope of the bottom direct and focus the waves for their final assault on the coast. Straight, gently sloping shores accept energy uniformly, whereas headlands, points, and peninsulas tend to attract and concentrate energy.

The energy available to nearshore waters is dissipated in various ways, including the reflection of waves, the generation of turbulence and currents, the transportation of sediment, and the formation of other kinds of waves.

Fig. 1. Beauty died here.

Some energy appears to become "trapped" against the coast rather than reflected, thus leading to a higher energy level at the coast. The trapped energy may take the form of edge waves (*3*), which are special modes of surface waves that travel along the coast, or long-period resonant oscillations called "shelf seiche."

Circulation Cells and Mixing

The many forms of energy flux and the high rates of energy dissipation over the shelf and in the surf zone further complicate processes within the nearshore environment. Although in deep water the mutual interaction of waves is relatively weak, in shallow water the interaction of waves with other waves, of waves with currents, and of currents and waves with the bottom can produce strong interchanges of energy. For example, the waves in shallow water produce bottom-boundary currents flowing in the direction of wave propagation, and these currents play a significant role in the transport of sediments over the shelf (*4*). Pressure fields produced by waves traveling in shallow water change the average water level, reducing it near the breaker zone and increasing it where the waves run up the beach face (*5*).

The interaction of surface waves moving toward the beach with edge waves traveling along the shore produces alternate zones of high and low waves that determine the position of rip currents (Fig. 2). The pattern that results from this flow takes the form of a horizontal eddy or cell, called the nearshore circulation cell (*6, 7*). The rip currents are the "freeways" across the surf zone for experienced surfers and the greatest cause of drownings for inexperienced swimmers.

The nearshore circulation system produces a continuous interchange between the waters of the surf zone and the waters of the offshore zone, acting as a distributing mechanism for nutrients and as a dispersing mechanism for land runoff. Offshore water is transported into the surf zone by breaking waves,

Fig. 2. Aerial photograph of rip currents along a beach. The occurrence of rip currents is universal; the spacing between rips determines the longshore dimension of the nearshore circulation cell.

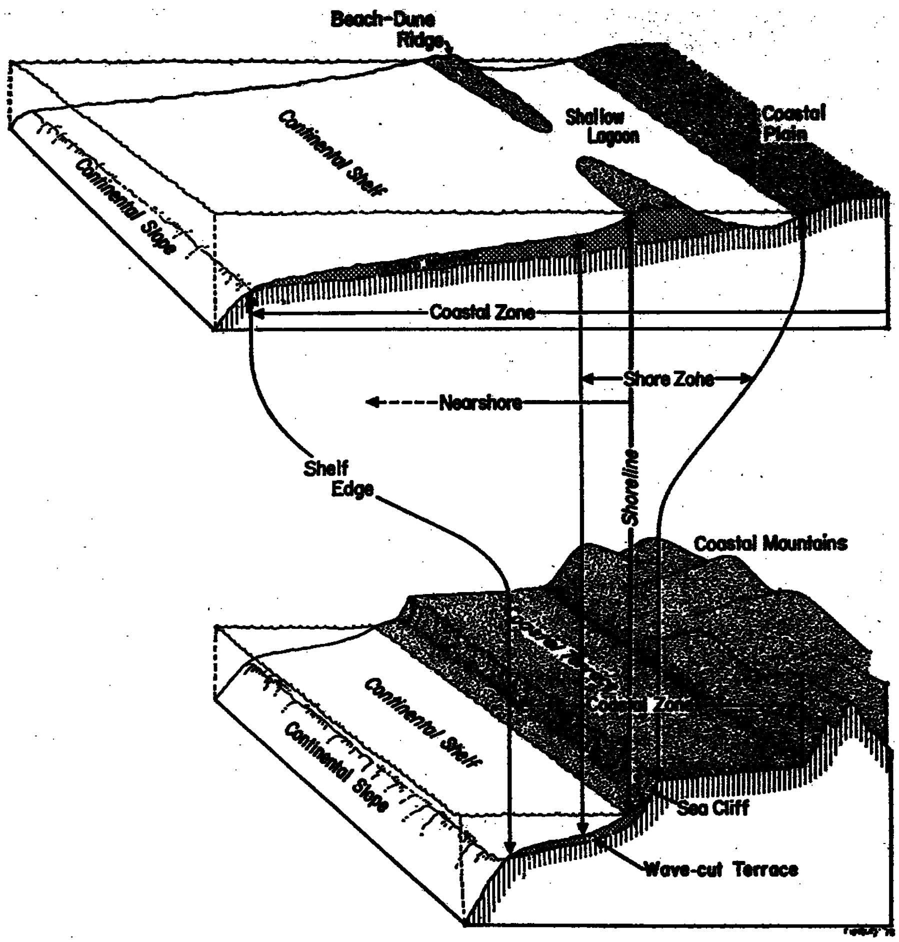


Fig. 3. Definition sketch for coastal zone nomenclature. The type of coast is related to its relative position on the moving plates of the tectosphere; wide-shelf plains coasts (upper part) and narrow-shelf mountainous coasts (lower part) are characteristic of the east coast (trailing edge) and west coast (collision edge) of the Americas, respectively. [After Inman and Nordstrom (*1*)] [Courtesy of the University of Chicago Press, Chicago, Illinois]

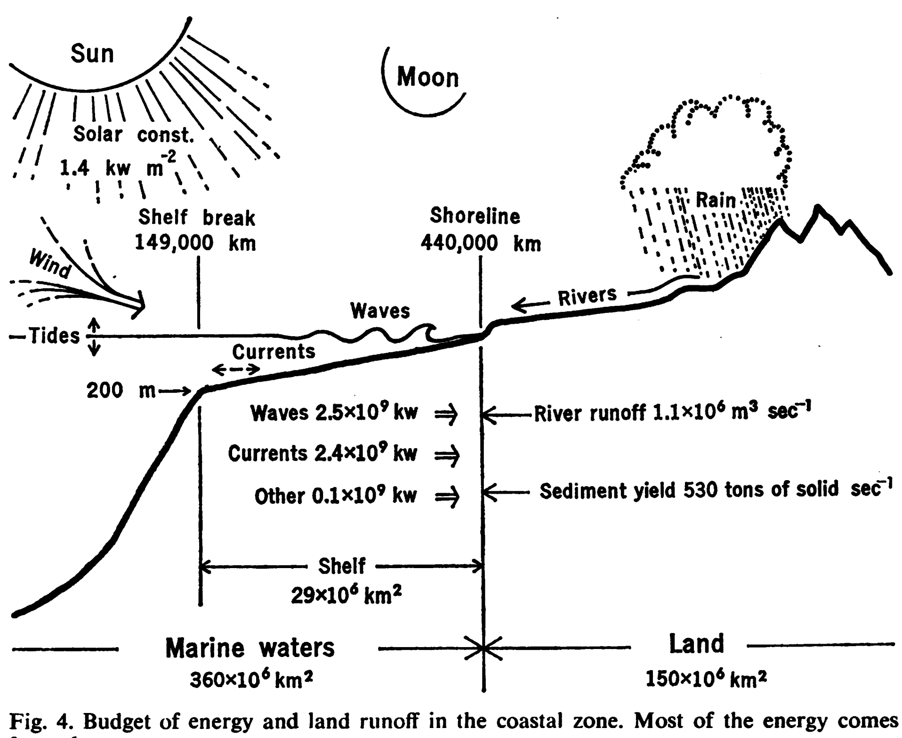


Fig. 4. Budget of energy and land runoff in the coastal zone. Most of the energy comes from the open sea.

and particulate matter is filtered out on the sand of the beach face. Runoff from land and pollutants introduced into the surf zone are carried along the shore and mixed with the offshore waters by the rip currents (*8*).

Two well-defined mechanisms dominate mixing processes in the surf zone; each has distinctive length and time scales determined by the intensity of the waves and the dimensions of the surf zone. The first process is associated with the breaking wave and its bore, which produce rapid mixing in both the onshore and the offshore direction, alternatively. This mixing, when normalized and averaged over the surf zone width X_b, gives coefficients of eddy diffusivity of the order of H_bX_b/T, where H_b and T are, respectively, the breaker height and the period of the waves (Fig. 5). The second process is advective and is associated with the longshore and rip current systems in the nearshore circulation cell. A constant longshore discharge of water between cells Q_l gives a concentration N_n in the nth cell down-current (in the direction of current flow) from a continuously injected source of tracer of

$$N_n = N_0(Q_l/Q_m)^n \qquad (1)$$

where N_0 is the concentration of tracer leaving the injection cell and Q_m is the maximum longshore discharge of tracer within a cell (Fig. 5). As an approximation, the concentration decreases exponentially with the distance y from the injection point when n is replaced by y/Y, where Y is the spacing between rip currents. This relation gives an apparent longshore eddy mixing coefficient of the order of $Y \cdot v_l$, where v_l is the longshore current velocity. Along ocean beaches H_bX_b/T and $Y \cdot v_l$ are about 10 and 100 m^2 sec^{-1}, respectively.

Once the tracer front has passed through a particular cell, tracer is introduced into the adjacent offshore waters by the rip current. In the absence of coastal currents, the tracer remains in the offshore area where it is available for recirculation into the cell. Recirculation of tracer decreases the dilution capacity of the cell and causes the concentration to increase, as shown schematically in Fig. 6B. Thus the concentration becomes a function of both distance and time, and the simple equation for mixing (Eq. 1) no longer holds.

