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The Transgressive Barrier Model: An Alternative to Two-Dimensional Volume Balanced Models

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ABSTRACT

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As sea level rises, barrier islands generally transgress; sediments are eroded from the beach and shoreface and deposited in other shore areas. In turn, two-dimensional volume balanced models have been constructed to predict long-term rates of shoreline erosion and of volumetric change in shore compartments. These models have assumed that as barriers transgress sediments eroded from a beach and shoreface are deposited only in shore normal compartments; displaced sediments are not incorporated into the littoral drift. The transgressive barrier model, an alternative model to the two-dimensional volume balanced models, is presented as a set of equations which was applied to a segment of the Long Island, New York, barrier shoreline. For a 2.7 mm/yr relative rise in sea level, the model predicted a beach erosional rate of 0.7 m/yr, which is consistent with observed rates. In addition, the model reasonably showed that the sediment volume eroded from the transgressing beach and the shoreface was greater than the sum of that deposited in shore normal compartments and that the remaining amount was removed by littoral currents. At the study site, it appears that a relative rise in sea level in conjunction with wave and current action is the primary factor that governs long-term rates of shoreline erosion and of the gross littoral drift. Therefore, the universality of the two-dimensional volume balanced model appears not to be true.

ADDITIONAL INDEX WORDS: *barrier island, beach erosion, equilibrium profile, ramp, relative sea level rise, shoreface, transgression.*

INTRODUCTION

The results of field investigations along the mid-Atlantic coast of the United States have shown that with rising sea levels barrier islands transgress (HOYT, 1967; DILLON, 1970; KRAFT, 1971) and some extend laterally (FISHER, 1968; FIELD and DUANE, 1976; KRAFT *et al.*, 1978). Because most rivers deposit their loads in estuaries or lagoons, the major sediment source of washover and flood-tidal deposits as well as the littoral drift comes from the beach and shoreface compartments (FIELD and DUANE, 1976; BARTBERGER, 1976; INMAN and DOLAN, 1989). Two-dimensional volume balanced models (BRUUN, 1962; HANDS, 1983; DEAN and MAURMEYER, 1983; EVERTS, 1985) that predict long-term rates of shoreline change and of volumetric change of shore compartments have assumed that the magnitude of the gross littoral drift is unaffected by rising sea levels. As a barrier transgresses all sediments eroded from a beach and shoreface are assumed to be deposited in shore normal compartments; none of these sediments is displaced in the longshore direction. This assumption may not be universally true (SWIFT *et al.*, 1972; BELKNAP and KRAFT, 1981; KRAFT *et al.*, 1987). A relative rise in sea level might cause an increase in the rate of the gross littoral drift (SCOR WORKING GROUP, 1991).

There are two purposes for this paper. The first is to present a set of kinematic models, collectively referred to as the transgressive barrier model, that has been formulated without the assumption of a two-dimensional volume balanced budget. The transgressive barrier model estimates the long-term rates of (1) beach erosion, (2) of volumetric losses from the beach and shoreface, and (3) of volumetric gains on the backbarrier. This paper also presents general models that attempt to estimate long-term volumetric rates of sediment accretion on the inner-continental shelf and in lagoons; however, further development of these models is left for future research. The second purpose is to apply the transgressive barrier model to a segment of the barrier shore of Long Island, New York, in order to test the validity of the two-dimensional volume balanced assumption used in other models. This shore was selected as the test site because it has been extensively studied and the bathymetry has been mapped in detail.

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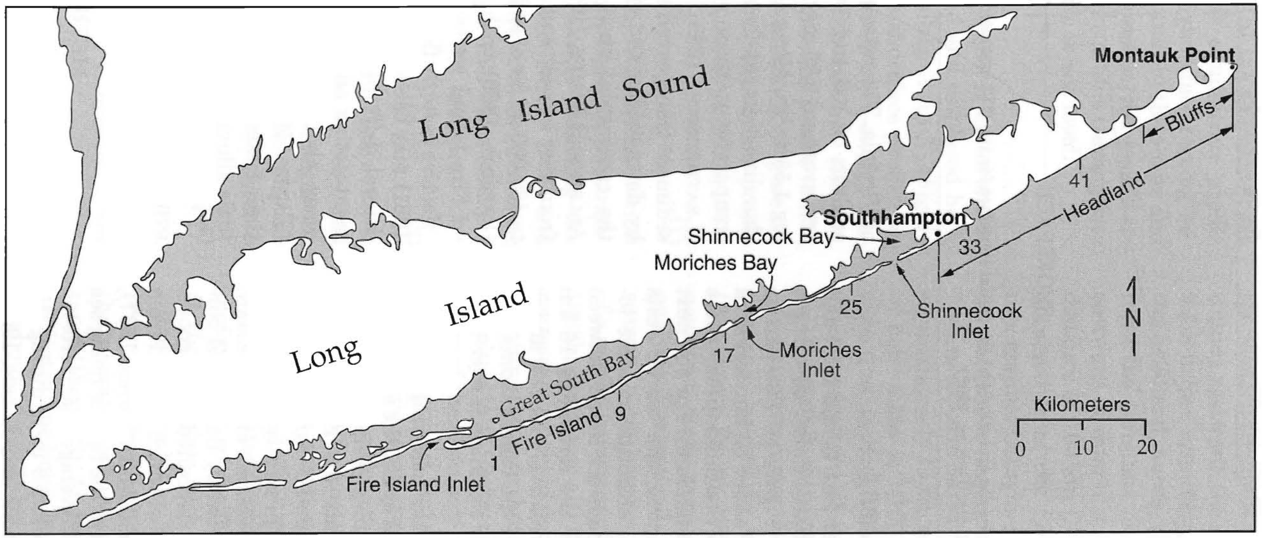

Figure 1. Location of study area. Numbers along the shoreline are profile line numbers.

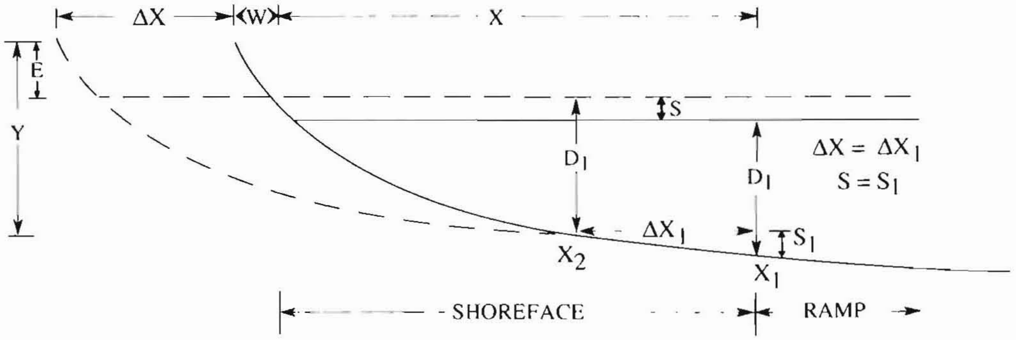

Figure 2. A rising sea level (S) elevates and displaces the initial shoreface forcing (D_1) landward, which in turn forces a new profile of equilibrium to be established (after Dubois, 1990).

