COASTAL PROCESSES AND BEACH EROSION

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1. First, let it be recognized that none of the coastal processes relating to beach erosion are understood with the exactitude of some other hydraulic phenomena. The gross processes are known and fairly well understood; however, the desirable quantitative understanding has not yet been established, though continuing research is directed to this end. Nevertheless, the understanding which is available is applied to actual engineering problems around our coasts, with increasingly encouraging results. The fundamentals of these coastal processes and their application to selected engineering problems are given in this paper.

Nature of the Coast

2. Most of our ocean coasts—and indeed most of the coasts of the world—are composed of unconsolidated, granular deposits in the form of sand or gravel. This material has reached the shore face through fluvial transport, glacial transport, or by deterioration and fragmentation of the adjacent uplands. By and large, we find that we work with the materials which have been laid down on the coast over the centuries. In the United States, a few rivers, such as the Mississippi and some of the West Coast rivers and streams, still contribute material in quantities which are significant in the local shore processes. However, in most of our shore problems, we are working with the sand that has already reached the shore and we can depend little if at all on new contributions.

3. As an example, our Atlantic beaches from Long Island to Key West receive practically no new shore building material from the uplands. Thus, what is lost in any manner from the shore face is essentially a permanent loss unless replacement is effected by works of man.

Wave Action

4. The dominant forces in coastal waters are the wind-generated waves from the sea. The internal currents and turbulence in the waves

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stir up and transport the sand in varying degrees depending on the type of wave and the type of bed material. Most of this activity takes place in the zone between the 50-foot contour and the limit of wave uprush on the shore; this may be defined as the active zone. Now in what direction is the sand moved by the waves? Onshore or offshore? Or along the coast? Let us first consider the question of the wave action itself.

5. Wave trains generated by the wind are complex in that they contain high waves, low waves, long waves, and short waves. The actual wave pattern, or spectrum, depends on the wind *duration,* the *wind velocity,* and the *fetch*—the fetch being the overwater distance which is under the influence of a wind blowing in a single direction. The spectrum of waves at the end of the fetch can be predicted with fair accuracy. (1) A study of this wave spectrum will show that certain wave heights and wave periods tend to dominate the spectrum; these dominant waves are frequently referred to as the *significant waves* of the spectrum. The wave length in deep water is related to the wave period by the formula:

$$L = \frac{gT^2}{2\pi}$$

where L = wave length in feet

T = wave period in seconds

g = gravity (32.2 ft/sec/sec)

Thus, knowing the significant wave period, the significant wave length can be computed. This length can then be compared to the significant wave height to give us a height/length (H/L) ratio or *wave steepness* ratio. This ratio will be shown to be very important in determining the effect of the wave on the beach.

6. It can be shown (2) that generally the wave steepness ratios of the significant waves in a wave generating area (i.e., within the fetch area) lie in the range of 0.014 to 0.040. Once the wave train leaves the generating area, the short period waves dissipate their energy more rapidly than the long period waves. Thus there is a gradual shift in the significant wave period and length to the long-period end of the spectrum. This shift is accompanied by a decrease in significant height due to a gradual dissipation of energy throughout the

spectrum. The net result is a shift in the H/L ratio of wave steepness ratio to smaller and smaller values. An example of this shift in steepness is shown in the following tabulation.

GENERATING CONDITIONS

Wind velocity	40 knots
Wind duration	12 hours
Fetch	200 miles

	Significant Wave Period	Significant Wave Length	Significant Wave Height	Steepness H/L
At end of fetch	11.0 sec.	620 ft.	19.3 ft.	0.031
100 miles later	13.0	865	11.6	0.013
500 miles later	14.6	1090	8.7	0.008
2,000 miles later	15.8	1280	4.4	0.003

From this tabulation, it can be seen that storms in the open ocean may generate wave trains which will eventually reach and affect shore hundreds of miles away. Waves from local storms reach the local shore as tempestuous storm waves with significant wave periods usually from 5 to 12 seconds and with heights up to twenty feet or more: waves from distant ocean storms generally reach the shore as long, low swells with significant periods ranging from about 10 to 20 seconds. The transition or decay, from storm waves to swells is, of course gradual. Methods exist for computing the decay of the wave train after it leaves the generating area. (3)