The tracer tends to remain in the secondary mixing zone (area, $X_r \cdot Y$) because the rip currents move slowly down the coast with the longshore current. Thus the rip currents continue to flow seaward into tracer-free waters until the entire secondary mixing zone is filled with tracer of concentration N_n. A situation in which the secondary mixing zone is about half filled with tracer is shown by the extent of offshore discoloration in Fig. 7.

It is apparent from Fig. 6B that the presence of background concentrations of tracer in the offshore zone decreases the concentration gradient by recirculating material already there. This in turn leads to an exponential buildup of concentration until both the surf zone and the region offshore become saturated.

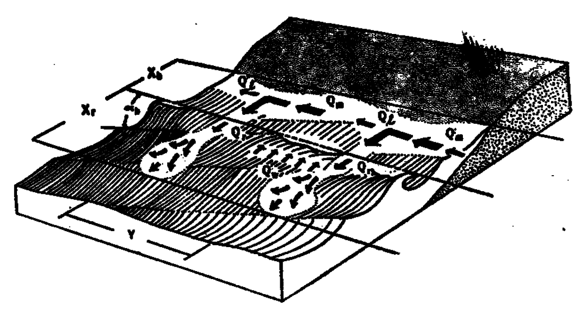


Fig. 5. Definition sketch of the model for mixing when waves break at angle α_b with the beach. The zone between rip currents constitutes a circulation cell; primary mixing occurring in the surf zone (area, $X_b \cdot Y$), and secondary mixing occurs in the offshore zone between the heads of the rip currents (area, $X_r \cdot Y$). The water discharges in volume per unit time are as follows: Q_l, from cell to cell; Q_m, maximum within a cell; Q_w, onshore transport associated with breaking waves; and Q_r, offshore flow in a rip current. [From Inman *et al.* (*8*)] [Courtesy of the *Journal of Geophysical Research*, Washington, D.C.]

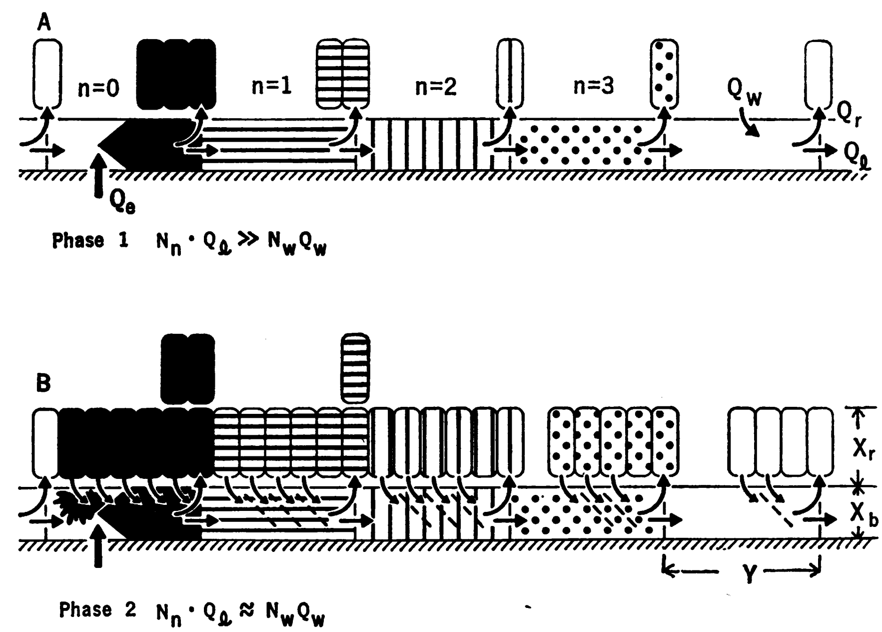


Fig. 6. Schematic diagram of the longshore mixing of tracer Q_e, continuously injected. (A) Phase 1 applies when recirculation from the secondary mixing zone is negligible; (B) phase 2 applies when the background concentration becomes significant and recirculation causes the system to become saturated. Symbols are defined in Fig. 5. [From Inman *et al.* (*8*)] [Courtesy of the *Journal of Geophysical Research*, Washington, D.C.]

Circulation over the Shelf

Coastal circulation on a much larger scale but of reduced intensity occurs over the entire shelf. This circulation may take the form of eddies and countercurrents from the permanent ocean current systems that flow across the shelf; the circulation may be due to tidal currents, or it may be induced locally by the wind in the form of the upwelling of deep water and the horizontal flow of water along the coast.

Coastal circulation cells of large dimension are also associated with the submarine canyons that cut across the shallow shelves of the world. These canyons act as deep, narrow conduits connecting the shallow waters of the shelf with deeper water offshore. At times, strong seaward flows of water occur in the canyons, so that they resemble large-scale rip currents. The canyon currents produce circulation cells having dimensions of the shelf width and spacing comparable to that between the submarine canyons (Fig. 8). These strong currents in submarine canyons seem to be caused by a unique combination of air-sea-land interactions (*9*) consisting of the following: (i) a pileup of water along the shoreline caused by strong onshore winds; (ii) down-canyon pulses of water caused by the surf beat of the incident waves; (iii) a shelf seiche excited by the waves and by the pressure fluctuations in the wind field; and, finally, (iv) the formation of steady down-canyon currents as the weight of the sediment suspended by the currents overcomes the density stratification of the deeper water.

There is less pileup of water by the wind over the canyon than over the

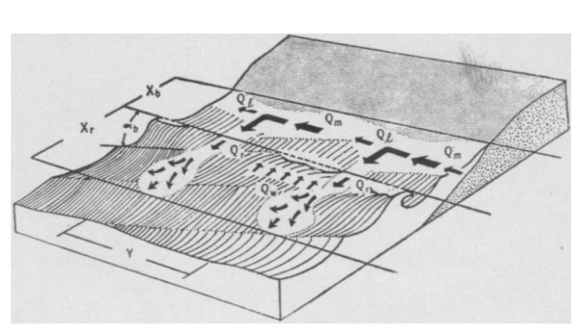


Fig. 7. Photograph showing phase 2 mixing and an increase in the offshore concentration by rip currents as shown by the plumes of discolored water. The discolored water is being recirculated, causing the mixing to approach saturation (see Fig. 6).

secular changes in sea level attain the
greatest height.
The wind systems are the direct lin
between the atmosphere and the ocea
and, through momentum exchange
the ocean's surface, transfer kine
energy at the rate of about 10^{11} kil
watts (1 kw = 10^{10} erg sec^{-1}) (15
Winds plus ocean and earth tides a
directly or indirectly responsible f
most of the energy dissipated in t
nearshore zones of the oceans. T
most common form of nearshore e

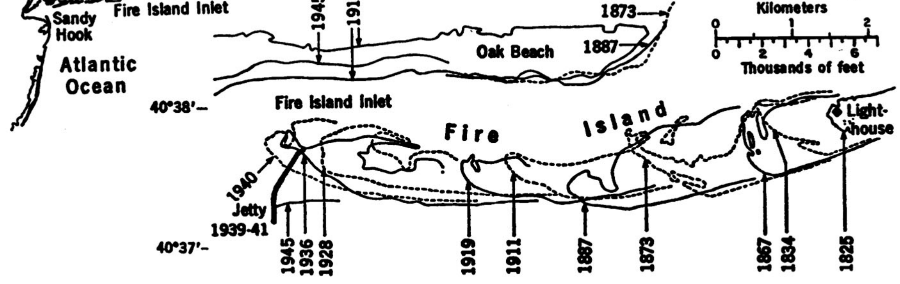


Fig. 9. Longshore sand transport has caused an extension of the Fire Island spit at an average rate of 100 m per year since 1825. [After S. Gofseyeff (*13*)] [Courtesy of J. W. Johnson, School of Engineering, University of California, Berkeley]

24

SCIENCE, VOL. 1

adjacent shelf, and, as a result, the shallower waters over the shelf flow along the coast toward the canyons and, as in the case of rip currents, flow seaward over the canyons. The surf-beat waves (waves caused by the beat of incident waves of different frequency) and the shelf seiche are very long waves, whose interaction with the shelf and canyon produces current pulses capable of suspending sediment. When these pulses are of sufficient velocity to suspend sediment and to maintain a suspended load of sediment, autosuspension results and the pulsating current is converted into a self-maintaining turbidity current that travels down the canyon into the adjacent deep waters of the ocean (*9*).

Longshore Transport of Sand

Wherever there are waves and an adequate supply of sand (or coarser material), beaches form. The back-and-forth motion of waves in shallow water produces stresses on the bottom that place sand in motion. The interaction of the wave stresses with the bottom also induces a net boundary current flowing in the direction of wave travel. Over a gently shoaling bed, the back-and-forth motion of sand in the presence of the boundary current produces a net transport of sand in the direction of wave travel. Thus, waves traveling toward the shore tend to contain sand against the shore, and eventually to produce a profile that is in equilibrium with the energy dissipation of the waves (*10, 11*).