STUDY AREA

The study area begins at Fire Island Inlet and extends eastward to Montauk Point, covering a distance of about 134 km (Figure 1). Two barrier islands span a distance of about 83 km eastward from Fire Island Inlet to Southhampton where the shore encounters the mainland. For the next 35 km east of Southhampton, the barrier rests against an outwash plain, although at some locations ponds and small bays are found between the barrier and plain. For the remaining 16 km of shoreline, the beach is relatively narrow and is backed by bluffs formed by the Ronkonkoma moraine; at some places, bluff elevation is over 18 m (Taney, 1961a).

Relative to this project, the following is a summary of the important facts about the study area. The shoreline has been transgressing for at least the past 5,000 yrs (Sanders and Kumar, 1975; Williams, 1976; Rampino and Sanders, 1980). A relative rise in sea level is presently occurring at a rate of about 2.7 mm/yr (Hicks and Hickman, 1988). Sediments transported by flood-tidal currents through inlets are deposited in lagoons. Washover sediments, some of which derived from the shoreface (Williams and Meisburger, 1987), maintain barrier elevation in the face of rising sea level (Leatherman, 1985). Average beach erosion rates have varied from 0.3 to 0.9 m/yr during the past 150 years (Leatherman and Allen, 1985). In addition for this study area, a data base consisting of beach erosional rates spaced at an interval of about 50 m for a total of 2,580 observations was provided to the writer by the Department of Environmental Sciences, University of Virginia. The rates were obtained by end-point analysis of 109 and 149 years (1830/1870–1979) and averaged 0.95 m/yr, a standard deviation being 1.55 m/yr. Along the bayside of the barriers, shoreline segments have been also eroding at rates comparable to those recorded on the ocean side (Leatherman, 1985). During storms, shoreface sediment transported seaward of the 15 m isobath by downwelling and rip currents may be lost to the continental shelf (Niedoroda *et al.* 1985; Allen and Psuty, 1987). The net littoral drift is from east to west and ranges from about 230,000 to 460,000 m^3/yr of sediments at Fire Island Inlet (Panuzio, 1969); with time, this drift has extended Fire Island westward (Taney, 1961a). A less effective easterly flow (McCormick and Toscano, 1981) may cause an undetermined annual rate of littoral drift past Montauk Point. Mass movement acting on the glacial till bluffs is contributing about 76,400 m^3/yr to the littoral drift (Taney, 1961a). Because most streams deposit their loads in bayside marshes and lagoons, very little alluvium is introduced into the littoral drift (Taney, 1961b). Likewise, biogenic production contributes negligible amounts of material to the shore zone (Taney, 1961b).

METHODOLOGY

The transgressive barrier model consists of two parts. The first part addresses a method for predicting the rate of shoreline erosion in response to a relative rise in sea level, while the second discusses a method for predicting volumetric rates of change for transgressing shore compartments. In both parts, the model (Figure 2) assumes that

(a) the shoreface profile reflects an equilibrium energy profile; progressive waves generate a shoreward net bottom stress that drives sands landward until an increasing shoreface slope has achieved equilibrium (INMAN and BAGNOLD, 1963; INMAN and DOLAN, 1989), (b) the shoreface base is the seaward limit of the equilibrium profile (EVERTS, 1987); therefore, shoreface forcing begins at the shoreface base, and (c) the shape and dimensions of a cross-sectional barrier profile remain reasonably constant as a profile transgresses in response to a relative rise in sea level.

Beach Erosion Model

As sea level rises (S), the depth of initial shoreface forcing (D_l) is elevated and displaced horizontally landward from position X_1 to X_2 (Figure 2). With D_l now at X_2, the shoreface profile becomes steeper and the rate of wave-energy dissipation increases along the bottom (BRUUN, 1988a), causing waves to erode the profile until a new equilibrium state is established (Figure 2). Given that the coordinates of a shoreface profile follow a power function (BRUUN, 1954; DEAN, 1977)

$$D = AX^m, \tag{1}$$

where D is the water depth, X is the horizontal seaward distance from shore, m is a shape parameter, and A is a scale parameter reflecting the texture of bottom sediments (DEAN, 1977) and time (PRUSZAK, 1993), the equation for predicting the loss of shoreline distance (ΔX) as a function of rising sea level (DUBOIS, 1990) becomes

$$\Delta X = (D_l/A)^{1/m} - [(D_l - S)/A]^{1/m}. \tag{2}$$

As the shoreface transgresses (Figure 2), it abandons a small slope segment at its base, and as time passes the sum of abandoned segments forms the ramp. Assuming nothing disturbs the ramp slope, the erosion rate (ΔX) is also given as

$$\Delta X = S/\tan \phi, \tag{3}$$

where ϕ is the degree angle of the ramp (EVERTS, 1987). Because the ramp surface follows a straight line equation (EVERTS, 1978), tangent ϕ is the regression coefficient (b_r) of

$$D_r = a_r + b_r X_r, \tag{4}$$

where a_r is the depth intercept, D_r and X_r are a ramp depth and corresponding offshore distance, respectively.

Equations (1) and (4) were solved by least square regression analysis of water depths and corresponding offshore distances for 43 profile lines. The values of A and m in (1) were employed to solve (2) while b_r in (4) was used to solve (3). The relative rate of sea-level rise (S) was taken as 2.7 mm/yr (HICKS and HICKMAN, 1988). Beginning at the western terminus of Fire Island Inlet and continuing eastward, the shoreline curves for the first 9 km before running reasonably straight towards the headland; hence, the profile lines begin 9 km from the terminus of Fire Island and continue eastward at intervals of 2.5 km spanning a total distance of 105 km (Figure 1). Profile data were obtained from the Long Island East and West topographic-bathymetric maps published by the United States Geological Survey (USGS) and the National Ocean Service. Map coverage terminates approximately 13 km west of the bluffs. The scale of both maps is 1:100,000. In water depths less than 6 m, isobath intervals vary from 1 to 2 m; whereas, seaward of about 6 m intervals are at 1 m. Horizontal map distances were measured with a linear micrometer. Because of the irregular topography caused by a longshore bar or terrace (ALLEN and PSUTY, 1987; ZARILLO and LIU, 1988), nearshore data were excluded from regression analysis. Theoretically the shape of a shore profile seaward of the breaker zone differs from the shape of a profile landward of the breaker zone (BRUUN, 1988b; INMAN *et al.*, 1993). The inclusion in the regression model of depths and offshore distances spanning this nearshore would have yielded A and m values in (1) reflective of the full symmetrical range of the shoreface. However, the reliability of (2) depends on A and m values that simply define the concave symmetry of the shoreface seaward of a nearshore terrace or bar. Thus, the zero distance mark of a shoreface profile was set at the first isobath seaward from the bar or terrace (INMAN *et al.*, 1993), which generally registered 4 or 5 m of water depth. From a two dimensional plot of depth and offshore distance, water depth at the shoreface base (D_l) was taken at the position where a break in slope symmetry occurred between the relatively steep concave shoreface and the planar gentle seaward-dipping slope of the ramp (Figure 3). Along the east coast of the United States, the break is generally found at a depth of about 15 m (EVERTS, 1978). The ramp range of depths and corresponding offshore distances extended from the shoreface base to the last seaward contour that ran reasonably straight and parallel to the shoreline (Figure 3); the depth value of the last seaward contour was about 20 m.