ONSHORE-OFFSHORE MOVEMENT

7. As stated previously, the waves advancing shoreward finally reach a depth where the internal wave currents begin to disturb and move the bottom particles. The action is particularly pronounced at the point where the wave breaks; here in the surf zone large quantities of sand are thrown into semi-suspension and quantities are also moved on the bottom somewhat as bed-load. Numerous laboratory experiments supported by a number of field studies have established that the short, tempestuous storm waves tend to drag material from the beach face and deposit it in deep water. Conversely, the long swells tend to push the offshore material back onto the beach.

8. Thus we find on most beaches a shuttling of the sand back and

forth between the inshore and offshore zone. A series of local storms, or a local storm of long duration, can erode the beach and dune area sufficiently to lay open the back shore area to considerable destruction. For instance, the beach width on the south shore of Long Island frequently erodes 50 to 100 or more feet during the winter storms only to rebuild itself during the subsequent summer season.

Effect of Wave Angularity

9. Wave trains seldom approach the shore at right angles. Even though refraction does tend to swing the crests into parallelism with the shore contours, the residual angle of the waves with the beach results in the generation of an alongshore current called the littoral current. This current is noticeable even seaward of the surf zone, but is most pronounced in and shoreward of the surf zone. Recent studies (4) indicate the incident wave and littoral current relationship for small approach angles for a laboratory beach on a 1:10 slope and for a natural beach to be:

$$V = gmT \sin 2\alpha$$

where V = longshore current velocity, m is beach slope, T is wave period, and α is angle between wave crest at breaking and shoreline. Though having some theoretical basis, the relationship is largely empirical. Under this relationship, the maximum velocity would be

$$V_{max} = gmT \text{ when } \alpha = 45°.$$

Refraction effects would, however, seldom, if ever, permit a breaker angle of 45°, values between zero and about 20° being much more common. Littoral current velocities estimated by the above relationship are given in the following tabulation although laboratory data indicate that a correction must be made to the equation for V at the larger angles, the correction acting to reduce the predicted V's for the larger angles. Though these estimated velocities are based on a relationship derived largely from laboratory tests, the estimated velocities appear to be in the right order in light of known field conditions. The absence of the wave height H, from this relation is due to the fact that an increase in H causes the wave to break farther offshore; this in turn increases the total littoral current volume but apparently has only a secondary effect on its velocity.

Estimated Littoral Drift Velocities
(ft/sec)

m	.01			.025			.04		
T / α	5	10	15	5	10	15	5	10	15
5°	.28	.56	.84	.70	1.40	2.10	1.12	2.24	3.36
10°	.55	1.10	1.65	1.38	2.75	4.13	2.20	4.40	6.61
15°	.81	1.61	2.42	2.01	4.02	6.04	3.22	6.44	9.66
20°	1.03	2.07	3.11	2.58	5.18	7.77	4.13	8.28	12.43

where:

m = beach slope

T = wave period in sec.

α = angle of breaker with shore

10. Thus we find that the incoming waves usually generate an alongshore, or littoral current. The velocity of this current is in many cases too low to, of itself, move the bed materials; however, it always acts to move with itself any material which has been placed into even temporary suspension by wave action. This combination of the stirring action of the waves and the littoral current acts to transport sizeable quantities of sand along the shore face. Measurements on coasts subjected to the constant pounding of the trade winds have indicated littoral drift rates of in excess of five million cubic yards per year, though most coastal areas exhibit less than one million cubic yards per year of littoral drift.

11. Numerous laboratory tests coupled with a few field observations show an empirical relationship (5) between incident wave energy and alongshore sand transport. Though admittedly needing additional study and refinement, the relationship is useful. The relationship is expressed as

$$Q = KE_i^{0.8} = 210\ E_i^{0.8}$$

where Q_i = rate of alongshore sand transport in cubic yard per day

E_i = alongshore component of incident wave energy in millions of foot-pounds per foot of beach per day

K = factor of proportionability (tentatively 210).