When waves approach the coast at an angle, they cause sand to be transported along the shore. For the special case of longshore transport of sand in the surf zone, the breaking wave supplies the power needed to place the sand in motion, as well as the longshore current that carries the sand load. The longshore transport of sand I, expressed in immersed weight (for example, newtons per second) is directly proportional to the onshore flux of

tively known, so that the volume of littoral transport along oceanic coasts is traditionally estimated from the rate of growth of spits (Fig. 9) (*13*), or from the observed rates of erosion or accretion, most often in the vicinity of coastal structures such as groins or jetties. In general, beaches build seaward up-current from obstructions and are eroded on the lee side of the current where the supply of sand is diminished. Such observations indicate that the rate of transport of sand varies from almost zero to several million cubic meters per year, with average values of 150,000 to 1,600,000 m^3 $year^{-1}$. Along the shores of smaller bodies of water, such as the Great Lakes, the littoral transport rate can be expected to range from about 1,000 to 150,000 m^3 $year^{-1}$ (*14*). In general, these are conservative estimates, since the volume of material moved commonly exceeds that indicated either by deposition or by erosion.

Natural Balance of Energy and Sediment

The energy which drives processes in the nearshore zone comes from the sea and atmosphere. Waves and currents from the open ocean propagate toward coasts where they are concentrated and eventually dissipated. At the shoreline the breakers, storm surges, tides, and secular changes in sea level attain their greatest height.

The wind systems are the direct links between the atmosphere and the ocean, and, through momentum exchange at the ocean's surface, transfer kinetic energy at the rate of about 10^{11} kilowatts (1 kw = 10^{10} erg sec^{-1}) (*15*). Winds plus ocean and earth tides are directly or indirectly responsible for most of the energy dissipated in the nearshore zones of the oceans. The most common form of nearshore en-

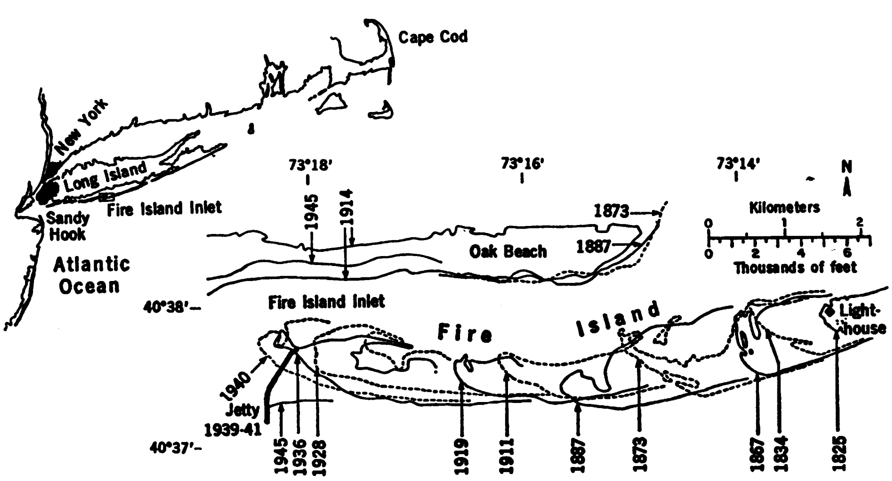


Fig. 9. Longshore sand transport has caused an extension of the Fire Island spit at an average rate of 100 m per year since 1825. [After S. Gofseyeff (*13*)] [Courtesy of J. W. Johnson, School of Engineering, University of California, Berkeley]

ergy is that associated with the wind-generated surface waves.

A wave 3 m high transmits energy at the rate of 100 kw per meter of its crest line. Toward 1 km of coastline it transmits 100,000 kw. The power of such waves is equivalent to a solid line of automobiles, each 270 horsepower, advancing side by side at full throttle (*16*). On an oceanwide basis, wind-generated waves probably have an average height of about 1 m, and they transmit power at a rate of about 10 kw per meter of wave crest. If these waves were to break continuously along the 440,000 km of the world's shoreline, they would dissipate energy at the rate of 4.4×10^9 kw. This number is probably too high for a worldwide average dissipation of energy because all shorelines are not exposed to the open ocean. A reasonable estimate of the average rate of energy dissipation of surface waves in nearshore waters is about one-half to two-thirds of this amount, say, 2.5×10^9 kw, which is equivalent to the energy production of 10,000 large power plants (Table 1).

Tides produce motion even in the deepest oceans. However, this motion is usually only a few centimeters per second so that tides dissipate very little of their energy on the deep sea bottom. The principal tidal dissipation results from the flow of strong tidal currents in shallow areas, such as the Bering Sea, the Okhotsk Sea, and the Argentine Shelf. About half of the tidal current dissipation occurs in five shallow seas having a total area of only 10 percent of the shelf area of the world. The total rate of energy dissipation by lunar and solar tides in the shallow waters of the world oceans is about 2.2×10^9 kw, or only slightly less than the rate from wave action (Table 1).

By comparison with waves and tides, other sources contribute relatively little energy to coastal waters. For example, the most spectacular waves in the sea are tsunamis, which are well known because of the loss of life and great damage to coastal structures associated with their passage. However, large tsunamis with energy contents as high as 5×10^{15} joules occur only about five times per century (*17*). The average rate of energy dissipation of a tsunami is about 10^5 kw, which is four orders of magnitude less than the total for waves and tides.

The total rate of dissipation of mechanical energy in the shallow waters of the world is about 5×10^9 kw (Table 1). Dissipation by one process or another occurs over the entire shelf (Fig. 4). The wind-generated surface waves dissipate their energy primarily nearshore, especially in the breaker zone, whereas tidal and other ocean currents and internal waves dissipate most of their energy over the outer portions of the shelf. Internal waves, edge waves, shelf seiche, and local winds may produce water motion over the continental shelf and submarine canyons. Thus, it is apparent that an understanding of processes in the nearshore environment requires a careful assessment of the amounts of energy in the various kinds and modes of wave and current motion as well as a determination of the mechanics of interaction of waves, currents, and sediments.

Table 1. Estimates of the natural rates of dissipation of mechanical energy in the shallow waters of the world (*16*) in units of 10^9 kw (1 kw = 10^{10} erg sec^{-1}).

Source	Rate
Wind-generated waves breaking against the shoreline (*39*)	2.5
Tidal currents in shallow seas (*40*)	2.2
Large-scale ocean currents in shallow seas (Guiana Current off the northeastern coast of South America, 0.13; Falkland Current over the Argentine Shelf, 0.03)	0.2
All other sources (wind stress on the beach, 0.01; internal waves, 0.01; edge waves; shelf seiche; tsunamis; rivers entering the oceans)	0.1
Total	5.0

Beaches are composed of whatever clastic material is locally in greatest abundance. The principal sources of beach and nearshore sediments are as follows: the rivers, which bring large quantities of sand directly to the coast; the unconsolidated material of the sea cliffs, which is eroded by waves; and material of biological origin, such as shells, coral fragments, and skeletons of small marine organisms. Many beaches, such as those along the east coast of the United States, are supplied by sand that has been reworked by waves and currents from ancient river and glacial material deposited during former stillstands in sea level (*18*).

Table 2. Estimate of the natural run-off of fresh water and solids from the continents into the coastal waters of the world (see Fig. 4).

Source	Rate
Discharge of water into the oceans from all rivers (*41*)	1.1×10^6 m^3 sec^{-1}
Flux of dissolved solids (*42*)	125 ton sec^{-1}
Flux of particulate solids (*43*)	530 ton sec^{-1}
Average erosion rate of land (*22*)	6 cm per 10^3 years

Streams and rivers are by far the most important source of sand for beaches in temperate latitudes. Cliff erosion probably does not account for more than about 5 percent of the material on most beaches, except locally on trailing-edge coasts such as the east coast of the United States. Wave erosion of rocky coasts is usually a slow process, even in cases where the rocks are relatively soft shales. On the other hand, erosion rates greater than 1 m $year^{-1}$ are not uncommon in unconsolidated sea cliffs.

The contribution of sand by streams in arid countries is surprisingly high. This is so because arid weathering produces sand-size material and inhibits the growth of vegetation that would protect the land from erosion. Therefore, in an arid climate, occasional flash floods transport large volumes of sand. The maximum sediment yield occurs from drainage areas where the mean annual precipitation is about 30 centimeters (*19*).

Traditionally, geologists have estimated long-term erosion and deposition rates from the amount of material deposited during geologic time. Such estimates give erosion rates varying from about 1 to 4 cm per 10^3 years for drainage basins of moderate relief to as much as 21 to 100 cm per 10^3 years for the Himalayas (*20*). Assessment of the volume of sedimentary material on the continental United States and in its adjacent sea floors indicates that the average erosion rate of the United States during the past 600×10^6 years was 3 to 6 cm per 10^3 years (*21*).

An increasing number of measurements of river discharge have provided an independent estimate of contemporary erosion rates of the land. The average discharge of the world's rivers totals 1.1×10^6 m^3 of water per second. Measurements suggest that the average suspended plus bed load is about 480 milligrams per liter, which gives a total discharge of particulate solids of 530 metric ton sec^{-1} (Table 2) (metric units are used throughout this article except in column 1 of Table 3). This gives a contemporary average erosion rate of the land of about 6 cm per 10^3 years (*22*), which is somewhat higher than the average erosion rates estimated from deposition during geologic time. As we will show below, the increase in the erosion rate is probably associated with man's intervention.

