Journal of Coastal Research	16	1	48–70	Royal Palm Beach, Florida	Winter 2000

The Use of Mathematical Models to Predict Beach Behavior for U.S. Coastal Engineering: A Critical Review

E. Robert Thieler†*, Orrin H. Pilkey, Jr.‡, Robert S. Young§, David M. Bush††, and Fei Chai‡‡

†U.S. Geological Survey
384 Woods Hole Road
Woods Hole, MA 02543, USA.
e-mail rthieler@usgs.gov

‡Division of Earth and Ocean Sciences
Nicholas School of the Environment
Duke University,
Durham, NC 27708, USA.

§Department of Geoscience and Natural Resource Management
Western Carolina University
253 Stillwell Hall
Cullowhee, NC 28723, USA.

††Department of Geology
State University of West Georgia
206 Callaway Hall
Carrollton, GA 30118, USA.

‡‡Department of Oceanography
University of Maine
223 Libby Hall
Orono, ME 04469, USA.

ABSTRACT

THIELER, E.R.; PILKEY, O.H., JR.; YOUNG, R.S.; BUSH, D.M.; and CHAI, F., 2000. The Use of Mathematical Models to Predict Beach Behavior for U.S. Coastal Engineerings: A Critical Review. *Journal of Coastal Research*, 16(1), 48–70. Royal Palm Beach (Florida), ISSN 0749-0208.

A number of assumed empirical relationships (*e.g.*, the Bruun Rule, the equilibrium shoreface profile, longshore transport rate equation, beach length: durability relationship, and the renourishment factor) and deterministic numerical models (*e.g.*, GENESIS, SBEACH) have become important tools for investigating coastal processes and for coastal engineering design in the U.S. They are also used as the basis for making public policy decisions, such as the feasibility of nourishing recreational beaches. A review of the foundations of these relationships and models, however, suggests that they are inadequate for the tasks for which they are used. Many of the assumptions used in analytical and numerical models are not valid in the context of modern oceanographic and geologic principles. We believe the models are oversimplifications of complex systems that are poorly understood. There are several reasons for this, including: (1) poor assumptions and important omissions in model formulation; (2) the use of relationships of questionable validity to predict the morphologic response to physical forcing; (3) the lack of hindsighting and objective evaluation of beach behavior predictions for engineering projects; (4) the incorrect use of model calibration and verification as assertions of model veracity; and (5) the fundamental inability to predict coastal evolution quantitatively at the engineering and planning time and space scales our society assumes and demands.

It is essential that coastal geologists, beach designers and coastal modelers understand these model limitations. Each important model assumption must be examined in isolation; incorporating them into a model does not improve their validity. It is our belief that the models reviewed here should not be relied on as a design tool until they have been substantially modified and proven in real-world situations. The "solution," however, is not to increase the complexity of a model by increasing the number of variables. What is needed is a thoughtful review of what beach behavior questions should or could be answered by modeling. Viable alternatives to the use of models do exist to predict the behavior of beaches. Three such alternatives to models are discussed for nourished beach design.

ADDITIONAL INDEX WORDS: *Analytical model; Bruun Rule; coastal processes; equilibrium profile; GENESIS; numerical model; SBEACH; sediment transport; shoreline change.*

INTRODUCTION

Mathematical models are playing an ever-increasing role in important societal decisions involving earth science. The debate surrounding the impacts of climate warming, for example, is replete with the results of global circulation and other models (IPCC, 1996); the siting of nuclear waste based on geological engineering models engenders similar debate (see references in ORESKES *et al.*, 1994). These highly visible societal issues have resulted in increased public awareness of the uses and misuses of the modeling approach to environmental prediction. The same also holds true for modeling in areas as diverse as fisheries management (KUNZIG, 1995) and the stock market (THE ECONOMIST, 1998). Those who predict the behavior of beaches are in public view as well, for such issues as beach nourishment and the impact of shoreline engineering.

For present purposes, predictive mathematical models of earth surface processes such as coastal evolution can be divided into two types: applied and academic. This paper is concerned entirely with applied modeling that is used to predict the behavior of beaches in an engineering time frame. Academic uses of coastal models, which are *not* the subject of this paper, include: 1) conceptualizing the various facets of an earth surface process or event, 2) facilitating the handling of large amounts of data concerning a process or event, 3)

98209 received 30 July 1998; accepted in revision 30 May 1999.

* The views expressed in this paper are those of the authors and do not necessarily represent those of the U.S. Geological Survey or the U.S. Government.