The value of E_i is in turn defined as:

$$E_i = E_p \sin \theta \cos \theta$$

where E_p = potential energy of incident wave train.

θ = angle of wave crest with shore at point where wave height and length are measured.

The potential energy, E_p, is of course that portion of the total wave energy which moves shoreward as opposed to the kinetic energy, E_k, which does not move shoreward. The value of E_p is expressed by:

$$E_p = 0.64\ WTh_s^2\ n\ (\tanh 2\pi\ d_s/L_s)\ t$$

where E_p = summation of forward-moving (potential) energy, ft/lbs.

T = wave period, sec.

h_s = wave height (ft.) at point of observation

d_s = depth (ft.) of water at point of observation

L_s = wave length (ft.) of water at point of observation

n = fraction of total energy transmitted forward with wave form

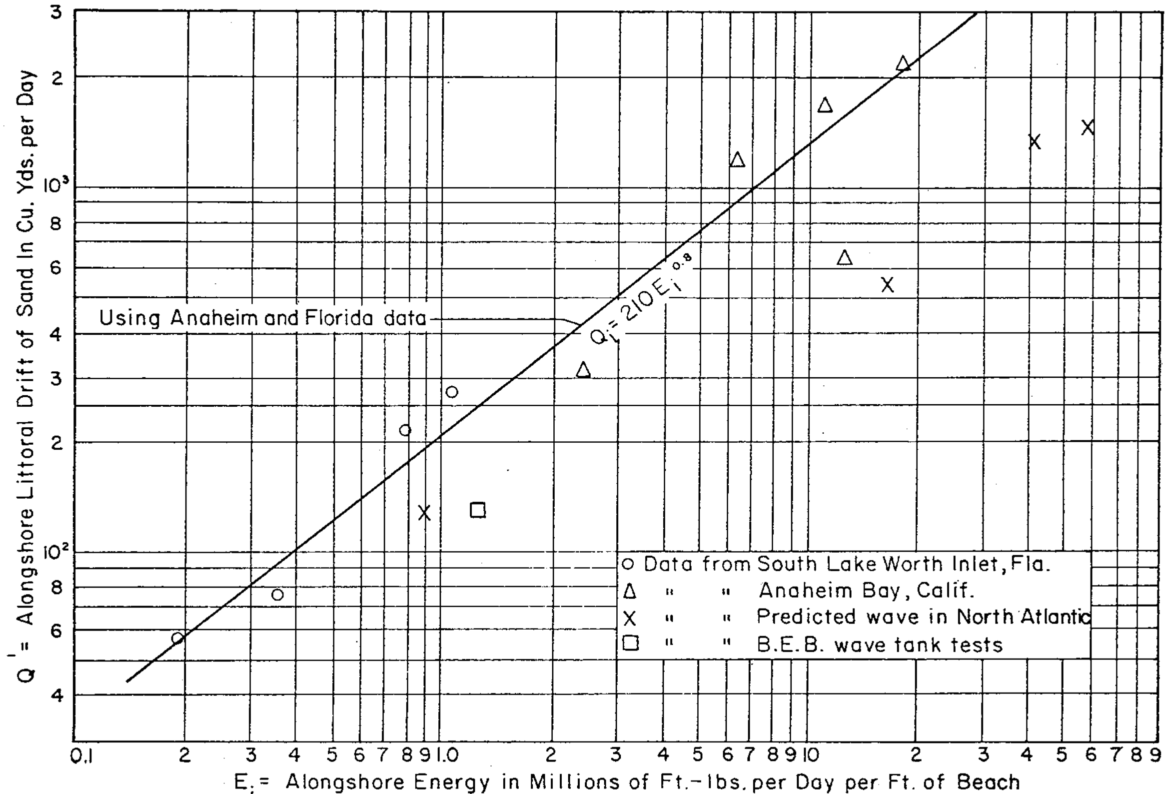
t = time interval (seconds) over which energy is summarized

W = specific weight of liquid in pound per cubic foot (64.0 for sea water).