It is of interest to compare the total fluxes of energy and sediments (particulate solids) into the coastal waters of the world. Since energy may be thought of as the ability to do work, the flux of energy associated with waves and currents gives some measure of their potential to transport sediment. For example, let us assume that the estimated total flux of wave energy (2.5×10^9 kw) is available for transporting sand along the world's coastline, and that the longshore-directed energy flux, P_l in Eq. 2, is equal to one-tenth of the incident energy flux. From Eq. 2 this gives a rate of immersed weight transport of 1.9×10^{11} newton sec^{-1}, which is equivalent to a (dry) mass transport of 3.1×10^7 ton sec^{-1} for the world's beaches, a mass flux 5.8×10^4 greater than that supplied to the coast by all of the erosion of the continents.

The budget of sediment for a region is obtained by assessing the sedimentary contributions and losses to the region, and their relation to the various sediment sources and transport mechanisms. However, it is not a simple matter to determine the budget of sediment, since such a calculation requires a knowledge of the rates of erosion and deposition as well as an understanding of the capacity of the various transport agents.

Studies of the budget of sediment show that coastal areas can be divided into a series of discrete sedimentation compartments called "littoral cells." Each cell contains a complete cycle of littoral transportation and sedimentation, including sources and sinks of sediment and transport paths (*11*).

Along the coast of Southern California (Fig. 10), the principal sources of sediment for each littoral cell are the rivers, which periodically supply large quantities of sandy material to the coast. The sand is transported along the coast by waves and currents until the "river of sand" is intercepted by a submarine canyon, which diverts and channels the flow of sand into the adjacent submarine basins and depressions.

There are five littoral cells in Southern California. Each cell begins with a stretch of rocky coast where the supply of sand is limited (Fig. 10). In a downcoast direction, determined by the prevailing waves, the beaches gradually become wider and the coastline straightens where the streams supply a sufficient amount of sand. Submarine canyons terminate the littoral cell by capturing the supply of sand, thus causing the next cell to begin with a rocky coast devoid of beaches.

The concept of littoral cells and their sedimentary budget applies to all coasts, the budget differing principally in the nature of the sources and sinks for the sediment. Along coasts having large estuaries such as the east and gulf coasts and portions of the Oregon coast, the river sand is trapped in the estuaries and cannot reach the open coast (*23*). For these coasts the sediment is produced by the erosion of sea cliffs and shelf sediments deposited at a lower stand of the sea, whereas the sinks are sand deposits that tend to close and fill the estuaries (Fig. 9).

Table 3. Potential for man's intervention in terms of the use of energy and the disposal of waste in recent years (1967–1971). The "extrapolated world value" is based on present U.S. standards of use and a population of 200×10^6 extrapolated to a present world population of 3.5×10^9. Heat units are converted to their mechanical equivalents.

Item, location, source, and amount	U.S. per capita value (metric units)	U.S. doubling time (years)	World value extrapolated from U.S. standards (metric units)
Power, United States, 1968			
Total energy consumed, 62.5×10^{15} British thermal units (*44*)	10.4 kw	14–20	36.4×10^9 kw
Electrical energy consumed, 1.33×10^{12} kilowatt-hours (*44*)	0.8 kw	9	2.7×10^9 kw
Waste heat (coolant) from the generation of electrical energy (1.5 watts of coolant per watt distributed)	1.5 kw	8	5.3×10^9 kw
Sewage			
Southern California, 10^7 people, 1968, 1.1×10^9 gallon day^{-1} (*45*)	416 liter day^{-1}		
New York City, 8×10^6 people, 1970, 1.3×10^9 gallon day^{-1} (*46*)	615 liter day^{-1}		20×10^3 m^3 sec^{-1}
Solids from domestic sewers into coastal waters, 500×10^3 ton $year^{-1}$ (*47*)	15 kg $year^{-1}$		
Oil			
Spillage into world oceans (*27*)		15	2.4×10^6 ton $year^{-1}$
Solid waste, United States			
Collected per capita in 1967, 5.2 pound day^{-1} (*44*)	2.4 kg day^{-1}	10	97 ton sec^{-1}
Dumped by barge into coastal waters, 1968, 62×10^6 ton $year^{-1}$ (*48*)	320 kg $year^{-1}$	10	36 ton sec^{-1}
Dredge fill, United States, 1971			
Bypass, disposal, and maintenance, 3×10^8 cubic yards (*49*)	1.6 ton $year^{-1}$	4	172 ton sec^{-1}
Mining of sand and gravel, 1970			
California, 23.5×10^6 U.S. tons (*35*)	1.1 ton $year^{-1}$		122 ton sec^{-1}
Great Britain, dredged from the North Sea, 13×10^6 British tons (*36*)	260 kg $year^{-1}$	5	29 ton sec^{-1}

The Extent of Man's Intervention

The continental shelves are the sites of rich oil and mineral deposits, and the shallow waters covering them include much of the plant and animal life in the sea. Nearshore waters impinge on the beaches, harbors, and estuaries, where utilities, industry, recreation, and the human habitat compete for the water supply. Thus man's intervention takes three interrelated forms: (i) the impact of numbers of people, all competing in diverse and complex ways for portions of the coastal zone; (ii) the pollution and contamination of coastal waters; and (iii) the critical modification of the natural balance in the ecology of plants and animals and in the sources of sediments that constitute the world's beaches. This impact on the coastal zone is occurring not only in America but throughout the world, especially in the more technically advanced countries. Thus the problems that prevail along the coastlines of the United States are all present in various degrees along the coasts of the Black Sea, the North Sea, the Sea of Japan, the Mediterranean Sea, in fact, wherever man has access to the coast (*24*).

Population

In terms of the present world population, the amount of shoreline is even now quite limited. If everyone in the world decided to spend some time along the 440,000 km of world shoreline, each person would have less than 13 cm of shoreline. Much of the shoreline would be in the Arctic and Antarctic regions, and there would be insufficient space for each person to stand and face the sea. In the State of California alone, there are approximately 500,000 pleasure craft registered, a sufficient number, at a length of 5 m per boat, to form a solid line twice the length of the coastline of the state. In recent years there has been an increase in migration toward the coastal zone. For example, California has increased in population from 6.9×10^6 in 1940 to 20×10^6 in 1970. Thus the population of California doubles every 14 years, whereas for the United States as a whole the population doubles every 50 years.

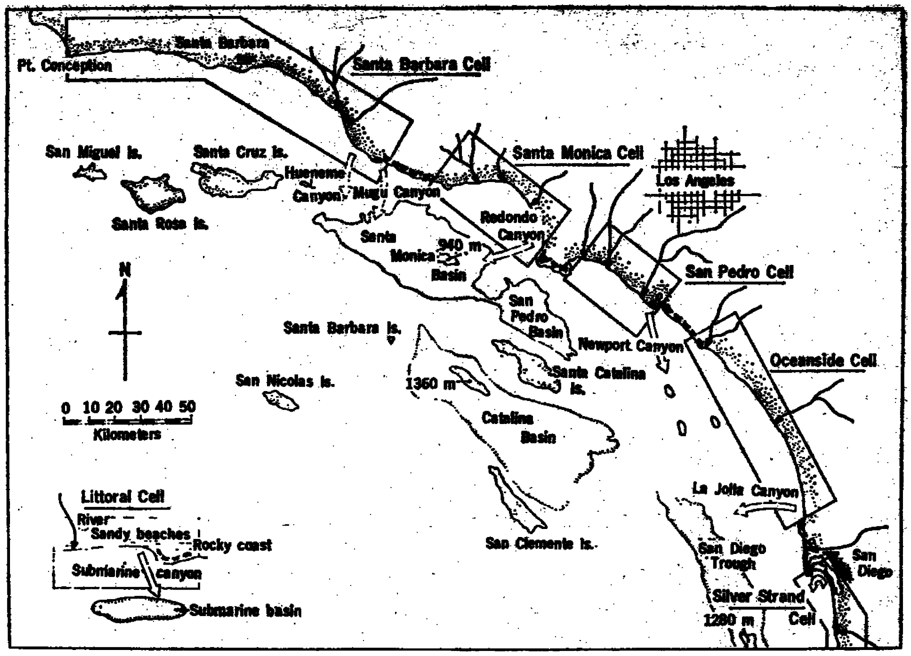


Fig. 10. Illustration of the five littoral cells along the Southern California coast. Each cell contains a complete sedimentation cycle. Most sand is brought to the coast by streams, carried along the shore by waves and currents, and lost into offshore basins by submarine canyons. [After Inman and Frautschy (*11*)]