Table 1. *Possible modeling questions asked about a hypothetical nourished beach.*

Quantitative (when, where, how much) Questions	Qualitative (how, why) Questions
How long will the nourished beach last?	What are the mechanisms of sediment dispersal on a nourished beach?
Where will the erosion spots be?	Do nourished beaches behave differently than their natural predecessors?
Where will the shoreline be (± a few meters) in 1, 5, 10 and 50 years?	What attributes are most important in determining the beach life span (grain size, wave climate, storms)?
What volume of sand will be required to keep the beach in place for the desired time interval?	

determining whether our understanding of a process is missing important variables, and 4) evaluating the correctness of individual variables assumed to impact on a process or event. The modeling of fluid dynamics, sediment transport, and morphological evolution of beach, shoreface and shelf environments has long been a focus of academic investigation (*e.g.*, GRANT and MADSEN, 1979; BAILARD, 1981; GUZA and THORNTON, 1985b; ROELVINK and STIVE, 1989; KEEN and SLINGERLAND, 1993; WIBERG and HARRIS, 1994; COWELL, *et al.*, 1995; WERNER, 1995). These and related efforts, however, are not necessarily directed at solving societal problems or making predictions that form the basis for specific coastal management decisions. Rather, they are concerned with understanding the physical basis for sediment transport and morphologic evolution of the coastal environment through combined theory, observation, and modeling. This is a far different endeavor than the specific prediction of future beach nourishment volumes, benefits and costs for a particular beach over the next 10–50 years that is frequently the focus of applied coastal modeling (*e.g.*, USACE, 1999). Thus, it is important to distinguish between models that answer quantitative ("when, where and how much") questions and those that answer qualitative ("how and why") questions (Table 1). Models used for the purpose of coastal engineering are used to answer specific, quantitative questions. Many important questions about beach behavior, however, are qualitative and can be answered with basic scientific models.

There is a large difference between these two types of models. Engineering models used to predict the life span of a nourished beach must account for all significant factors that will affect beach durability. Omitting an important factor, or miscalculating the result of several interacting factors, may result in inaccurate answers that have significant ramifications for project planning and design. For basic science modeling of beach behavior, however, the goal may be to use an absolute minimum number of model parameters. Generally, what are believed the most important controlling parameters and their interactions are considered and if varying a parameter(s) reproduces observations, the parameter is assumed to be important. Recent examples of such models are WERNER and FINK's (1993) study of beach cusp origin, and MURRAY and REYDELLET's (submitted) description and explanation of rip currents in Pacific Coast surf zones.

Both analytical and numerical models are used to predict beach behavior for coastal engineering purposes. Some of the models, such as the widely-used GENESIS and SBEACH models, are rather complex and are based on a large number of geologic and oceanographic assumptions, presumed to be valid universally. These models are used widely in applied coastal engineering studies, where a specific project lifetime and a specific project cost are needed. For example, the GENESIS model (HANSON and KRAUS, 1989) has been used in a variety of coastal settings to predict beach nourishment sand volume requirements (USACE, 1991; EBERSOLE *et al.*, 1996), and thus forms the basis for presenting project lifetimes, costs and presumed environmental impacts to funding or regulatory agencies, legislative bodies, or clients such as municipalities and community groups. Underlying these models, however, are a number of assumptions regarding coastal behavior (sediment transport, wave climate, beach/shoreface profile, *etc.*) that many geoscientists consider invalid (KRAFT *et al.*, 1987; CARTER and WOODROFFE, 1994; PILKEY *et al.*, 1993; RIGGS *et al.*, 1995; THIELER *et al.*, 1995; YOUNG *et al.*, 1995). Concern about the validity of these assumptions in producing a model's "answer" is often expressed, but rarely do model users analyze or quantify the uncertainties (*e.g.*, HODGENS, 1993; *cf.* WISE and SMITH, 1996).

The review and criticism of mathematical models of beach behavior, from a geologic perspective, is not new (*e.g.*, PILKEY *et al.*, 1993; CARTER and WOODROFFE, 1994; THIELER *et al.*, 1995; YOUNG *et al.*, 1995). These criticisms, however, appear to have had little impact on applied modeling. For example, a critical concept that underlies virtually all models used to predict beach behavior is the shoreface profile of equilibrium (DEAN, 1977; 1991). PILKEY *et al.* (1993) criticized this concept in detail, arguing that for most shorelines it may not exist. These criticisms, although recognized in the scientific literature (*e.g.*, DUBOIS, 1993; DELANGE and HEALY, 1994; COWELL *et al.*, 1995; FRENCH *et al.*, 1995; RIGGS *et al.*, 1995; STIVE and DEVRIEND, 1995; WEHMILLER *et al.*, 1995; PLAG *et al.*, 1996; GUILLEN and HOEKSTRA, 1996; BRAY and HOOKE, 1997), have remained unanswered in the applied coastal modeling or engineering literature.