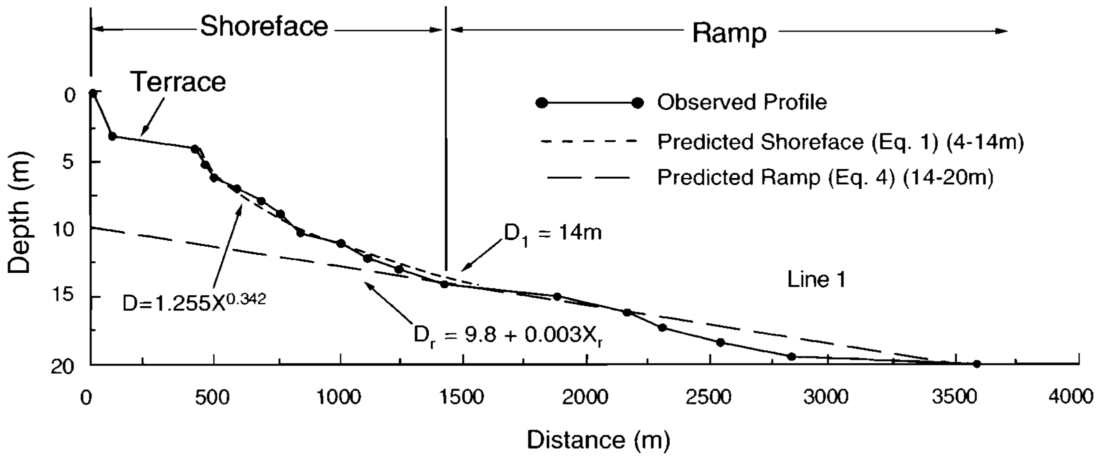

Figure 3. Observed and predicted shore segments for line one.

Seaward of about 20 m of water depth, the bottom topography was highly irregular, which may reflect the spatial variability of erosional and depositional action caused by shelf currents. Equation (4) was solved for 37 lines; 6 lines were excluded from analysis because each line had a highly irregular ramp topography.

Volumetric Models

For a three-dimensional transgressing barrier system not receiving inputs of terrestrial material, an annual volumetric sediment balanced model exists as

$$V_s = V_b + V_{bio} - (V_{bb} + V_l + V_f + V_{dc} + V_{ld}) = 0, \qquad (5)$$

where V_s and V_b are the volumes of material eroded from the shoreface and beach, respectively, V_{bio} is the biogenic production along the shoreface; V_{bb} and V_l are the volumes of material deposited on the backbarrier and lagoon, respectively, V_f is the fines portion of V_s that is deposited offshore, V_{dc} is a sand size portion of V_s that is swept by downwelling currents and deposited offshore, and V_{ld} is the gross littoral drift for a shoreline. Reasonable estimates can be made for the terms in (5). Kinematic equations, explained in the following sections, have been formulated to estimate V_s, V_b, V_{bb}, V_l, and V_{dc}. V_{ld} has been estimated between 230,000 and 460,000 m^3/yr at Fire Island Inlet (Panuzio, 1969) and is unknown at the eastern end of the shoreline. V_{bio} and V_f are given values of zero; shell content is negligible (Taney, 1961b), and the shoreface cuts through barrier and nearshore sands (Kumar and Sanders, 1976; Rampino and Sanders, 1980; Panageotou and Leatherman, 1985). For the Long Island shore, an additional term (V_{mm}), which reflects the contribution of receding glacial bluffs by mass movement, must be added as a source of sediment supply; V_{mm} has been estimated at 76,400 m^3/yr (Taney, 1961a).

Beach and Shoreface Compartments

By definition a transgressing shore profile retreats landward in both the horizontal and vertical directions. Analyzing each directional movement separately yields the following results. First, if a shore profile is retreating horizontally and for a unit length of shore, the volumetric rate of sediment loss (V_h) is (Figure 4A)

$$V_h = \Delta XY, \qquad (6)$$

where Y is the vertical distance. Second, if a shore profile vertically increases in place with a rising sea level (S), the volumetric rate of sediment accretion (V_v) is (Figure 4B)

$$V_v = \Delta YX, \qquad (7)$$

where ΔY is equal to the vertical rate of change and to S. Therefore, the volumetric rate of sediment loss (V_t) for a transgressing profile (Figure 4C) is the volumetric difference between paral-