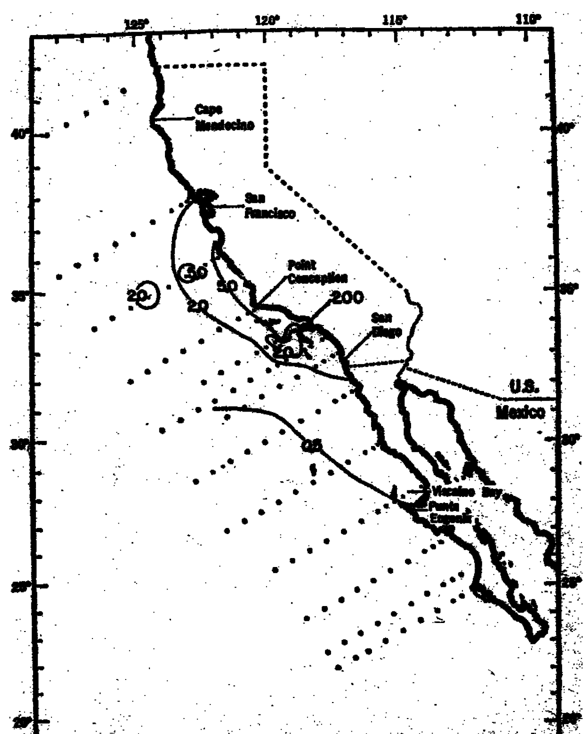
Pollution of Coastal Waters

The coastal zone receives the bulk of man's wastes, and coastal waters are beginning to show this impact in terms of a degradation of water quality arising from the presence of numerous types of biological and chemical pollutants, thermal pollution, and acoustic pollution. Although the surf zone characteristically has high mixing rates (Fig. 6), this is not true of the shelf as a whole. Wind- and wave-induced surface currents tend to produce circulation patterns that favor the retention of particulate material near the coast (Fig. 8), whereas biological scavenging and absorption by suspended particles (both biogenous and inorganic) concentrate dissolved pollutants in coastal waters (*25*). For example, one can trace the plume of the Columbia River for nearly 400 km along the Oregon coast by measuring the ^{51}Cr in the surface waters (*26*); the spatial distribution of DDT [1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane] in zooplankton exhibits "hot spots" along the California coast from north of San Francisco to the Mexican border, and significant amounts for 600 km south to Punta Eugenia in Baja California, Mexico (Fig. 11).

Major oil spills of various types and their conspicuously detrimental effects on beaches, marine organisms, and birds are now an everyday fact of life (*27*). The amount of spillage, presently 2.4×10^6 tons per year (Table 3), will inevitably increase in the future with the increasing consumption of oil and the introduction of supertankers having capacities of 2.5×10^5 tons and drafts in excess of 24 m. Moreover, the new big tankers have fewer bulkheads than the smaller tankers and thus have a potentiality for greater spillage when disabled.

So much plastic has been disposed of in the oceans that this material is now the most common type of flotsam on the world oceans; plastic particles in quasi-stable concentrations of 3500 pieces per square kilometer are widespread in the Sargasso Sea (*28*). Since every body of water has preferential windward shores (the prevailing wind systems cause some shores to be preferred to others), their beaches ultimately become the trash dumps for the world's flotsam. It was once romantic to find treasure at the shore—a

Fig. 11. Distribution of DDT and DDE [1,1-dichloro-2,2-bis(*p*-chlorophenyl)ethylene] in zooplankton (in units of 10^{-8} gram per cubic meter of surface water) along the coast of California and Baja California, Mexico, for 1969 (dots indicate sample locations). [From McClure and Barrett (*50*)] Since 99 percent of the DDT is absorbed on solid particulate material rather than in plankton, the total concentrations in seawater are approximately 100 times greater than shown here. [Courtesy of V. E. McClure and I. Barrett, National Marine Fisheries Service, La Jolla, California]



Japanese net float, a hatch cover for a fireside bench. Now the beaches are piled with an endless supply of "disposable" plastic containers.

Coastal waters are the principal recipient of sewage and of heat from power plants, both directly by marine outfalls and indirectly from rivers. This is particularly serious in regions where the population density is high. Inland waters arrive at coastal estuaries contaminated by diluents supporting floating solids and oils, chemical discards, mining tailings, and trash. Economic pressures on upstream communities often dictate a chain of relatively inefficient sewage "treatment" plants which remove only larger chunks, sparge chlorine gas into the mixture, and relay it downstream to the next community, and the next, until finally it arrives at the sea. Utilities and industries along the way avail themselves of water for heat exchangers, condensers, and extraction processes, thus raising the mean temperature of the water. It is estimated that, by the turn of the century, power-generating plants will produce roughly enough heat to raise by 20°C the total volume of water which runs over the surface of the United States (*29*).

Power plants operating on fossil fuel require the mechanical equivalent of 1.4 watts of waste heat (coolant) for each watt of electrical power generated, whereas nuclear power plants require about 2.1 watts of coolant for each watt of electrical power. The predicted power plant requirements for the California coast for 1980 are 37,000 megawatts. According to this estimate, coolant will be used at the rate of 1.2×10^{10} calories per second, and this is equivalent to the heating of a flow of about 15,000 m^3 of seawater per second by 1°C. This flow is equivalent to one-half of the estimated average flow over the California shelf, and is 10^{-3} of the total flow of the California Current, which is one of the ocean's permanent current systems (*30*).

Southern California with approximately 10×10^6 people discharges sewage into the Pacific Ocean at the rate of 48 m^3 sec^{-1}; New York City with 8×10^6 inhabitants discharges sewage into the Hudson Estuary and ultimately into the Atlantic Ocean at the rate of 57 m^3 sec^{-1} (Table 3). The sewage effluent is rich in nitrates and phosphates which locally may contribute to red tides, fish mortality, and the contamination of edible mollusks. However, more damaging in the long term is the introduction of an entire spectrum of organic and inorganic materials (*31*). Many of these are highly toxic and become concentrated in the organs of various fish and shellfish.

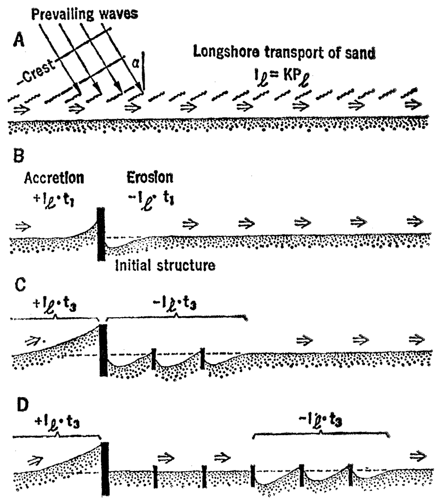


Fig. 12. Erosional chain reaction following the installation of a single coastal obstruction: (A) straight beach with prevailing waves producing a longshore transport of sand, I_l; (B) accretion and erosion showing initial obstruction; (C) downcoast erosion requiring two additional groins; and (D) continuation of the downcoast erosion requiring three more groins. Note that the first three groins are now unnecessary.

A crucial fact frequently overlooked when one is considering the dispersion of pollutants in nearshore waters is that the effective rate of mixing depends both upon the mechanics of the phenomena (for example, turbulence in the breaking wave) and upon the concentration gradient of the pollutant that is being mixed (that is, the change in the concentration of the substance with distance). The concentration gradient is dependent upon the nature of the substance and its past history of dispersion in the area. The concentration gradient is particularly sensitive to the background concentration of the substance already present in the receiving waters. The presence of background concentrations decreases the effectiveness of the mixing process by recirculating material already there, and this in turn leads to an exponential buildup of concentration in the receiving waters. Thus the presence of background concentrations progressively leads to saturation and a complete breakdown in mixing even though the mechanical mixing mechanism remains undiminished. This effect is demonstrated in the comparison shown in Fig. 6, A and B, and in the coastal concentrations shown in Figs. 7 and 11.

Critical Modification of Shorelines

Man's modification of the balance of sediment and his increasing depletion of the supply of sand to the beaches of the world has reached a critical state. On the one hand, man's use of the land has markedly increased the rate of erosion of the continents and increased the supply of sediment to rivers and streams. Paradoxically, the increasing construction of dams on most major streams results in the trapping and depositing of sediment behind the dams, thus shortening the life of the dam and intercepting the sediments that previously nourished the coasts and beaches. In this regard, the Aswan Dam on the Nile River is proving to be a major catastrophe.

The effect of dams on beaches is not always readily apparent. Erosion begins in the up-coast end of each sedimentation cell (Fig. 10) and progresses down the coast (Fig. 12). Most of the streams along the Southern California coast have dams and no longer supply sand to the coast. However, concurrent with the construction of dams, sand dredged from harbors and marinas has been placed on the beaches at approximately the same rate as sand supplied naturally by streams. For example, the Silver Strand littoral cell (Fig. 10, southern portion) has had no natural source of sediment since the Rodriquez Dam was completed in 1937. Silver Strand Beach has been maintained by artificially replacing 22×10^6 m^3 of sand in the period between 1941 and 1967.

The mining of beach and dune sands has further depleted this source, and the entrapment of coastal material by harbors, groins, and jetties has seriously reduced the supply of sand on beaches where it serves to protect the coast from the erosive action of waves. Moreover, sand is a valuable recreational asset that is now in very short supply. It is a natural resource which, like forests, streams, and mountains, should be protected.

It is well known that some of the activities of man, especially agriculture, construction, and deforestation, have in many places increased the rates of erosion of land by nearly an order of magnitude above the natural rate (*32*). The estimates of natural erosion listed in Table 2 are undoubtedly influenced by this factor, for man's influence on erosion can be documented to pre-Christian eras (*33*). On a global basis, it would appear that the present yield of sediment from the continents may be about twice what it was before man's introduction of large-scale agricultural and constructional activities during the past century. The increased yield of sediment causes an anomalous situation with regard to the supply of beach sand from rivers. The effective life of a dam is shortened by the rapid fill of sediment, and the very existence of beaches is imperiled by the termination of their natural source of sand (*34*).