An example of this situation is a plot from DEAN (1983; 1987; 1991) (Figure 1) showing the presumed relationship between the equilibrium profile scaling parameter A and sediment grain size. As summarized below, A is the only variable in the equation determining the shape of the equilibrium profile. This relationship between A and grain size, based on the work of MOORE (1982), is presumed to be a worldwide phenomenon. PILKEY *et al.* (1993) re-plotted Moore's original data, and suggested that no relationship between A and grain size exists, particularly for the sand-size range important in coastal engineering applications like beach nourishment (see Figure 1). Nonetheless, DEAN (1996) and KOMAR (1998a) continue to advocate the concept that A or grain size controls the shape of shorefaces, without providing new evidence of this relationship or answering previous criticisms. We are hopeful that this review paper of U.S. beach behavior modeling will attract the serious consideration of applied coastal modelers

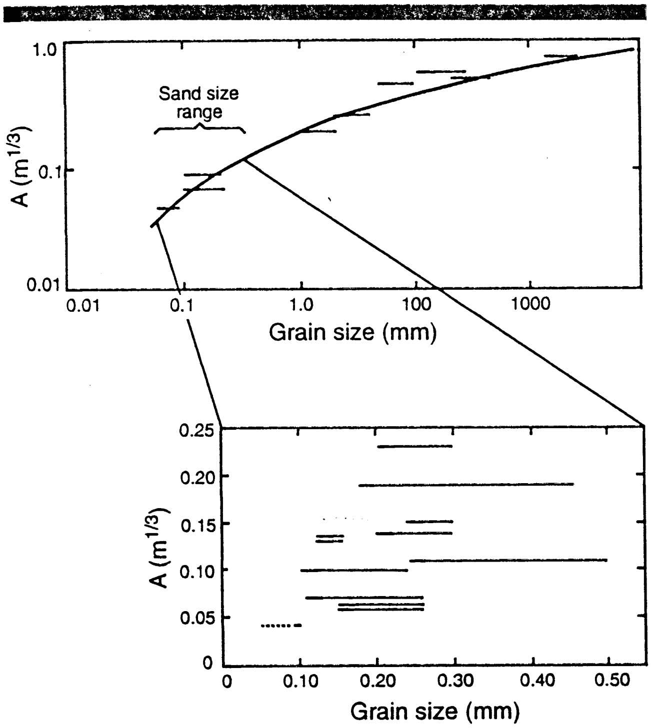

Figure 1. Two plots showing the relationship between the sediment scaling parameter A and sediment grain size. (After PILKEY *et al.*, 1993, and PILKEY and DIXON, 1996.)

and begin a beneficial dialogue between field-based geologists and modelers.

This review paper identifies some of the major weaknesses in several widely used deterministic coastal engineering models, examines the origin and development of several of these models, and presents three alternatives for nourished beach design that are not model-dependent. We examine here only those models that attempt to predict local to regional shoreline evolution or beach behavior over a time span of hours to decades with the purpose of addressing a societal problem such as the erosion of protective and recreational beaches. This is the domain of coastal engineering, management, and planning; and the areal and temporal framework with which our society is concerned.

We have selected seven empirical relationships and deterministic models (hereafter collectively referred to as models) to illustrate their major shortcomings or over-simplifications. The models include: (1) the Bruun Rule (BRUUN, 1962), (2) the equilibrium shoreface profile equation (DEAN, 1977), (3) the longshore transport equation (or "CERC Formula") from the Shore Protection Manual (USACE, 1984), (4) the nourished beach length:durability relationship (DEAN, 1983), (5) the renourishment factor (R_J) (JAMES, 1975; USACE, 1984), (6) the GENESIS shoreline change model (HANSON and KRAUS, 1989), and (7) the SBEACH beach profile change model (LARSON and KRAUS, 1989). These models have been discussed extensively elsewhere (see references above and below); a brief summary of each is presented below.

Bruun Rule

The empirical relationship that eventually became the "Bruun Rule" (the term was coined by SCHWARTZ, 1967) was first proposed by Bruun (BRUUN, 1954) for the Danish North Sea coast, and can be written as

$$R = \frac{L}{(B + h)} S \qquad (1)$$

where R is the recession due to sea-level rise S, L is the width of the active profile, B is the berm height, and h is the depth of the active profile base. BRUUN (1962) used this relationship to develop a simple model for coastal evolution, in which a constant profile shape (of the form in equation (2) below) translates landward and upward over time in response to rising sea-level. The limiting conditions for this concept include no net longshore transport of sediment, and no significant seaward-directed sediment transport occurs beyond a certain water depth, or closure depth.

Equilibrium Shoreface Profile

The concept of the shoreface profile of equilibrium is the basis for most models used to predict beach evolution. LARSON (1991) defined an equilibrium profile as follows: "a beach of specific grain size, if exposed to constant forcing conditions, normally assumed to be short-period breaking waves, will develop a profile shape that displays no net change in time." The concept of the shoreface profile of equilibrium was first developed by BRUUN (1954; 1962) and later modified by DEAN (1977). Dean used a least squares approach to fit the profile data of HAYDEN *et al.* (1975) to an equation of the form

$$h = Ax^m \qquad (2)$$

where h is water depth, A is a profile scaling parameter, x is the distance offshore, and $m = 0.67$ (DEAN, 1977). DEAN (1987) related A to sediment fall velocity by transforming MOORE's (1982) sediment grain size data to the equation

$$A = 0.067w^{0.44} \qquad (3)$$

where w is the sediment fall velocity in cm s^{-1}.