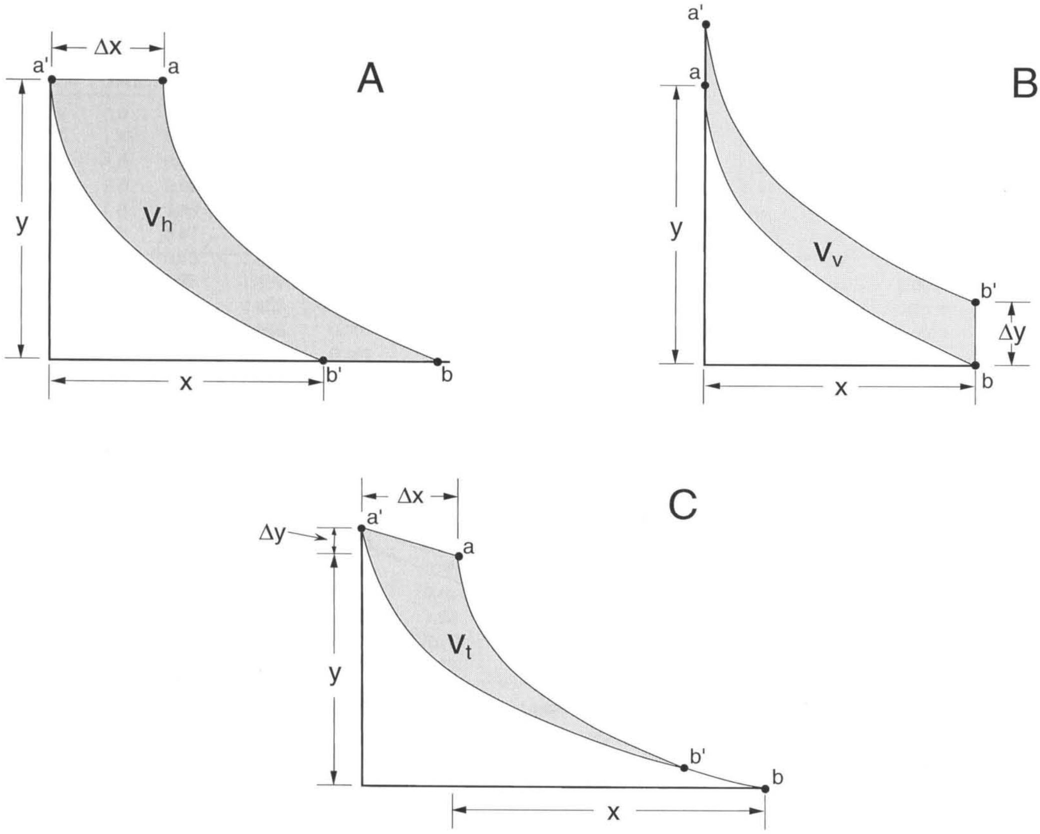

Figure 4. A recessing (A), aggrading (B), and transgressing (C) shore. For each panel, profile a–b is placed to a'–b'.

lelogram (A) and (B) in Figure 4 or

$$V_t = (\Delta XY) - (SX). \tag{8}$$

Thus, for a transgressing shoreface, the volumetric rate of sediment loss (V_s) is

$$V_s = (\Delta XD_l) - (SX). \tag{9}$$

For a beach, the volumetric rate of sediment loss (V_b) is (Figure 2)

$$V_b = \Delta XE - SW, \tag{10}$$

where E is the foredune elevation and W is the beach width, which is the distance between the foredune crest and the shoreline.

Backbarrier and Lagoon Compartments

For a backbarrier recessing landward on a preexisting platform, the volumetric rate of accretion (V_{rb}) is equal to that eroded from the ocean side and is given as (Figure 5A)

$$V_{rb} = \Delta E_b W_b, \tag{11}$$

or

$$\Delta E_b W_b = \Delta XE, \tag{12}$$

where W_b is the backbarrier width between the foredune crest and lagoon, and ΔE_b is the backbarrier rate of elevational increase. However, as a barrier transgresses, a foundation (V_{rb}) is required upon which to do so (Figure 5B); thus, the volumetric rate of accretion for a transgressing backbarrier (V_{bb}) is

$$V_{bb} = \Delta XE + SW_b + 0.5[S(S/-\text{Tan}\,\beta)] \tag{13}$$

where β is the degree angle of the backbarrier. In addition, the volumetric rate of accretion along a lagoon margin bordering a barrier (V_l) can be

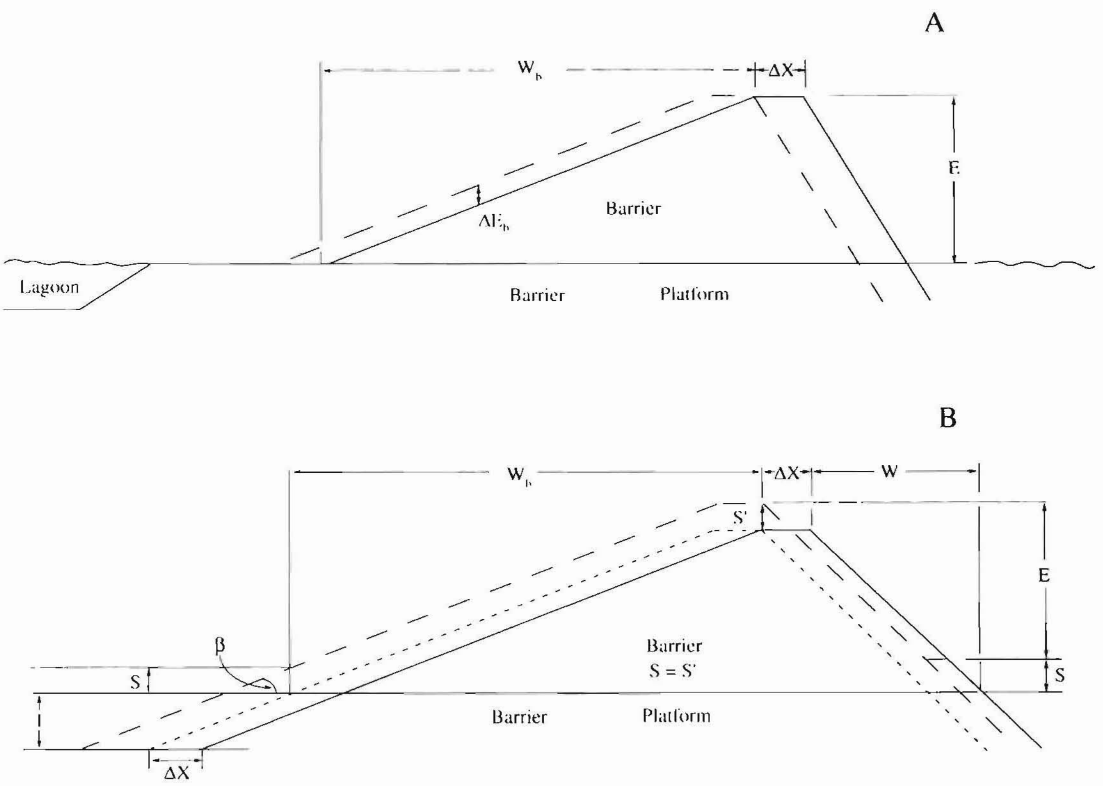

Figure 5. A recessing (A) and transgressing (B) subaerial barrier.

estimated as

$$V_l = \Delta X l + (S/\mathrm{Tan}\ \beta) l, \qquad (14)$$

where l is the lagoon depth (Figure 5B). Equation (14) assumes that the lagoon bottom adjacent to the barrier is flat or slopes very gently towards the lagoon center. Thus, the total volumetric rate of backbarrier and lagoon accretion (V_{bbl}) is

$$V_{bbl} = V_{bb} + V_l. \qquad (15)$$

Equations (9), (10), and (13) were solved for each of the 43 lines, while (14) and (15) were solved for the first 30 lines which traversed barrier islands. At each line, beach width (W), foredune elevation (E), and backbarrier width (W_b) were measured from USGS topographic maps (1:24,000). Tangent β was taken as a ratio of E divided by W_b. The lagoon margin depth (l) was estimated at 1.0 m for each of the first 30 lines.