The mining of beach sand has become an important industry in many areas. During 1970, 21.3×10^6 tons of sand and gravel were mined from beaches, river beds, and coastal sand dunes in California (*35*) (Table 3). During the same year, 112×10^6 tons were mined in Great Britain, of which 13.2×10^6 tons were mined from offshore banks, many of which provide essential protection to the coastline from wave erosion (*36*). A classic example is the erosion of the village of Hallsands which occurred in 1894 after 500,000 tons of gravel had been removed from a bank just offshore from the village (*37*).

By far, the most dramatic coastal intervention occurs when man interrupts the longshore transport of sand by the construction of jetties, breakwaters, and groins. Any artificial structure that produces a local accretion of sand by interrupting the transport of sand along a coast will cause, at least temporarily, a corresponding local erosion just down the coast from the area of accretion. Since the structure causes erosion to occur in a locality where erosion did not previously occur, or at a higher rate than occurred previously, a second structure is often needed to protect the new area of erosion. When built, this second structure in its turn causes erosion farther down the coast and a third structure is required to remedy this new situation, and so forth. Thus the construction of the first structure can set off a chain reaction that results in a requirement that the entire coastline be fronted by protective structures (Fig. 12).

The real "need" for a second or third structure may have been only temporary and may have diminished once the normal rate of longshore transport had been reestablished around the structure that caused the problem initially. However, if additional structures are built, the down-coast erosion becomes more severe with each succeeding structure, until finally a "point of no return" is reached where the need for additional protection from erosion becomes so urgent that the only choices are: (i) to continue to build protective works, (ii) to find a new source of beach sand, or (iii) possibly a combination of both.

From the foregoing it becomes apparent that the point of no return actually depends upon the longshore rate of transport of sand and the time needed to reestablish a normal transport rate around a structure. If a structure traps a large proportion of the total amount of sand transported longshore for a long period of time, the point of no return may be reached when only a single structure is built. On the other hand, it is possible to trap small amounts of sand at widely separated points along a coast provided that: (i) the total longshore transport rate is accurately known, so that the structure can be properly designed, and (ii) provisions are made to cope with the down-coast erosion until equilibrium in the longshore transport of sand is again established.

Comparison with Natural Phenomena

It is apparent that man's intervention in the coastal zone has both material and esthetic connotations. Almost all aspects of his impact on the environment are directly related to his numbers (the present population of the world is 3.5×10^9 people) and his relative affluence. An acceptable procedure for evaluating the extent and possible future consequences of man's intervention would be to assess his present intervention in the world's coastal zones and extrapolate these values to some future time, say, the year 2000, when it is estimated that the population will be 8×10^9 people. Unfortunately, the data are hopelessly inadequate except for a few of the advanced countries which constitute a small percentage of the population. Thus, an alternative, although less rigorous, procedure becomes necessary. We will assume that the present world population extrapolated to present U.S. standards of living constitutes a useful guide to man's potential for intervention in the future. Although admittedly less rigorous, this criterion is based on known and well-documented values of population and standards of living, thus providing an inherent simplicity in the assumptions and arithmetic. Global values for man's possible interventions, extrapolated to the present population from present U.S. standards, are shown in column 4 of Table 3.

It becomes readily apparent when Tables 1 and 2 are compared with Table 3 that man's intervention is indeed substantial. Man's extrapolated power consumption of 36.4×10^9 kw is over five times the total amount of natural energy dissipated in the shallow waters of the world, whereas the amount of waste heat (coolant) from electrical generators to be dissipated in the near-shore zone is slightly greater than the energy driving the dissipating mechanisms! It is more difficult to compare the effect of pollution of various types because the toxicity of the particular pollutant is not directly related to its volume or weight. However, the extrapolated volume of sewage effluent alone is 2 percent of all the discharge of the world's rivers. The extent of the distribution of DDT is dramatically illustrated in Fig. 11.

Man's solid waste disposal is much simpler to assess. Waste materials now cover significant portions of the sea floor adjacent to large metropolitan areas. Recent surveys show that waste-containing deposits cover about 210 km² of New York Harbor and the adjacent continental shelf (*38*). The extrapolated value for the waste disposal in coastal waters is 7 percent of the total discharge of solids from the world's rivers, whereas the extrapolated value for the bypassing of solid material by dredging is 32 percent of the world's supply of solids from land! Even more significant is the effect of the mining of sand and gravel, which would constitute 23 percent of the world's solids, when only about 10 percent of the solids supplied by rivers are in sand and gravel sizes, the remainder being silt and clay which is not suitable for beaches or building materials.

Planning Criteria

Our understanding of shore processes is still in a rudimentary stage, and it is not yet possible to describe many important phenomena and their interactions by rigorous theory. Only during the past 5 years or so have experiment and measurement progressed to the point where even general concepts can be formulated and tested. However, as this brief résumé of the physical processes shows, it is beginning to be possible to identify and to understand some of the mechanisms that are currently being studied, and to place what we do know in a planning context.

It has become evident with more intensive study that shorelines all over the world are subject to similar dynamic experiences. As a result, it will soon be possible to forecast the mixing ability of the waters over the shelf on a local regional basis. It will be possible to predict the longshore transport rate of sand, and to assay the effectiveness of various techniques for bypassing sand around coastal obstructions and harbors (Fig. 13). It is possible to estimate and pace man's intervention both in terms of utilization and waste. There is a desperate urgency associated with fitting these components into a coherent planning effort: the impact is harsh and frighteningly nonlinear, and the need is great right now!

If resolute planning is undertaken at once, the needs of society in terms of the coastal zone may be served with a directed and justified meliorism. The history of efforts to influence the utility of coasts and harbors extends far back in time, but the concern for preservation and conservation has been a recent addition. Two types of efforts have been made: historical efforts made on a palliative local basis with limited tools and technology, and more recent undertakings characterized by emerging knowledge of basic principles combined with single-remedy technology. (This type of technology may solve the single problem but may also create other problems.)

The systems concept is now a mandate; the balance of nature has its corollary in coastal undertakings. Previous self-perpetuating mistakes not only have left visible scars, they also have affected the environment in ways easily detectable to a concerned observer. Any guidelines fundamental to coastal planning necessarily involve an understanding of the natural physical processes active in the environment. It has been shown that these processes are driven by primary interrelated forces that are essentially systematic and regular in form. This observation is borne out by recent findings that the extent of the mixing of water in the surf zone can be predicted from a knowledge of the breaker height and the width of the surf zone, and the longshore transport of sand is directly proportional to the longshore component of the energy flux of the incident waves. Thus a coherent approach to the formulation of unifying planning criteria seems clearly within our grasp; and it is becoming apparent that the driving forces (that is, the nearshore "climate" which consists of waves, winds, and current in nearshore waters) and the budget of sediment in a given coastal region are the principal environmental measurements that must be assessed for effective planning.

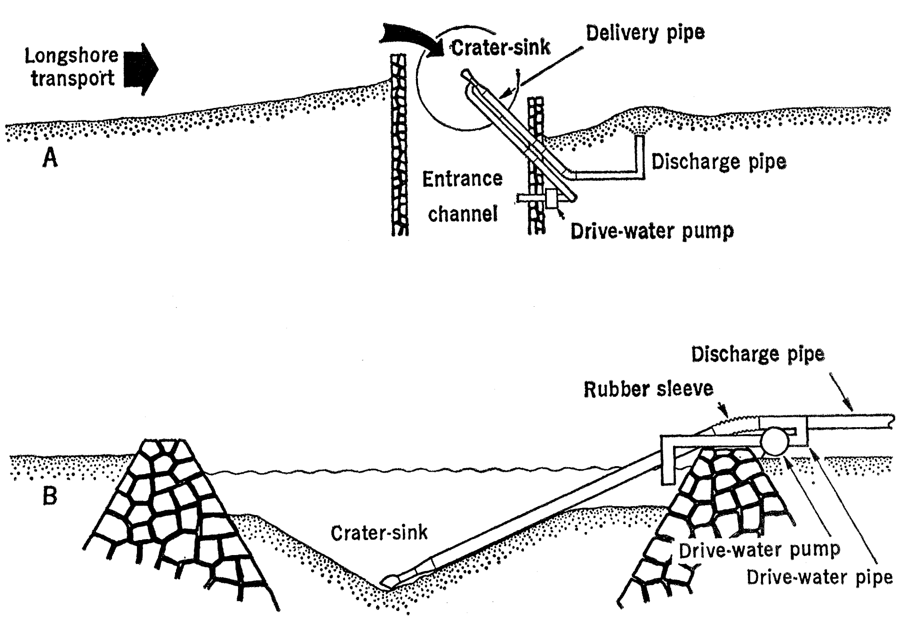


Fig. 13. The "crater-sink" sand transfer system, one of the systems under study for improving the bypassing of sand around harbors without requiring large entrapment basins and their accompanying offshore breakwaters: (A) plan of the entrance channel; (B) enlarged cross section. This system may be installed and operated at a relatively low cost. A jet pump (similar to a steam ejector) and a suction nozzle are located in the bottom of a crater-like depression in the sea floor which acts as a collecting basin for sand. The crater-sink assures that the water will be deep at the entrance. [From Inman and Harris (*51*)]

At least three distinct approaches are necessary if we are to achieve the overall goal of determining the essential qualities of unifying criteria: (i) specific studies of phenomena vital to our understanding of nearshore processes, (ii) the development of the sensors and systems for data-handling that permit effective monitoring of coastal climate and sediment transport, and (iii) the development of new planning criteria and the dissemination of information on known processes.