Beach Length: Durability

DEAN (1983) proposed that the life span of a beach nourishment project is related to its length by a square law relationship based on

$$(t_p)_2 = (t_p)_1 \frac{l_2^2}{l_1^2} \frac{K_1}{K_2} \qquad (4)$$

where t_p is the time to lose a percentage (p) of the fill volume, l is the alongshore length of the project, and K is a rate constant. The subscripts (1 and 2) denote two projects contemplated for the same site. This relationship for beach planform evolution is derived from the one-line diffusion model of PELNARD-CONSIDÉRE (1956), assumes all erosion occurs at the ends of the beach planform, and that offshore losses are negligible. For example, DEAN (1983) states that doubling the length of the nourished beach will increase its longevity by a factor of four. This reasoning has led to the publication of

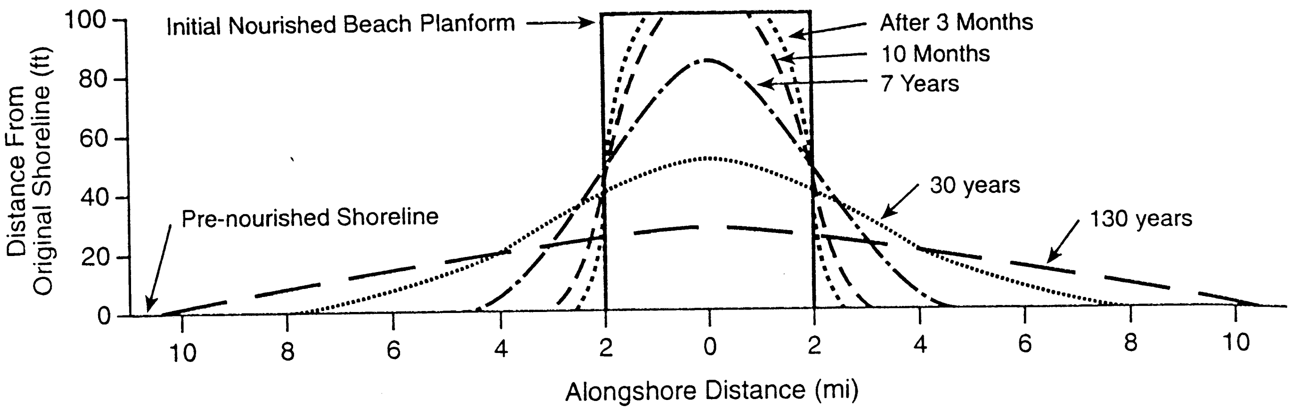

Figure 2. Figure from the NATIONAL RESEARCH COUNCIL (1990) showing the presumed evolution of a beach fill over a 130-year period, utilizing the beach length: durability square law relationship given by DEAN (1983), which is based on the model of PELNARD-CONSIDÉRE (1956). Example assumes an initially rectangular planform, with a length of 4 miles, width of 100 feet, and effective wave height of 2 feet. (Modified after NATIONAL RESEARCH COUNCIL, 1990.)

modeled beach life spans exceeding a century (NATIONAL RESEARCH COUNCIL, 1990) (Figure 2).

CERC Formula

The most widely used longshore sediment transport equation (USACE, 1984) relates total load (suspended and bed load) transport in the surf zone to longshore energy flux (*e.g.*, Joules sec^{-1}), one form of which is

$$Q = k\frac{\rho H_b^2\sqrt{gd_b}}{16(\rho_s - \rho)a'}2 \sin \alpha_b \tag{5}$$

where k is an empirical coefficient, H_b is breaking wave height, d_b is water depth at breaking, ρ_s is the density of quartz sand, ρ is the density of the fluid, a' is the sediment density, and α_b is the breaking wave angle. This relationship is also known as the "CERC Formula" (NIELSEN, 1992).

Renourishment Factor

The renourishment factor (R_J) is used to estimate the time after initial nourishment when a beach will require renourishment, and is a ratio expressing the rate at which a borrow sediment of a given grain size distribution erodes relative to the erosion rate of the native sediments. The relationship presented by JAMES (1975) is given in the Shore Protection Manual (USACE, 1984) as

$$R_J = e\left[\Delta\left(\frac{M_{\phi b} - M_{\phi n}}{\sigma_{\phi n}}\right) - \frac{\Delta^2}{2}\left(\frac{\sigma^2_{\phi b}}{\sigma^2_{\phi n}} - 1\right)\right] \tag{6}$$

where M and σ are the respective phi (ϕ) mean and standard deviation of the sediment, and the subscripts n and b refer to the respective native and borrow area sediment characteristics. A winnowing parameter (Δ) is used to express any size-selectivity of borrow material erosion. A large value of Δ indicates that all grain sizes are being removed at nearly equal rates. A small Δ value indicates the erosion process is discriminatory and removes certain grain sizes more quickly than others. In practical use (*e.g.*, USACE, 1984), Δ is set to unity. Curves for R_J are given by JAMES (1975) and USACE (1984).