RESULTS AND DISCUSSION

Beach Erosion Models

The average beach erosional rates as predicted by (2) (0.67 m/yr, Table 1) and (3) (0.77 m/yr, Table 2) are reasonably close rates reported in the literature (0.3 to 0.9 m/yr; LEATHERMAN and ALLEN, 1985) and provided to the author (0.95 m/yr). Other United States barrier shorelines are also transgressing at rates predicted by (2) (DUBOIS, 1990). For many barrier islands, it appears that the rate of a relative rise in sea level in conjunction with wave and current action is the major controlling variable that is regulating the long-term rate of shoreline erosion. In addition, as the Long Island shore transgresses, a segment of the lower shoreface base is abandoned; and with the passage of time, the sum of the abandoned segments forms a seaward dipping ramp whose slope tangent is equal to the ratio of the rate of sea level rise (S) divided by the rate of shoreline erosion (ΔX) (Ta-

Table 1. *Parameters and solutions to Equations 1 and 2.*

	Equation 1					Equation 2
L	R	No.	r^2	A	m	ΔX
1	4–14	10	0.98	1.255	0.342	0.65
2	4–13	8	0.96	1.427	0.333	0.47
3	4–13	8	0.99	1.887	0.289	0.57
4	4–16	12	0.96	1.069	0.353	1.02
5	4–13	8	0.96	1.603	0.293	0.90
6	4–14	9	0.97	1.131	0.360	0.58
7	4–10	5	0.98	1.341	0.340	0.29
8	4–13	8	0.93	1.459	0.308	0.82
9	4–12	7	0.94	1.465	0.319	0.51
10	4–14	9	0.94	1.586	0.307	0.76
11	4–14	9	0.91	1.576	0.301	0.91
12	4–15	10	0.97	1.447	0.319	0.86
13	4–17	12	0.97	1.735	0.305	0.93
14	4–17	12	0.94	1.113	0.360	0.86
15	4–13	9	0.87	2.185	0.245	1.23
16	4–16	11	0.94	1.110	0.362	0.74
17	4–16	11	0.94	0.537	0.462	0.57
18	4–14	10	0.95	0.726	0.407	0.68
19	4–14	9	0.85	1.616	0.303	0.79
20	4–14	9	0.94	1.278	0.334	0.75
21	4–14	9	0.95	1.068	0.364	0.62
22	4–15	10	0.87	1.824	0.279	1.23
23	4–14	9	0.94	1.868	0.278	0.97
24	4–15	10	0.98	0.626	0.446	0.50
25	4–14	8	0.91	1.079	0.365	0.59
26	4–15	10	0.96	0.948	0.399	0.46
27	4–15	10	0.96	1.711	0.305	0.73
28	4–14	9	0.96	0.446	0.495	0.41
29	4–13	9	0.98	0.305	0.544	0.43
30	4–15	10	0.96	2.065	0.268	1.10
31	4–15	11	0.95	1.263	0.332	0.94
32	4–14	9	0.99	1.282	0.343	0.60
33	4–14	10	0.96	1.341	0.328	0.75
34	4–15	10	0.99	1.525	0.325	0.63
35	4–15	10	0.99	1.636	0.312	0.70
36	5–15	9	0.99	2.076	0.283	0.69
37	4–14	7	0.98	1.924	0.296	0.53
38	4–13	7	0.99	1.427	0.347	0.35
39	5–12	5	0.98	1.369	0.359	0.27
40	4–14	9	0.98	1.397	0.349	0.41
41	4–12	6	0.95	0.368	0.565	0.19
42	4–13	8	0.98	2.471	0.255	0.55
43	4–11	5	0.99	1.998	0.281	0.38

Avg. ΔX (Eq. 2) = 0.67 m/yr S.D. ΔX (Eq. 2) = 0.25 m/yr

Note: Columns L, R, and No. refer to line number, range of water depths (m), and number of observations, respectively; r^2 is the coefficient of determination; Avg. is the mean; S.D. is the standard deviation

Table 2. *Parameters and solutions to Equations 3 and 4.*

	Equation 4					Equation 3
Line	Range	No.	r^2	a_r	b_r	ΔX
1	14–20	7	0.94	9.8	0.0030	0.90
2	na	na	na	na	na	na
3	na	na	na	na	na	na
4	16–18	3	0.94	12.8	0.0016	1.69
5	na	na	na	na	na	na
6	na	na	na	na	na	na
7	na	na	na	na	na	na
8	13–20	8	0.99	10.5	0.0021	1.29
9	12–20	9	0.95	9.2	0.0030	0.90
10	14–20	7	0.96	9.0	0.0035	0.77
11	14–20	7	0.97	9.9	0.0031	0.87
12	15–20	6	0.94	10.6	0.0031	0.87
13	17–19	3	0.99	10.5	0.0036	0.75
14	17–20	4	0.98	9.3	0.0041	0.66
15	13–20	8	0.99	7.3	0.0050	0.54
16	16–20	5	0.99	9.6	0.0038	0.71
17	16–20	5	0.97	8.5	0.0043	0.63
18	14–20	7	0.99	8.1	0.0047	0.57
19	14–20	7	0.95	8.0	0.0048	0.56
20	14–19	7	0.98	7.7	0.0048	0.56
21	14–22	9	0.99	8.6	0.0042	0.64
22	15–20	6	0.97	8.3	0.0044	0.61
23	14–22	9	0.97	7.2	0.0048	0.56
24	15–20	6	0.89	11.1	0.0029	0.93
25	14–19	6	0.92	7.6	0.0047	0.57
26	15–20	6	0.98	10.3	0.0033	0.82
27	15–22	8	0.96	6.6	0.0051	0.53
28	14–20	7	0.99	8.0	0.0048	0.56
29	13–21	10	0.94	8.0	0.0043	0.63
30	15–20	6	0.98	8.5	0.0041	0.66
31	15–22	8	0.96	8.9	0.0040	0.68
32	14–20	7	0.98	9.1	0.0037	0.73
33	14–22	9	0.90	8.0	0.0043	0.63
34	15–20	6	0.97	10.6	0.0031	0.87
35	15–22	8	0.97	10.0	0.0034	0.79
36	15–20	6	0.98	9.9	0.0033	0.82
37	14–20	7	0.99	10.7	0.0031	0.87
38	13–20	8	0.98	9.5	0.0033	0.82
39	12–20	9	0.98	9.5	0.0031	0.87
40	14–20	7	0.96	10.6	0.0027	1.00
41	12–18	7	0.97	9.3	0.0032	0.84
42	13–20	8	0.96	10.4	0.0028	0.96
43	na	na	na	na	na	na

Avg. ΔX (Eq. 4) = 0.77 m/yr S.D. ΔX (Eq. 4) = 0.23 m/yr

Note: Range is depth in meters; No. is the number of observations; r^2 is the coefficient of determination; ΔX is in m/yr; na is not applicable; Avg. is the mean; S.D. is the standard deviation

ble 2). Once a ramp has formed, its slope may be altered by tectonic or gradational processes (EVERTS, 1987), in which case, (3) could yield erroneous results. Thus, in selecting a model, (2) should be given priority over (3).