Coastal communities are presently in the curious position of rapidly acquiring and improving beach frontage while at the same time they lack criteria for evaluating the likelihood that the beach will still be in existence in 10 or 20 years. Certainly, the future of any coastal man-made structure placed in the path of the longshore movement in a littoral cell (Fig. 10) is questionable, and great reservations should accompany any commitment to build such a structure. Aerial photographs of Miami Beach, Florida, or Cape May, New Jersey, show the abuse to the coastline that can result when cascades of groins (Fig. 12) are erected without a master plan.

It is imperative that we develop the means to preserve the beaches and harbors that we now have and that we develop practical techniques for creating new beaches and nearshore structures that are less damaging to the environment. From an environmental standpoint there are three fundamental steps necessary for the good design of coastal structures: (i) identification of the important processes operative in an environment, (ii) understanding of their relative importance and their mutual interactions, and (iii) the correct analysis of their interaction with the contemplated design. To some extent we have considered all of these factors in earlier sections of this article, the emphasis being on the first two. There is no substitution for direct measurements in identifying and determining the relative importance of the various environmental parameters. It is also necessary that measurements be continued over a sufficient length of time so that predictions based on an earlier series of measurements can be tested for agreement with a subsequent series.

The need to develop new technologies to cope with specific problems is urgent. This type of development will likely be achieved simply because the need is specific and urgent, and there is a material objective. The stronger basic challenge lies in our ability to formulate satisfactory criteria for long-range planning and to develop an effective procedure for disseminating and implementing these criteria. It is now clear that man can no longer treat bits and pieces of a coast as individual entities; rather he must develop planning procedures that will include entire coastal zones and their adjacent ocean environments. This will require the development of planning criteria based on a far better understanding of both physical processes and environmental ecosystems than we now possess.

Human vanity does not encourage the recognition of failings, but one failing that must be recognized for survival is the fact that evolution has never prepared our species to think exponentially; this ability is a hard-won achievement of the disciplined mind. Cogent arguments abound for early and resolute planning in the coastal zone, with due allowance for the exponential hazards.

The Freeway Effect

The freeway effect (growth breeds growth) occurred in California as a result of the construction of improved, limited-access roadways. These roads were intended to relieve traffic congestion. They caused, instead, increased use of the available roadways, and people changed their living habits to suit their convenience. The freeway effect may be noted in population growth, energy production, automobile and appliance design, and agriculture. The unidirectional animus specifically threatens the coastlines, because it encourages one to believe that it is beneficial to build unlimited numbers of marinas, to erect increasing numbers of power plants, to construct housing developments adjacent to existing housing developments, or to increase the number of drilling sites, or the number of commercial and shipping facilities with insufficient evaluation of possible alternatives.

If planning efforts are ineffective and ill-informed, then people are inclined to proceed with each of the foregoing proposals as though the others should give way before it. An informed and concerned public reaction of hitherto unknown magnitude may possibly lead to solutions for the problem of slowing and redirecting the machine, without wrecking the machinery: that is the coastal challenge.

References and Notes

1. D. L. Inman and C. E. Nordstrom, *J. Geol.* **79**, 1 (1971).
2. F. P. Shepard, *Submarine Geology* (Harper & Row, New York, ed. 2, 1963), p. 257.
3. F. Ursell, *Proc. Roy. Soc. Ser. A* **214**, 79 (1952).
4. M. S. Longuet-Higgins, *Phil. Trans. Roy. Soc. London Ser. A* **245**, 535 (1953); D. L. Inman and A J. Bowen, in *Proceedings of the Eighth Conference on Coastal Engineering*, J. W. Johnson, Ed. (Council on Wave Research, University of California, Berkeley, 1963), pp. 137–150.
5. M. S. Longuet-Higgins and R. W. Stewart, *Deep-Sea Res.* **11**, 529 (1964); D. L. Inman, A. J. Bowen, V. P. Simmons, *J. Geophys. Res.* **73**, 2569 (1968).
6. A. J. Bowen and D. L. Inman, *J. Geophys. Res.* **74**, 5479 (1969); E. B. Thornton, *Proceedings of the Twelfth Coastal Engineering Conference* (American Society of Civil Engineers, New York, 1970), pp. 291–308.
7. F. P. Shepard and D. L. Inman, in *Proceedings of the First Conference on Coastal Engineering*, J. W. Johnson, Ed. (Council on Wave Research, University of California, Berkeley, 1951), pp. 50–59.
8. D. L. Inman, R. J. Tait, C. E Nordstrom, *J. Geophys. Res.* **76**, 3493 (1971).
9. D. L. Inman, *Trans. Amer. Geophys. Union* **51**, 319 (1970); R. A. Bagnold, in *The Sea, Ideas and Observations: The Earth Beneath the Sea*, M. N. Hill, Ed. (Interscience, New York, 1963), vol. 3, pp. 507–528.
10. D. L. Inman and R. A. Bagnold, in *The Sea, Ideas and Observations: The Earth Beneath the Sea*, M. N. Hill, Ed. (Interscience, New York, 1963), vol. 3, pp. 529–553.
11. D. L. Inman and J. D. Frautschy, in *Coastal Engineering* (Santa Barbara Specialty Conference) (American Society of Civil Engineers, New York, 1966), pp. 511–536.
12. Here $P_l = P \sin \alpha \cos \alpha$, where P is the power per unit crest length of the breaking wave and α is the breaker angle [see P. D. Komar and D. L. Inman, *J. Geophys. Res.* **75**, 5914 (1970)].
13. S. Gofseyeff, in *Proceedings of the Third Conference on Coastal Engineering*, J. W. Johnson, Ed. (Council on Wave Research, University of California, Berkeley, 1953), pp. 272–305.
14. J. W. Johnson, *Amer. Ass. Petrol. Geol. Bull.* **40**, 2211 (1956); *J. Waterways Harbors Div. Amer. Soc. Civil Eng.* **83**, 1211 (1957).
15. J. S. Malkus, in *The Sea, Ideas and Observations: Physical Oceanography*, M. N. Hill, Ed. (Interscience, New York, 1962), vol. 7, p. 98.
16. D. L. Inman, in *Oceanography: The Last Frontier*, R. C. Vetter, Ed. (Basic Books, New York, in press).
17. W. G. Van Dorn, in *Advances in Hydroscience*, V. T. Chow, Ed. (Academic Press, New York, 1965), vol. 2, pp. 1–48.
18. J. H. Hoyt and V. J. Henry, Jr., *Geol. Soc. Amer. Bull.* **82**, 59 (1971).
19. S. A. Schumm, *U.S. Geol. Surv. Prof. Pap. 454-H* (1963).
20. J. Gilluly, *Geol. Soc. Amer. Spec. Pap. 62* (1955), pp. 7–18; H. W. Menard, *J. Geol.* **69**, 154 (1961).
21. J. Gilluly, J. C. Reed, Jr., W. M. Cady, *Geol. Soc. Amer. Bull.* **81**, 353 (1970).
22. This is based on the assumption that continental rock with a density of 2.7 ton m^{-3} erodes to form 20 percent dissolved load and 80 percent solid particulate load.
23. K. O. Emery, *Amer. Ass. Petrol. Geol. Bull.* **52**, 445 (1968).
24. For example, M. I. Goldman, *Science* **170**, 37 (1970); D. W. Hood, Ed., *Impingement of Man on the Oceans* (Wiley, New York, 1971); W. Marx, *The Frail Ocean* (Ballantine, New York, 1967).
25. E. D. Goldberg, W. S. Broecker, M. G. Gross, K. K. Turekian, in *Radioactivity in the Marine Environment* (Committee on Oceanography, National Academy of Sciences, Washington, D.C., 1971), pp. 137–146.
26. C. Osterberg, N. Cutshall, J. Cronin, *Science* **150**, 1585 (1965).
27. R. Revelle, E. Wenk, B. H. Ketchum, E. R. Corino, in *Man's Impact on Terrestrial and Oceanic Ecosystems*, W. H. Matthews, F. Smith, E. D. Goldberg, Eds. (M.I.T. Press, Cambridge, Mass., 1971), pp. 297–302; M. Blumer and J. Sass, *Science* **176**, 1120 (1972); Ocean Science Committee, *Marine Environmental Quality* (National Academy of Sciences, Washington, D.C., 1971); Massachusetts Institute of Technology, *Man's Impact on the Global Environment* (C. L. Wilson and W. H. Matthews, chairmen) (M.I.T. Press, Cambridge, Mass., 1971).
28. E. J. Carpenter and K L. Smith, Jr., *Science* **175**, 1240 (1972); E. J. Carpenter, S. J. Anderson, G. R. Harvey, H. P. Miklas, B. B. Peck, *ibid.* **178**, 749 (1972).
29. P, M. Boffey, *ibid.* **168**, 1554 (1970). These data are projected from the 1980 base established in "National Power Survey, A Report by the Federal Power Commission 1964" (Government Printing Office, Washington, D.C., 1964), p. 36; we here assume 12.3×10^{12} kilowatt-hours for the year 2000 and a water flow of 4.2×10^{11} m^3 $year^{-1}$.
30. W. S. Wooster and J. L. Reid, Jr., in *The Sea, Ideas and Observations: Composition of Seawater*, M. N. Hill, Ed. (Interscience, New York, 1963), vol. 2, pp. 253–280.
31. E. D. Goldberg and M. G. Gross, in *Man's Impact on Terrestrial and Oceanic Ecosystems*, W. H. Matthews, F. Smith, E. D. Goldberg, Eds. (M.I.T. Press, Cambridge, Mass., 1971), pp. 371–376; E. D. Goldberg, in *Fertility of the Sea*, J. D. Costlow, Jr., Ed. (Gordon & Breach, New York, 1971), pp. 143–156; see also (*25*).
32. H. W. Lull, in *Man's Impact on Terrestrial and Oceanic Ecosystems*, W. H. Matthews, F. Smith, E. D. Goldberg, Eds. (M.I.T. Press, Cambridge, Mass., 1971), pp. 240–251; R. H. Mean, *Geol. Soc. Amer. Bull.* **80**, 1265 (1969); S. Judson, *Amer. Sci.* **56**, 356 (1968).
33. S. Judson, *Science* **160**, 1444 (1968).
34. C. P. Vetter, *Iowa Univ. Studies Eng. Bull.* **34**, 5 (1952).
35. *Calif. Geol.* **25** (No. 4), 90 (April 1972).
36. A. A. Archer, in *North Sea Science*, E. D. Goldberg, Ed. (M.I.T. Press, Cambridge, Mass., in press).
37. W. A. Price, personal communication.
38. M. G. Gross, *Geol. Soc. Amer. Bull.* **83**, 3163 (1972).
39. For example, B. Kinsman [*Wind Waves* (Prentice-Hall, Englewood Cliffs, N.J., 1956), p. 154] estimates that the energy dissipated by waves hitting the shoreline is 1.9×10^9 to 2.2×10^9 kw.
40. On the assumption that the dissipation of lunar tidal energy in shallow water is 1.7×10^9 kw, and that the ratio of the flux of solar to lunar tidal energy is the same as their torques, that is, 1 : 3.4. W. H. Munk and G. J. F. MacDonald [*The Rotation of the Earth* (Cambridge Univ. Press, London, 1960), p. 201] estimate the total dissipation of lunar tidal energy as 2.7×10^9 kw, of which two-thirds is dissipated in shallow seas [G. R. Miller, thesis, University of California, San Diego (1964)].
41. Average value from K. K. Turekian, in *Impingement of Man on the Oceans*, D. W. Hood, Ed. (Wiley, New York, 1971), chap. 2, pp. 9–72, based on data of D. A. Livingstone [*U.S. Geol. Surv. Prof. Pap. 440-G* (1963), p. 64], O. A. Alekin and L. V. Brazhnikova [*Gidrokhim. Mater.* **32**, 12 (1961)], and J. N. Holeman [*Water Resour. Res.* **4**, 737 (1968)].
42. R. M. Garrels and F. T. Mackenzie, *Evolution of Sedimentary Rocks* (Norton, New York, 1971), table 5.1.
43. On the assumption that the total particulate load consists of 15 percent bed load and 85 percent suspended load, where values of the suspended load are averages from Garrels and Mackenzie (*42*), Turekian (*41*), and Holeman (*41*).
44. U.S. Department of Commerce, *Statistical Abstracts of the United States, 1970* (Government Printing Office, Washington, D.C., ed. 91, 1970).
45. Southern California Coastal Water Research Project, 1100 Glendon Avenue, Los Angeles 90024 (unpublished report, 1970).
46. M. Eisenbud, *Science* **170**, 706 (1970).
47. E. D. Goldberg, *McGraw-Hill Yearbook of Science and Technology, 1970* (McGraw-Hill, New York, 1971), pp. 65–73.
48. D. D. Smith and R. P. Brown, "Ocean Disposal of Barge-Delivered Liquid and Solid Wastes from U.S. Coastal Cities," report prepared for the Environmental Protection Agency by the Dillingham Corporation, La Jolla, California (1971); M. G. Grass, in *Man's Impact on Terrestrial and Oceanic Ecosystems*, W. H. Matthews, F. Smith, E. D. Goldberg, Eds. (M.I.T. Press, Cambridge, Mass., 1971), pp. 252–260.
49. "Disposal of Dredge Fill," report to the