Of course, if the wave measurements are made in deep water ($d_s > 1/2\ L_s$) the energy expression can be simplified to

$$E_p = 0.64\ WTh_s^2$$

12. From the above, it can be seen that, given the wave height, length, and direction, it is possible to predict the value of the alongshore component of wave energy, E_i. From this value it then is possible to estimate the rate of littoral drift. Or, as a further possibility, given the applicable weather maps, it is possible to predict the incident wave pattern and from this the alongshore drift. This latter computation was made for four points on the New Jersey shore for which a set of wave predictions (or wave "hindcasts") covering three years had been made by the Beach Erosion Board for other purposes. The rate of drift at



RELATION OF ALONGSHORE DRIFT TO ALONGSHORE WAVE ENERGY

FIG. 1

the four selected points is known fairly accurately from field measurements made by the Corps of Engineers. A comparision of the various points established by the above work is shown on Fig. 1. Though showing a promising degree of consistency, the plotted points indicated that additional refinement is still needed.

13. Another approach to the question of littoral transport is through measurements of the material thrown into suspension on the shore face coupled with the velocity of the littoral current. Measurements of sand in suspension in and near the surf zone were made in 1950-51 at Mission Bay, California, by the Beach Erosion Board. (6) A pump-type sampler was used to take over 170 samples under a wide range of wave conditions and indicated concentrations ranging from about 0.10 to over 4.5 parts per thousand by weight with most samples being in the 0.15 to 0.70 ppt. range. The samples were taken between the 12-foot contour and the shore. The samples, when combined, indicated the amount of sand in suspension per foot of shore to about as follows: (6)

Range of wave height	Sand in suspension in cubic yard per foot of shore
1-2 ft.	140
2-3 ft.	260
3-4 ft.	475
4-6 ft.	450

14. Combining these suspensions according to the relative incidence of the various wave conditions at Mission Bay it is possible to construct a hypothetical table of the rate of littoral drift movement due to suspended material being carried along by the littoral current. (6) This table assumes no reversals in drift which is seldom the actual

Littoral Current		Rate of Drift
ft/min	ft/sec	cu yd/yr
2	0.03	16,000
6	0.10	50,000
15	0.25	125,000
30	0.50	250,000
45	0.75	375,000
60	1.00	500,000
90	1.50	750,000
120	2.00	1,000,000
180	3.00	1,500,000
360	6.00	3,000,000

case; so in a sense it represents the total drift rather than the net drift. The littoral current velocities given above are in the ranges normally encountered along the shore. Also, the indicated rates of littoral drift are of the same order as those observed along our shores. This correlation indicates that while movement of sand along the bottom as bed load is probable, movement as suspended load is a major if not the predominant manner of movement.

15. From the above, it can be seen that the incident wave energy has a certain capacity for stirring up the sand and for generating a littoral current. These two actions result in a transport of material along the shore face as littoral drift. Varying wave directions may reverse the drift direction; however, most areas have a dominant drift direction and the net movement in that direction is referred to as the net drift. The net drift is of course the difference between the gross drift upcoast and downcoast.

16. A shore sector can be in equilibrium only if the net amount of material leaving the sector at one end is balanced by an equal net amount entering the sector at the other end. The presence of inlets, estuaries, bays, and other irregularities in the shore alignment coupled with changing patterns of wave energy from one shore point to another seldom permits the equilibrium balance to be maintained in a shore sector. The result will be either accretion or erosion of the sector. Unfortunately, the factors producing erosion dominate in most areas. Let us now examine the ocean shore of New Jersey as a field laboratory of shore processes.

Littoral Processes in New Jersey

17. The ocean coastline of New Jersey extends for some 120 miles, being oriented roughly in a north-south direction (see Fig. 2). It is a sandy shore broken by ten major inlets and somewhat sheltered at the north by the eastward extension of Long Island. Except for three small headland sectors—one at Cape May, one near Bayhead, and one near Long Branch—the entire coast is a series of barrier islands separated from the mainland by bays, lagoons, and tidal marshes in various states of deterioration. The tide range is about 5 feet and the shore is subject to extra-tropical storms (northeasters) and to hurricanes. The entire coast comprises a large and important summer resort area.