It must be emphasized that the predicted beach erosion rates of (2) are long-term averages for a long shoreline. The erosional model is not very useful for predicting rates of short shoreline segments, because intrinsic coastal conditions can induce considerable progradation or retrogradation, causing a segment to extensively deviate from the overall trend of the total shoreline (FENSTER and DOLAN, 1993). Refer to CROWELL and LEATH-

Table 3. *Descriptive statistics of shore variables and volumetric rates of change in shore compartments.*

	Shore Variables							
Statistics*	X	W	D_l	E	W_b	Tan β	X_{10}	D_s
Avg.	1350	67	14.0	6.0	333	0.0240	535	4.0
S.D.	294	27	1.4	1.6	154	0.0127	231	1.3

Eq.**	m^3/m/yr	km		m^3/yr (coastal compartment)
V_s	5.7 ×	134	=	763,800 (erosion of shoreface)
V_b	3.8 ×	118	=	448,400 (erosion of barrier beach)
V_b	1.3 ×	16	=	20,800 (erosion of beach at bluffs)
V_{mm}	(Taney, 1961a)		=	76,400 (erosion of bluffs)
				1,309,400 (total to be removed)
V_{bbl}	5.7 ×	83	=	473,100 (deposited on barrier/lagoon)
V_{bb}	4.9 ×	35	=	171,500 (deposited on headland barrier)
V_{dc}	1.2 ×	134	=	160,800 (deposited offshore)
				805,400 (total deposits normal to shore)
1,309,400 − 805,400			=	504,000 (gross littoral drift)

Note: Avg. is the mean; S.D. is the standard deviation; Eq. is equation

*Number of observations is 43; length dimensions are in meters

**In all equations, $\Delta X = 0.67$ m/yr

ERMAN (1985) for an erosional rate at a specific segment of the Long Island barrier shore.

Volumetric Models

The following is a discussion of volumetric rates of change for coastal compartments of the transgressing barrier shore. Values of variables needed to solve volumetric equations are presented in Table 3 or are given in this discussion. It is advisable to view the volumetric rates of change (Table 3) as averages that span centuries.

Erosional Compartments

For the entire shore length, approximately 763,800 m^3/yr of sediments must be displaced in order for the shoreface to transgress in response to the present rate of relative rise in sea level (Table 3). The transgressing 118 km barrier beach annually contributes an additional 448,400 m^3, while the beach seaward of the bluffs, assessed to have an average elevation of 2 m (E) and an average width of 10 m (W), adds 20,800 m^3/yr to the system. TANEY (1961a) estimated that the receding bluffs contributed about 76,400 m^3/yr to the littoral zone. Thus, to transgress the beach and shoreface in response to a 2.7 mm/yr relative rise in sea level, about 1.3 million m^3 of sediments must be displaced each year (Table 3).

Depositional Compartments

From the available 1.3 million m^3, about 473,100 m^3 are needed annually to sustain 83 km of transgressing barriers, while a lesser amount of 171,500 m^3 is required for the 35 km of headland barrier, which lacks the lagoonal compartment.

Estimating the average annual amount of sediments deposited in lagoons is problematic. For the Long Island shoreline, the primary mode by which lagoon bottoms are aggraded involves storm processes that first create inlets by breaching barriers (LEATHERMAN, 1985); once an inlet is formed, sediments are driven through by flood-tidal currents and deposited in the form of a flood-tidal delta. Eventually barriers transgress over these deltaic deposits; however, before the deltaic deposits are buried, some of the material may be retransported by waves and currents and redeposited in other lagoonal areas. Overwash, although it elevates the backbarrier, contributes little towards accreting a lagoon bottom (LEATHERMAN, 1985), and for this reason, it may be inappropriate to apply (14) to this study area. However, given that a long-term accretionary rate for the Long Island lagoons has not been published, (14) was used to estimate this rate and yielded a value of 0.78 m^3/m/yr or about 65,000 m^3/yr for 83 km of shoreline.

For the Long Island shore, some shoreface sediments should be swept seaward by downwelling currents generated during storms and lost from the shoreface sediment supply. Starting at a depth of about 15 m, the asymmetrical orbital motion of onshore shoaling waves along with wind-driven currents begin to transport bottom sediments in a landward direction. This onshore motion is intensified in depths less than 10 m (SWIFT *et al.*, 1985); eventually, the entrained sediments are driven to the breaker zone and incorporated into the littoral drift (NIEDORODA and SWIFT, 1981). During storms, downwelling currents at depths beyond 10 m can generate a bottom force greater than the onshore force, driving shoreface sediments offshore to be deposited at depths where fair weather processes may be unable to retransport them back to the shoreface (SWIFT *et al.*, 1985).

For the long-term, an important reason why some sediments are not returned to the shoreface may be a function of rising sea levels. If sea level was not rising, then offshore deposition would cause the bottom to aggrade to a level where fair-weather coastal processes could drive the sediments back to the shoreface. This cyclic exchange of sediment between the shoreface and the inner shelf caused by storm and fair-weather processes would be similar to the exchange that now takes place between the beach and the nearshore. However, with rising sea levels, a potential sediment sink is created seaward of the shoreface. Along coasts where strong downwelling currents exit, sediments are swept offshore where a continuous rise in sea level maintains water depths that prevent onshore forces from returning the sediments to the shoreface; on the other hand, if downwelling currents do not exists or are ineffectual in transporting sediments offshore, then all of the shoreface sediments should be displaced landward.

Determining the net volumetric rate of offshore deposition is also problematic. Not only do downwelling currents transport sediments offshore, but so do rip currents (ALLEN and PSUTY, 1987) and ebb-tidal currents flowing seaward through inlets (LIU and ZARRILLO, 1990). How much of the sediments that are deposited offshore remain is unknown. In an attempt to make a rough estimate of the net volumetric rate of offshore deposition, the following two assumptions were made: (1) the volume of sediments deposited offshore by ebb-tidal and rip-currents during storms is equal to the volume returned to the shoreface by swells, and (2) that all sediments from the 10 m to the D_l isobath are swept seaward by downwelling currents and permanently lost from the shoreface as it transgresses. Given these assumptions, the volume of sediment displaced from the shoreface (V_{dc}) can be calculated from (9) by substituting D_s, which is the depth difference between D_l and 10 m, for D_l, and X_{10}, which is the horizontal distance between the 10 m and the D_l isobath, for X (Table 3). With substitutions in place and for the total shoreline length, calculations yield an offshore loss of 160,800 m^3/yr (Table 3). This volumetric rate is the maximum amount that the lower shoreface can sustain and yet maintain its transverse shape and dimensions as it transgresses in the face of a relative rise in sea level.