U.S. Congress by the Chief of Engineers, U.S. Army (unpublished report, 1971).
50. V. E. McClure and I. Barrett, in *Baseline Studies of Pollutants in the Marine Environment*, E. D. Goldberg, workshop chairman (National Science Workshop, Brookhaven National Laboratory, New York, 1972), pp. 493–497.
51. D. L. Inman and R. W. Harris, *Proceedings of the Twelfth Coastal Engineering Conference* (American Society of Civil Engineers, New York, 1970), pp. 919–933.
52. This work was sponsored by the National Oceanic and Atmospheric Administration, Office of Sea Grant, under grant 04-3-158-22 with the Institute of Marine Resources, University of California. The background knowledge of basic mechanisms described in this study evolved under long-range support by the Office of Naval Research and the Coastal Engineering Research Center, U.S. Army Corps of Engineers, with the Scripps Institution of Oceanography, University of California, La Jolla.

Chemostimulatory Protein: A New Type of Taste Stimulus

Two proteins that taste sweet are now known.

Robert H. Cagan

A wide range of biological activities is known to be effected by various proteins, including enzymic catalysis, membrane transport, immunological specificity, hormonal activity, and maintenance of structural integrity. Until very recently, however, no macromolecule was known to act as a specific taste stimulus in man. Solms in 1969 (*1*) correctly summarized the earlier state of knowledge: "It is generally accepted that proteins exert no taste activity." In addition to the well-known sweet taste of many sugars, certain D-amino acids were known to possess some sweetness although their L-enantiomers were usually tasteless or bitter (*1, 2*). Recently, the synthetic dipeptide ester L-Asp-L-Phe-Me (*3*) and certain closely related dipeptide esters, as well as several other α-amides of L-aspartic acid, were shown to be sweet (*4*). Other small peptides, however, were known to be bitter, sour, or tasteless (*5*). Of the molecules previously known that evoke specific taste sensations, such as sweet, sour, salty, and bitter, none have been proteins. In this article I review recent discoveries of three taste-active proteins of plant origin, and propose that two of these proteins should be called "chemostimulatory proteins" because of their sensory effect. The third protein was originally called both the "taste-modifying protein" and "miraculin" (*6, 7*). "Taste-modifier protein" is used here as a generic term, and the specific designation "miraculin" is retained for the single known protein of this type.

Both of the known chemostimulatory proteins are intensely sweet. The single known taste-modifier protein changes the normal taste sensation of acids from sour to sweet after the tongue has been treated with the protein. Chemostimulatory and taste-modifier proteins are to be distinguished from receptor proteins. The latter are cellular proteins, often in the plasma membranes of the receptor cells, that interact with extracellular chemicals. Examples of receptor proteins are the acetylcholine-receptor proteins of neural tissues (*8*), the insulin-receptor proteins of liver and fat cells (*9*), and the galactose-binding protein that is essential for chemotaxis of the bacterium *Escherichia coli* toward galactose (*10*). On the other hand, receptor proteins have not been isolated from taste receptor cells (*11*) although their existence has often been postulated in the past.

Three Taste-Active Proteins

The botanical origins, geographical distributions, and biochemical properties of the three proteins (miraculin, monellin, and thaumatin) now known to have defined effects on the taste system of humans are summarized in Tables 1 to 3. Perhaps the most extraordinary of the three proteins from a phenomenological point of view is miraculin, the taste-modifier protein. After the tongue is treated with this glycoprotein, acids which are normally sour then taste sweet. The effect of the drug is prolonged; for example, the effect lasted for more than 3 hours after a 2.3 micromolar solution of miraculin was held in the mouth for 5 minutes (*12*). Miraculin does not itself taste sweet. The fruit and its effect have been known for many years (*13*) and the isolation of the glycoprotein was reported in 1968 independently by two laboratories (*6, 7*). It has substantial potential as an experimental tool in taste research.

Monellin was isolated in electrophoretically pure form and characterized as a sweet-tasting protein (*14*); almost simultaneously thaumatin was partially purified and reported to be a sweet-tasting protein (*15*), confirming independently that a protein can act as a specific taste stimulus. The finding that monellin is a protein was not in agreement with an earlier conclusion (*16*) that the sweet principle in *Dioscoreophyllum cumminsii* is a carbohydrate; the conclusion that it is a protein has been confirmed, however, by recent independent findings (*17, 18*). Because of the intensity and persistence of the sweet taste of monellin, this protein holds considerable promise as an experimental tool in taste research.

Chemistry of Miraculin, Monellin, and Thaumatin

Unlike miraculin, neither monellin nor thaumatin are glycoproteins. The molecular weights of the chemostimulatory proteins are considerably lower than that of miraculin (Table 2) (*19*). Active monellin consists of a single polypeptide chain of molecular weight 10,700 (*20*). The size of the active thaumatin molecule is not known with

The author is a member of the Monell Chemical Senses Center, University of Pennsylvania, a research scientist at the Veterans Administration Hospital, Philadelphia, and assistant professor of biochemistry, School of Medicine, University of Pennsylvania, Philadelphia 19104.