18. *Wave Energy*. Wave hindcasts (7) were made by the Beach

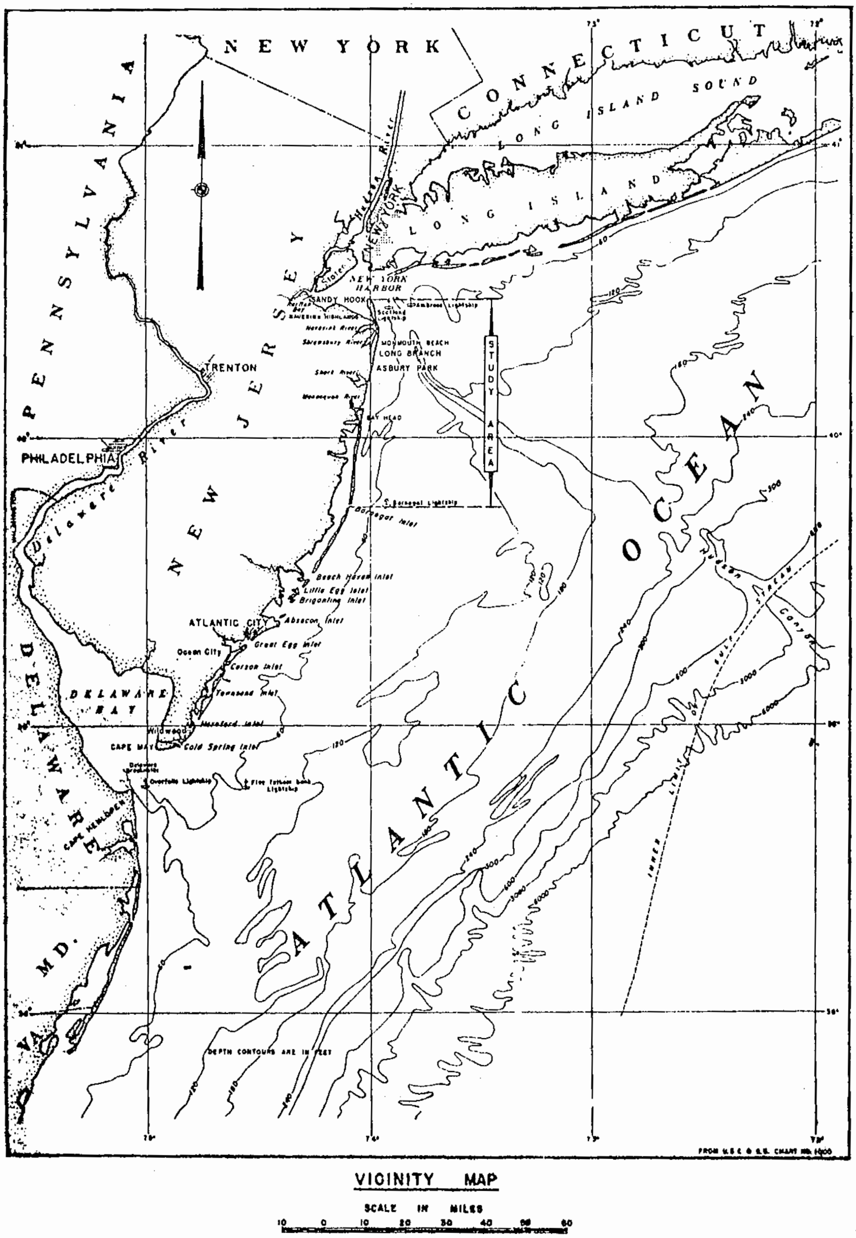

NEW YORK
CONNECTICUT
PENNSYLVANIA
NEW JERSEY
LONG ISLAND SOUND
LONG ISLAND
NEW YORK HARBOR
SANDY HOOK
MONMOUTH BEACH
LONG BRANCH
ASBURY PARK
TRENTON
PHILADELPHIA
STUDY AREA
Barnegat Inlet
Beach Haven Inlet
Little Egg Inlet
Brigantine Inlet
ATLANTIC CITY
Absecon Inlet
Great Egg Inlet
Ocean City
Corson Inlet
Townsend Inlet
Hereford Inlet
Wildwood
CAPE MAY
Cold Spring Inlet
DELAWARE BAY
DELAWARE
MD.
VA.
ATLANTIC OCEAN
DEPTH CONTOURS ARE IN FEET
VICINITY MAP
SCALE IN MILES

FIG. 2

Erosion Board for points off Sandy Hook and off Cape May using three years of North Atlantic weather maps. The analysis showed that the wave energy pattern would be essentially the same at the two points, except for the sheltering action of Long Island. In other words, the wave energy approaching from the southeast quadrant is essentially equal over the entire coast: that from the northeast quadrant is more prominent at Cape May than at Sandy Hook due to the greater shelter which Long Island provides the Sandy Hook area. Further, the wave energy patterns indicate that the wave energy from the north is greater than that from the south; thus a net littoral drift to the south can be expected where the effect of Long Island is too great.

19. *Measured Drift Rates.* In connection with shore erosion problems, the Corps of Engineers has determined the rates of littoral drift at two points along the New Jersey coast, one at Cold Springs Inlet and the other at Sandy Hook. Sandy Hook accumulates essentially all the sand moved northward to it from the New Jersey beaches to the south. The drift movement south off Sandy Hook is, to all purposes, zero; so the rate of sand accumulation on Sandy Hook represents both the gross northbound drift and the net drift at this point. This rate is determined as 500,000 cubic yards per year; the determination was made from a series of accurate surveys made at various times of the past 100 years.