GENESIS

The GENESIS shoreline change model (HANSON and KRAUS, 1989) is an empirically based, one-line numerical model designed to simulate the long-term shoreline changes resulting from coastal engineering and/or beach nourishment activities that may alter spatial and temporal gradients in longshore sediment transport. GENESIS is also used to develop regional-scale sediment budgets. According to KOMAR (1998a; p. 448), "the most recent advances in numerical line models to simulate shoreline change have been incorporated into GENESIS." The governing transport equation used in GENESIS is based on the CERC longshore transport formula described above, coupled with a shoreline change equation. A summary of GENESIS features and proposed applicability is presented by HANSON (1989). A critical review of GENESIS has been presented by YOUNG *et al.* (1995).

SBEACH

SBEACH (LARSON and KRAUS, 1989) is an empirically based numerical model used to predict storm-induced beach and dune erosion, as well as bar formation and movement. Its primary application is in the design of beach nourishment projects, where it is used to evaluate the response of various beach configurations to simulated storms. The model assumes that profile change is the result only of cross-shore processes due to breaking waves. Sand conservation is assumed, such that there is no net loss or gain of material. The direction and rate of cross-shore sediment transport is based on empirical criteria derived from wave-tank experiments. Longshore processes are assumed to be uniform and therefore are not considered.

COASTAL MODEL ASSUMPTIONS

Table 2 lists a number of geologic and oceanographic assumptions, and how they are addressed in the various em-

Table 2. *Geologic and oceanographic principles, and how they are addressed as assumptions in seven widely used coastal engineering models for prediction of beach behavior.*

Model	Bruun Rule	Eq. Prof.	CERC Q Eqn.	Length Eqn.	Renour. Factor	GENESIS	SBEACH
Geologic Considerations							
1 Are different coastal types recognized? (e.g., cliffed, rocky, sandy, barrier island, etc.)	N	N	N	N	N	N	N
2 Is an equilibrium shoreface profile assumed?	Y	Y	Y	Y	N/A	Y	Y
3 Is a closure depth assumed?	Y	Y	Y	Y	N/A	Y	Y
4 Is smooth shoreface bathymetry assumed?	Y	Y	Y	Y	N/A	Y	N
5 Is shoreface geology considered?	N	N	N	N	N/A	N	N
6 Is sand conservation assumed?	Y	Y	Y	Y	N	Y	Y
7 Are areal and temporal variations in sediment supply considered?	N	N	N	N	N	Y	N
8 Is longshore loss/gain of sediment considered?	N	N	N	N	N/A	Y	N
9 Is offshore loss/gain of sediment considered?	N	N	N	N	N/A	N	N
10 Is overwash loss of sediment considered?	N	N	N	N	N	N	N
11 Is aeolian loss/gain of sediment considered?	N	N	N	N	N	N	N
12 Is areal and temporal grain size variability considered?	N	N	N	N	N	N	N
13 Are other sedimentary attributes (e.g., grain shape and density) or sediment physical properties (e.g., shell lags, cohesion, organic mats, etc.) considered?	N	N	N	N	N	N	N
14 Are the effects of bedforms on sediment transport considered?	N	N	N	N	N	N	N
15 Is the effect of offshore bars on sediment transport considered?	N	N	N	N	N	N	Y
16 Is the effect of beach state (e.g., antecedent, modal, seasonal, etc.) on erosion potential considered?	N	N	N	N	N	N	Y
17 Are the effects of engineering structures (e.g., groins, seawalls) on the beach/shoreface considered?	N	N	N	N	N	Y	N
18 Are variations in dune characteristics (e.g., extent of vegetation, slope, width, overwash gaps, etc.) considered?	N	N	N	N	N	N	N
19 Is the distribution of Q (total amount of sediment transported) uniform across the surf zone?	N/A	N/A	Y	N/A	N/A	Y	N/A
20 Is sediment transport seaward of the surf zone considered?	Y	Y	N	N	N/A	N	Y
21 Is the effect of the water table on sediment erodibility considered?	Y	Y	N	N	N/A	N	Y
22 Is bed liquefaction or elevated pore water pressure in surf zone sediments considered?	N	N	N	N	N	N	N
Oceanographic Considerations							
Waves							
1 Is a storm considered?	N	N	N	N	N	N	Y
2 Are multiple randomly occurring storm events considered?	N	N	N	N	N	N	N
3 Is cross-shore sediment transport assumed to be caused only by waves?	Y	Y	Y	Y	Y	Y	Y
4 Are wave refraction/diffraction effects considered?	N	N	Y	N	N/A	Y	N
5 Is smooth shoreface bathymetry assumed?	Y	Y	Y	Y	N/A	Y	N
6 Is frictional dissipation of wave energy across the shoreface considered?	N	N	N	N	N/A	N	N
7 Does the model use monochromatic, unidirectional waves?	N	Y	Y	Y	N/A	N	Y
8 Are the effects of bottom type (e.g., surface roughness, bedforms) on wave energy considered?	N	N	N	N	N/A	N	N
9 Are the effects of offshore bars on wave energy considered?	N	N	N	N	N/A	N	N
10 Are wave shape/breaker type considered?	N	N	N	N	N/A	N	N
11 Are landward boundary conditions (e.g., wave reflection off a seawall or steep beach) considered?	N	N	N	N	N/A	N	N