After the sum of sediment volume that is deposited inshore normal compartments has been subtracted from the volume that is eroded from the beach and shoreface, the difference yields about 500,000 m^3/yr (Table 3) or 3.7 m^3/m/yr. In all likelihood, this amount is transported by littoral currents to the shore ends and is sufficient to sustain the observed annual westerly littoral drift of 230,000 to 460,000 m^3 at Fire Island Inlet (PANUZIO, 1969). The difference between the gross littoral drift and the amount passing by Fire Island Inlet would account for the easterly drift; a minimum annual value would be about 40,000 m^3 of sediments.

It is important to recognize that in the preceding discussions the method employed to calculate the volumetric rates of change for the subaerial barrier was designed to yield average rates that span centuries. It was assumed that the total barrier length of 118 km transgressed (Table 3). However, for shorter time frames, not all barrier segments transgress at the same time. For example because of high foredunes, overwash has been significantly reduced along a 13 km shore segment spanning east from Fire Island Inlet to Ocean Beach (LEATHERMAN and ALLEN, 1985) and for the barrier shore along the headland (J.R. ALLEN, National Park Service, *personal communication*). What this means, therefore, is that present day littoral, rip, and downwelling currents may have to contend with an additional 100,000 to 200,000 m^3/yr, the bulk of which may be transported by the westerly littoral current. Thus, the actual average discharge at Fire Island Inlet may be greater than 460,000 m^3/yr of sediment.

In the long-term, Fire Island spit has been extending westward as sediments of the westerly littoral drift have been deposited (TANEY, 1961a). Similarly along other shorelines where beach erosion (DOLAN *et al.*, 1989) and a relative rise in sea level have been recorded (HICKS and HICKMAN, 1988), the shoreline termini have also been lengthening (FIELD and DUANE, 1976; EVERTS *et al.*, 1983; KRAFT *et al.*, 1987; ALLEN, 1981). At other locations, the littoral drift has been sustaining shoals (PIERCE, 1969; KRAFT *et al.*, 1987) and sand ridges (MOODY, 1964) in the face of a relative rise in sea level. It appears, therefore, that a relative rise in sea level, in conjunction with wave and current actions, not only directly influences the average annual rate of beach erosion but also the average annual rate of the gross littoral drift, which in turn is used in some cases to lengthen shorelines and sustain some submarine depositional landforms.

Other Models

Other models have been constructed to predict long-term rates of beach erosion and of volumetric

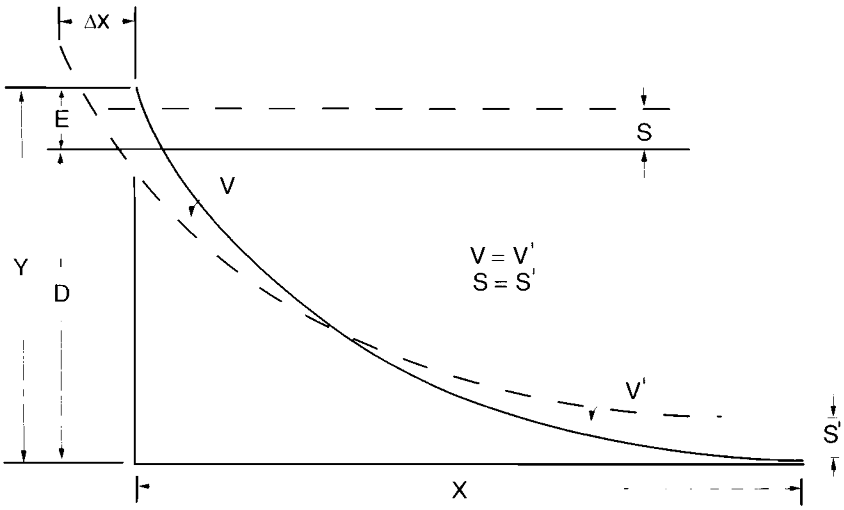

Figure 6. Bruun's rule implies that the volume eroded from the beach and shoreface (V) must be equal to the volume deposited offshore (V') (after BRUUN, 1988b).

change of shore compartments as a function of rising sea level. BRUUN (1962, 1988b) theorized that if sea level rises above a shore profile at equilibrium, then coastal processes will erode sediments from beach and shoreface and deposit them on the ramp so as to elevate the ramp in direct proportion to the rise in sea level. This model is known as Bruun's rule (SCHWARTZ, 1967, 1987). Bruun's rule (Figure 6) predicts the rate of beach erosion (ΔX) as

$$\Delta X = XS/Y. \tag{16}$$

Equation (16) is a two-dimensional volume balanced model, meaning that for a unit length of shoreline the volume of material eroded from the beach and shoreface (ΔXY) must be equal to that deposited on the inner shelf (XS). BRUUN (1983) later recognized that the shoreface profile could transgress through fine sediments and that these fines might be swept seaward beyond the closure depth. Therefore, (16) was modified to compensate for the loss of fines to yield

$$\Delta X = XS(1 + \mathrm{r}/100)/Y, \tag{17}$$

where r is equal to a percent of sediment size less than 0.06 mm relative to the total amount of erodible material.

WEGGEL (1979) revised (16) so as to yield

$$\Delta X = (-S/\alpha Y)\ln(S/d), \tag{18}$$

where α is a shape parameter, d is the limited depth of sediment transport, and ln is the natural logarithm. Model (18) is likewise a two-dimensional volume balanced budget.

HANDS (1983) developed a model that included a term to account for a shore profile in disequilibrium within a controlled volume of longshore length. The rate of beach erosion is predicted as

$$\Delta X = (XSR_A/Y) - (Q_t/YZ), \tag{19}$$

where R_A is the overfill ratio which accounts for fines that are eroded from a shoreface and deposited offshore, Z is an alongshore length, and Q_t is the net discharge of sediment for a controlled volume of longshore length as caused by some natural and/or anthropomorphic cause(s) other than a relative rise in sea level. For an equilibrium profile, Q_t/YZ is equal to zero, and (19) becomes a two-dimensional volume balanced model similar to (17).