20. Cold Springs Inlet is maintained artificially to provide direct access from the Atlantic into Cape May Harbor. The inlet is flanked by two jetties of considerable length constructed in 1910. The north jetty has provided an impoundment area which has entrapped the littoral drift moving down from the north. The average rate of impoundment, as determined from successive surveys is 200,000 cubic yards per year. This rate is the net rate as waves from both the northeast and southeast quadrants reach the impounded area and the impounded material represents the difference in the resulting movements.

21. As stated previously, the wave energy from the south is essentially uniform over the New Jersey coast. Thus the northbound drift rate of 500,000 cubic yards/year at Sandy Hook can also be taken to approximate the northbound drift at Cold Springs Inlet. Combining the above two figures we get for Cold Springs Inlet:

Northbound drift	= 500,000 cubic yards/year
Net drift (south)	= 200,000 cubic yards/year
Southbound drift	= 700,000 cubic yards/year

From this figure, it can be seen that the total sand in transit along the beach face in the Cape May area is (500,000 + 700,000) = 1,200,000 cubic yards per year. Thus, any unprotected inlet in this area is potentially subjected to shoaling from some 1,200,000 cubic yards/year of sand being shuttled back and forth along the shore face.

22. *North Jersey*. Starting from the nodal point at Dover Township, 35 miles south of Sandy Hook, we find the net rate of littoral drift increasing from essentially zero at Dover Township to 500,000 cubic yards per year northbound at Sandy Hook. Obviously, then, the 500,000 cubic yards furnished to Sandy Hook must come from the 30 miles or so of shore between Dover Township and Sandy Hook. There is no river-borne sand added to the shore face over these 30 miles. Also, surveys dating back about 100 years show no evidence of sand being supplied to the shore by offshore deposits over these 30 miles. Thus, the conclusion is that the material to supply 500,000 cubic yards per year to Sandy Hook must come from beach face itself. How does this check with the facts?