Table 2. *Continued.*

Model	Bruun Rule	Eq. Prof.	CERC Q Eqn.	Length Eqn.	Renour. Factor	GENESIS	SBEACH
12 Is linear wave theory used in wave transformations?	N/A	N/A	Y	Y	N/A	Y	Y
13 Are infragravity waves considered?	N	N	N	N	N/A	N	N
Currents							
14 Are turbidity currents considered?	N	N	N	N	N	N	N
15 Are rip currents considered?	N	N	N	N	N	N	N
16 Are storm surge ebb currents considered?	N	N	N	N	N	N	N
17 Are gravity-driven currents considered?	N	N	N	N	N	N	N
18 Are wind-driven up/downwelling currents considered?	N	N	N	N	N	N	N
19 Are wind-drive longshore currents considered?	N	N	N	N	N	N	N
20 Are wave setup/down-induced currents considered?	N	N	N	N	N	N	N
21 Are the effects of forced long waves and/or groupy incident waves on currents considered?	N	N	N	N	N	N	N
22 Are wave–current interactions considered?	N	N	N	N	N	N	N
Tides, Water Level, *etc.*							
23 Is storm surge considered?	N	Y	N	N	N	N	Y
24 Are tidal currents considered?	N	N	N	N	N	N	N
25 Is the tidal range considered?	N	N	N	N	N	N	Y

Notes: Y = principle is used in the model; N = principle is not used in the model; N/A = not acceptable.

pirical relationships and models. These assumptions cover a wide variety of issues, ranging from the fundamental distinction of coastal type to grain size. They encompass a broad range of spatial and temporal scales that should be relevant to modeling at the space and time scales of the models (DEVRIEND, 1991a; 1991b). For example, the basic principles governing wave breaking may be applied over a surf-zone space scale, and a time frame on the order of seconds that is pertinent to the application of sediment transport rules. At the other end of this spatial and temporal scale, geologic setting is a property defining the entire system under study. Its specification might involve variations in morphology (*e.g.*, changes within and between beach, dune, inlet, shoreface, and headland environments) at the kilometer scale that impact on coastal behavior over decadal and centennial time frames.

For each assumption listed as a question in Table 2, its treatment in or the significance of its omission from the models is described below. In some cases, we have grouped together a discussion of several related assumptions.

Geologic Considerations

(1) Are different coastal types recognized? (*e.g.*, cliffed, rocky, sandy, barrier island, *etc.*)

Different coastal types are not recognized by the models. However, different coasts evolve in different fashion, even in response to similar wave climates. There is a voluminous literature on the morphologic characteristics and large-scale behavior of different coastal systems, including DAVIS (1985), FLETCHER and WEHMILLER (1992), and LIST and TERWINDT (1995). The relative importance of overwash, littoral transport, cross-shore transport, and inlet processes, for example, varies greatly between micro- and meso-tidal barrier islands (HAYES, 1979); other things being equal, more sand is likely to be "lost" in a landward direction through overwash on a microtidal island, relative to a mesotidal island. For the most part, however, the models are designed for use on (or assume) unconsolidated, straight, sandy coasts. In practice, the models have been applied to a variety of coastal types. For example, the Bruun Rule has been applied in such different environments as the Great Lakes (HANDS, 1980), the Chesapeake Bay (ROSEN, 1978), and the open-ocean shoreline of North Carolina (PILKEY and DAVIS, 1987).

(2) Is an equilibrium shoreface profile assumed?

The assumption of an equilibrium shoreface profile is perhaps the most basic assumption of all the models. Based on the results of field investigations, however, the existence of such a profile as defined in the models has been strongly questioned (WRIGHT *et al.*, 1991; PILKEY *et al.*, 1993; CARTER and WOODROFFE, 1994; THIELER *et al.*, 1995). PILKEY *et al.* (1993) argued that there are four basic assumptions behind the equilibrium profile concept that are invalid. These assumptions are: 1) sediment is moved only by diffusion due to wave energy gradients; 2) there is no net cross-shore movement of sediment seaward of a specified closure depth; 3) underlying geology does not play a role in determining profile shape or rates of profile translation; and 4) the only variable determining the shape of any shoreface profile is sediment grain size. WRIGHT (1995) notes that true equilibrium may be approached, but is rarely attained, because of the rapidity of changes in wave climate. He states, (p. 16) "it may therefore be more appropriate to regard the steady or average state as representing the average disequilibrium condition than the average equilibrium condition."

(3) Is a closure depth assumed?