DEAN and MAURMEYER (1983) have also presented a two-dimensional volume balanced model to predict beach erosion rates for an equilibrium profile. The DEAN-MAURMEYER model differs from Bruun's rule in that it is designed for a cross-section of a barrier island and therefore includes the volume of sediment deposited by overwash and aeolian action on a backbarrier and into a lagoon as an island transgresses. Their model is given as

$$\Delta X = S(L_o + W + L_l)/(B_o + h_{bo}) - (B_l - h_{bl}) \qquad (20)$$

where L_o, W, and L_l are the widths of the accreting nearshore zone, subaerial barrier, and lagoon bottom, respectively; h_{bo} and h_{bl} are the water depths at wave break-point on the ocean and bay side, respectively, while B_o and B_l are the heights of berms on the ocean and bay side, respectively.

For a longshore disequilibrium condition, DEAN and MAURMEYER (1983) formulated a model similar to (19) and is given as

$$\Delta X = [LS + (\partial Q_{sx}/\partial z)\Delta t]/PY, \qquad (21)$$

where L is the width of the beach and shoreface, $\partial Q_{sx}/\partial z$ is the gradient of the longshore sediment transport for a controlled volume of longshore length, Δt is time interval during a relative rise in sea level, and P is the percentage of eroded material that is textural compatible with the surf-zone sands. Similar to (19), (21) assumes that the eroded sediments from a transgressing beach and shoreface are deposited in a shore normal compartment and that none is introduced into the littoral drift. When $\partial Q_{sx}/\partial z$ is equal to zero and P to one, then (21) reverts to (16).

EVERTS (1985, 1987) also developed a three-dimensional model that includes a term to account for a possible longshore volumetric gain or loss for a referent cross-shore segment (V_o). His model is given as

$$kV_l + V_o - (V_g + V'_g) = 0, \qquad (22)$$

where V_l is the annual volume eroded from the shoreface and k is the portion of shoreface materials equal to or greater than sand size; V_g and V'_g are the annual volumes of material deposited on a transgressing backbarrier and on the shoreface base, respectively. All other volumetric changes in (22) not caused by a relative rise in sea level are included in V_o (EVERTS, 1985). Therefore, in terms of volumetric changes of shore compartments in response to just a relative rise in sea level, (22) is deduced to a two-dimensional model. The rate of beach erosion is obtained by a trial and error procedure that employs integration to solve for V_l, V_g, and V'_g; k and V_o are estimated (EVERTS, 1985, 1987).

Any attempt to predict rates of beach erosion as a function of a relative rise in sea level by implementing any of the aforementioned volumetric balanced models is problematic for the following reasons. Bruun's rule and model (18) fail to account for the volume of sediment that is deposited on barriers and in lagoons as a barrier profile transgresses (SWIFT *et al.*, 1972; McCLEAN, 1973; BELKNAP and KRAFT, 1981), and therefore (16), (17), and (18) underestimate the rate of beach erosion. The DEAN-MAURMEYER model (20) assumes that transgression of a shoreface profile begins at a water depth of wave break-point (h_{bo}), which during storms along the United States east coast ranges from 4 to 8 m (HALLERMEIER, 1981). The model excludes the transgressive responds of the lower shoreface profile, and therefore underestimates the sediment volume eroded from the shoreface. In addition, model (18) calculates just the vertical accretion of the subaerial barrier and lagoon margin [$S(L_o + W)$] and not the accretion as caused by transgression (13, 14). Finally, all of the aforementioned models assume that all sediments from a transgressing beach and shoreface profile are deposited in shore normal compartments and that none enters the littoral drift. The results of this Long Island study shows that this assumption is not universally true; in turn, two-dimensional volume balanced budget models may underestimate the rate of beach erosion and miscalculate the rates of volumetric change in shore normal compartments. An alternative method for predicting the long-term rates of beach erosion and of volumetric change of shore compartments has been presented in the form of the transgressive barrier model.

SUMMARY AND CONCLUSION

Studies have shown that barrier islands have transgressed in the face of a relative rise in sea level during long periods of time. In turn, two-dimensional volume balanced models have been constructed to predict long-term rates of shoreline erosion and volumetric change of shore compartments as a shore adjusts to rising water levels. A fundamental assumption of these models is that sediment displacement of a transgressing shore profile is confined in two dimensions; all sediments eroded from a beach and shoreface are deposited in shore normal compartments. Based on reasonable assumptions, the results of this Long Island study contradicts this fundamental assumption by showing that the volume eroded from a transgressing beach and shoreface zone is, in all probability, greater than volumetric sum of that deposited in shore normal compartments and that the residual volume of about 500,000 m^3/yr is dispersed by littoral currents. Thus, the reliability of two-dimensional volumetric balanced models to reasonably predict rates of shoreline erosion and of volumetric change of shore compartments should be questioned.

For the Atlantic shore of Long Island and in response to a 2.7 mm/yr relative rise in sea level, the transgressive barrier model predicts a long-term shoreline erosional rate of about 0.7 m/yr, which is consistent with observed rates, and an annual displacement of about 1.3 million m^3 of sediments from the beach and shoreface. Of this total amount about 49% should be deposited on barriers and in lagoons, while 12% may be lost to the inner-continental shelf. The remaining 39% should be dispensed by littoral currents, most of which by westerly flowing currents.

It bears repeating that the volumetric rates of change for shore compartments are long-term averages. No doubt from year-to-year or from decade-to-decade, these rates will vary. For example, when the frequency of hurricanes and extratropical storms striking the shore is high, the gross littoral sediment discharge and the volumetric rates of subaerial barrier, lagoon, and inner-continental shelf accretion should be relatively high. Conversely, the opposite should be true when major storms are infrequent. The rates of shoreline erosion and of volumetric change for the beach, shoreface, and backbarrier seem credible. However, the volumetric rates of lagoon bottom accretion and of sediment loss to the inner shelf are estimated in a broad sense. Clearly more studies are needed in these two areas.

For barriers in general, displaced beach and shoreface sediments not used to accrete barriers or lagoons and not deposited on the inner shelf are transported by littoral currents; some of these materials will be used to laterally extend spits, aggrade shoals off of capes, and sustain nearshore sand ridges. Further, as a shoreface transgresses, it abandons its lower base segment, and over time the sum of these segments forms a ramp with a gentle seaward-dipping slope. Thus, as sea level rises along barrier shores, there appears to be an assemblage of depositional landforms as well as a ramp that evolve at the expense of a transgressing beach and shoreface. Should the rate of sea level substantially increase or decrease, then the rates of shoreline erosion and of the gross littoral drift should likewise increase or decrease, respectively as a shore adjusts to major changes in sea levels. The lag time between changing rates of sea level and responding changing rates of shoreline and compartment adjustments is unknown at this time.

Finally, the transgressive barrier model is a kinematic model. Although it can predict plausible rates of shoreline erosion and of volumetric sediment displacement from the beach and shoreface, the model does not include the physics of the hydrodynamics responsible for the readjustment of a shoreface following a relative rise in sea level. Additional theoretical studies, substantiated by wave-basin results, should be conducted to fill this gap of knowledge.

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