23. Comparisons of surveys made in 1838 and 1953, a 115-year span, show that the 30 miles of shore south of the base of Sandy Hook retreated shoreward some 500 feet (or about 5 feet per year) during this period. During the first sixty years or so the rate of accretion on Sandy Hook was 525,000 cubic yards/year. During the last fifty years, the rate has been 475,000 cubic yards/year. This 12% reduction is thought to be due to the construction of multitudinous groins and jetties in the 30 miles of eroding shore. It is interesting to note that the wholesale attempt to halt erosion by groin construction apparently reduced the rate of erosion by only 12%; thus, in this area at least, groins were found to be ineffective as beach building or beach stabilizing devices.

24. Studying in more detail the 50-year period, 1885-1935, the average rate of accretion on Sandy Hook was 493,000 cubic yards per year. The erosion from the thirty miles of shore south of Sandy Hook for this 50-year period averaged 723,000 cubic yards/year. This excess of erosion over accretion is due to the fact that only about 2/3 of the eroded material is sand, the remaining 1/3 being silt and clay which, once eroded, are lost into the sea and play no part in the beach building processes at Sandy Hook. Thus, we find the entire 30 miles of shore under erosion in order to supply the net littoral drift demanded by the wave action impinging on this section of the shore.

25. *Practical Solutions*. The erosion described above, about 5

feet per year, has been very damaging to the economy of the thirty miles of shore. Attempts to control the erosion by groins and seawalls have been largely unsuccessful and the continuing erosion gradually undermined and destroyed the shore structures. The replenishment of the shore face by adding sand to the littoral drift stream presents itself as a desirable solution. Let us examine this possibility.

26. The north end of Barnegat Bay extends some 4 or 5 miles north of Dover Township, and the Bay bottom contains large deposits of sand suitable for replenishing the eroding shore face. The question then arises as to the efficacy of pumping 500,000 cubic yards of sand per year from Barnegat Bay onto the beach near Mantoloking just north of Dover Township. To visualize whether or not this would provide a solution to the North Jersey erosion problem, it is advisable to construct the following table:

TABLE
EROSION AND LITTORAL DRIFT, CUBIC YARDS/YEAR

	Mantoloking to Manasquan	Manasquan to Asbury Park	Asbury Park to base of Sandy Hook	Base Sandy Hook to tip of Sandy Hook
Net litt. drift entering sector	0	74,000 (n)	319,000 (n)	493,000 (n)
Net litt. drift leaving sector	74,000 (n)	319,000 (n)	493,000 (n)	—
Litt. drift deficit in sector	74,000	245,000	174,000	—
Average shore erosion (incl. silt & clay)	109,000	364,000	256,000	493,000 (acc.)
Sand erosion	74,000	245,000	174,000	493,000 (acc.)

From this table, it is seen that the net littoral forces are capable of moving only 74,000 cubic yards/year out of the first sector into the second sector, whereas the second sector supplies 310,000 cubic yards/year to the third sector. Thus the second sector needs an additional supply of 245,000 cubic yards/year of sand to overcome the present erosion in the second sector. However, the littoral forces in the first sector are already moving their full capacity of sand into the second sector. Thus, the only potential capability in the use of Barnegat

Bay sand is to supply the 74,000 cubic yards/year presently being lost in the first sector. If we place an excess of sand in the first sector, it will only serve to widen the beach in this sector without benefiting the second sector. Thus, sand placed to aid the second sector will have to be placed on the beach in the second sector. This relationship between sectors holds true for successive sectors to the north and shows the impossibility of assisting adjacent sectors by over-supply to the preceding sectors.

27. This same relationship explains why it is inevitable that the northerly shore of New Jersey will erode under natural conditions, for each successive sector shows increasing net littoral forces and net littoral drift. A beach erosion control study of this section of the shore was made in 1954; this study recommends that restoration of the shore be accomplished by rebuilding the beaches with sand and then maintaining them by periodic replenishment at intervals along the shore face. The cost of the initial restoration was estimated to be about $22,000,000 with a yearly maintenance cost thereafter of about $1,700,000. This plan was considered satisfactory and acceptable by the State, but funds have to date been appropriated to initiate only about one-third of the restoration project.