Most models assume that no significant amount of sediment escapes beyond an offshore seaward limit or closure depth. In effect, closure depth is a barrier past which sand simply does not move. Specification of closure depth is an important part of nourished beach design, since it basically determines the volume of sand required. Simple geometry dictates that the shallower the closure depth, the smaller the volume of sand required for a nourished beach. Closure depth is an example of a simplifying principle put into models that has little basis in reality. Significant amounts of sand transport on the continental shelf (PILKEY and FIELD, 1972; STERNBERG and LARSEN 1975; GADD *et al.*, 1978; LAVELLE *et al.*, 1978; CACCHIONE and DRAKE, 1982; VINCENT *et al.*, 1982; WIBERG and SMITH, 1983; CACCHIONE *et al.*, 1987; 1994; WILLIAMS and MEISBURGER, 1987; WRIGHT *et al.*, 1986; 1991; 1994; among many others) as well as the surf zone have been well-documented, which casts doubt on the idea that the two environments are somehow separated by a zone of insignificant sediment movement.

On most inner shelves, there is a depth (generally between 8–12 m on the U.S. East Coast) at which there is a break in slope that does not vary appreciably on a regional or temporal basis. This change in profile geometry has been inferred to correspond to a limiting depth of sediment transport, primarily because depth changes in this region are difficult to resolve (e.g., LEE and BIRKEMEIER, 1993). But as WRIGHT (1995, p. 25) notes, "vertical fluctuations of only a few centimeters translate into large volumes of sediment when integrated over across-shelf distances of hundreds or thousands of meters."

Gulf of Mexico current meter and sedimentologic studies have documented storm transport of nearshore sediment to the edge of the continental shelf (HAYES, 1967; MORTON, 1988; SNEDDEN *et al.*, 1988). Another dramatic example of the importance of offshore sediment transport across shorefaces is illustrated by sidescan sonar records showing shore-perpendicular scour across the Myrtle Beach, South Carolina shoreface resulting from storm surge ebb from hurricane Hugo (GAYES, 1991). Similar cross-shore depositional and erosional fabrics on shorefaces have been found by MORANG and MCMASTER (1980), AUBREY *et al.* (1982); CACCHIONE *et al.* (1984), FIELD and ROY (1984), HEQUETTE and HILL (1993) and THIELER *et al.* (1995).

(4) Is smooth shoreface bathymetry assumed?

Most models assume a perfectly smooth profile or straight and parallel bottom contours. This is an assumption that may be close to valid on sand-rich shorefaces, but may be completely invalid on sand-poor shorefaces such as those on most of the U.S. East and Gulf coasts, and on rocky coasts. Coupled with the concept of a smooth shoreface is the assumption of a thick sand sheet. But recent work has shown that rock outcrops and mud layers abound on many U.S. East Coast (RIGGS *et al.*, 1995; SCHWAB *et al.*, 1997) and Gulf Coast (DAVIS and KUHN, 1985; EVANS *et al.*, 1985) shorefaces. These features form irregular surfaces that impact on wave refraction and diffraction, wave energy attenuation, and ultimately on the magnitude of nearshore wave energy.

(5) Is shoreface geology considered?

None of the models considers the impact of underlying shoreface geology on either the details of the processes represented, or the impact of larger variability in geologic setting on coastal evolution. For many years, both geologists and engineers considered shoreface geology to be fairly homogeneous. There is increasing recognition, however, that geologic control of shoreface morphology and nearshore processes, including rates of shoreline retreat, play a fundamental role in local and regional coastal behavior (*e.g.*, RIGGS *et al.*, 1995). Clearly, a shoreface with abundant rock outcrops such as Onslow Bay, North Carolina (RIGGS *et al.*, 1996) and many California shorefaces (TAIT *et al.*, 1992), or protruding mud layers will retreat in different fashion than a shoreface composed of thick sand deposits (Gold Coast, Australia). RIGGS *et al.* (1995) have shown that significant differences in shoreline retreat rate may occur over short (kilometer) distances on barrier islands. Unconsolidated, inlet-fill shorefaces, for example, will erode faster than outcrop-armored shorefaces. These facts have also been highlighted by KRAFT *et al.* (1987), PILKEY *et al.* (1993), and THIELER *et al.* (1995).

(6–11) Is sand conservation assumed? Are areal and temporal variations in sediment supply, longshore loss/gain of sediment, offshore loss/gain of sediment, overwash loss of sediment, or eolian loss/gain of sediment considered?

These factors are generally not considered in the models, but if they are, it is done in simplistic fashion, such as including a source or sink of an estimated or assumed quantity of sediment based on limited or no field measurements. In general, the models typically assume a closed set of boundary conditions that preclude net gains or losses of material. In the field, however, such gains and losses are the norm, varying considerably from year to year and from coastal type to coastal type. For example, the importance of barrier island beach sand loss by overwash will vary depending on a number of factors including tidal range and island elevation. Low-lying, transgressive islands like Masonboro Island, North Carolina and Assateague Island, Maryland receive overwash sand on a frequent basis (several times a year) (CLEARY and HOSIER, 1979; LEATHERMAN, 1984). On St. Simon Island, Georgia, with its extensive dune development, overwash sand is relatively unimportant.