28. *South Jersey.* From the nodal area at Dover Township, the New Jersey shore extends southerly some 85 miles to its terminus at Cape May. The same reasoning as developed for North Jersey brings us to a similar conclusion to the effect that the South Jersey shore must show a net loss of 200,000 cubic yards per year between Dover Township and Cape May; this is indicated by the net drift of zero at Dover Township and 200,000 cubic yards/year to the south of Cold Springs Inlet. Without further examination, it might be proposed that the 85 miles of South Jersey shores could be stabilized by adding 200,000 cubic yards/year along the 85 miles. But let us now examine the actual shore processes.

29. A comparison of the North and South Jersey shores will show one great difference. The North shore is pierced by only two relatively small inlets which play only a minor part in the shore processes. The South shore, in contrast, is pierced by eight large inlets each of which has a great potential for interrupting the normal littoral drift movement along the shore. To determine if there is in fact such an effect, an erosion table for this 85 miles is drawn up as follows:

TABLE
ACCRETION AND EROSION, SOUTH JERSEY
cu. yd./year

	Gross drift	Net drift	Net erosion
Long Beach Island	1,050,000	50,000	520,000
Pullen Island	1,070,000	75,000	270,000
Brigantine Island	1,080,000	75,000	200,000
Absecon Island	1,100,000	100,000	110,000
Peck Beach	1,125,000	150,000	320,000
Ludlam Island	1,150,000	175,000	300,000
Seven Mile Beach	1,175,000	200,000	40,000
Totals	7,750,000	—	1,760,000
Two Mile Beach			200,000 (accretion)

A study of this table shows the average annual loss by erosion of the shore face to be 1,760,000 cubic yards. Surveys show that this material is not deposited offshore or in the outer bars at the inlets, but rather that it is swept into the inlets on flood tide where a significant portion remains permanently. In other words, the flood tide aided by the ocean waves carries more material into the interior bays and lagoons than the ebb tide, unaided by the waves, can return to the shore face.

30. A review of the above table shows that the gross drift shuttles approximately 1.1 million cubic yards of material back and forth at each of the seven inlets north of Cold Springs Inlet; thus a total of 7.7 million cubic yards per year is brought within the influence of the seven inlets. The permanent entrapment of the inlets is in the order of 23% or 1,760,000 cubic yards per year, or an average of about 250,000 cubic yards per year per inlet. From these figures, it can be seen that the net drift is grossly inadequate to compensate for the losses into the inlets; therefore general erosion of the shore face on a continuing basis can be expected unless steps are taken to bring the losses under control.

31. A study of the southerly 75 miles of shore will show that much of the beach has retreated by 500 feet or more during the past 100 years, though there has been a noticeable tendency for accretion at the south shoulders of the inlet. This erosion has of course presented a severe problem to the recreation communities along the shore.

32. Temporary solutions to this problem involve periodically

supplying new sand to the eroding shores and the use of groins and seawalls. The long-term solution will probably involve bringing the inlets under control by jetties of the proper length and spacing and the provision of sand by-passing arrangements to move the net drift past the jettied inlets; the elements of a long-term solution are already being constructed in phases at Absecon Inlet at Atlantic City. The proper control of the inlets will not only aid in the shore stabilization but will also reduce the cost of maintenance of the navigation channels in the inlets.

Summary

33. From the material presented above, it can be seen that the beach face is an active zone with a constant shuttling of the sands back and forth along the shore. Permanent beach losses occur along most of our shores due to: (a) an excess of littoral drift leaving a given sector; (b) material lost inland by the tidal action of inlets; and (c) material pulled offshore into deep water by local storms. The first two losses are permanent losses; the third loss may or may not be permanent depending on local conditions. The continuing erosion of a beach narrows the beach to where it is extremely vulnerable to severe erosion and wave overtopping during severe storms. The proper solutions to our many shore erosion problems involve basically a quantitative evaluation of the overall processes causing the erosion followed by the development of a plan to either prevent or to compensate for these losses. Much research still needs to be done to enable proper qualitative evaluation to be made in most coastal areas.

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