Variability in overwash characteristics is also dependent upon dune morphology and vegetation. GODFREY (1977) showed that dunes on northern U.S. barrier islands tend to be high and continuous due to the growth characteristics of the predominant beach grass, *Ammophila breviligulata*. Southern U.S. barriers tend to have low, hummocky dunes with frequent gaps due to the characteristics of the predominant beach grass, *Uniola paniculata*. In addition, the greater abundance of coarse shell material on southern barriers promotes the formation of shell pavements that stabilize overwash deposits. Overwash on northern barriers, however, tends to be blown back into the dunes.

We cannot yet measure accurately the quantities of these various sources and sinks of sand (overwash, shoreface sediment wedge, *etc.*), particularly over the time span of interest of the models. Even the total volume of longshore sand transport over any time frame (hour, day, week, or decade) has never been measured directly. It is usually estimated either by the use of the longshore transport equation (*e.g.*, JARRETT, 1977), volumetric changes such as impoundment at jetties (DEAN and PERLIN, 1977), or very short-term direct measurement at only a few points across a portion of the surf zone (*e.g.*, WANG *et al.*, 1998).

(12–13) Is areal and temporal grain size variability considered? Are other sedimentary attributes (*e.g.*, grain shape and density) or sediment physical properties (*e.g.*, shell lags, cohesion, organic mats, *etc.*) considered?

The models uniformly assume a set grain size, (*e.g.*, the median diameter d_{50}), or a small range of grain sizes, both across the surface and with depth in sedimentary section (HAFF, 1996). In the real world, there is substantial regional (RIGGS *et al.*, 1995; SCHWAB *et al.*, 1997), and local (AUBREY *et al.*, 1982; THIELER *et al.*, 1995; SCHWAB *et al.*, 1996) variability in grain size.

Shell and gravel lags are a common component of shallow shoreface sediments, and may delay or prevent sediment movement by waves and currents by bed armoring (WIBERG *et al.*, 1994). Cohesive sediments, bound by clay, algal mats, worm tubes, *etc.* may also resist wave and current induced transport (WRIGHT, 1989; WRIGHT *et al.*, 1997).

(14) Are the effects of bedforms on sediment transport considered?

The models do not account for the role of bedforms of any scale (ripples to sand waves) in sediment transport. None of the models considers seafloor surface roughness or bedforms, yet recent studies have shown that these factors may play an important role in determining both the direction and magnitude of sediment transport. NIELSEN (1988) postulated and both VINCENT and GREEN (1990) and WRIGHT *et al.* (1991) demonstrated in the field that sediment transport over ripples can be offshore during fairweather due to the 90 degree phase lag between suspended sediment concentration maxima and direction of flow under the wave. Under plane bed conditions, the same waves will move sand shoreward. WRIGHT *et al.* (1994) showed that onshore transport on the inner shelf off Duck, North Carolina during the waning phase of the October 1991 "Halloween" Northeaster was an order of magnitude greater than onshore transport during fairweather. They attributed this observation to the persistence of plane bed conditions during a period of high wave stress such that wave orbital asymmetry was effective in moving sediment shoreward.

(15) Is the effect of offshore bars on sediment transport considered?

With the exception of SBEACH, bars are not considered. In SBEACH, an offshore bar is a virtual requirement, even though many beaches rarely have such features. For example, LARSON and KRAUS (1992) derived empirical parameters describing longshore bar movement at Duck, North Carolina, and applied these criteria to predict the movement of an artificially formed "bar" at Silver Strand Beach, California. While the evaluation of empirical criteria is informative about processes occurring at Duck, the subjective assumption that all beaches, natural or human-made, will behave in this manner is questionable. Some beaches do not or only infrequently have bars (HOLMAN and STOCKDON, 1994). Some beaches nearly always have bars (HOWD and BIRKEMEIER, 1987). Some beaches show seasonal changes in morphology (SHEPARD, 1950). Some beaches fluctuate between end-member states of barred and non-barred forms, or exhibit a preferential form, or modal beach state (WRIGHT and SHORT, 1983). The resulting differential magnitudes of sediment transport on the foreshore, trough, bar or shoreface (DEIGAARD *et al.*, 1989; GREENWOOD and OSBORNE, 1991) are not represented by the models. Crescentic bars focus seaward sediment transport in rip currents. Linear bars concentrate longshore transport in the trough. On the Australian Gold Coast, tropical storms typically produce a double-bar storm beach configuration (PILKEY *et al.*, 1993). As a result, waves break three times: once on each bar and finally on the beach. Thus, the distribution of breaking wave energy is affected profoundly; thus bar morphology has a significant impact on the magnitude and direction of sediment transport.

(16) Is the effect of beach state (*e.g.*, antecedent, modal, seasonal, *etc.*) on erosion potential considered?

WRIGHT and SHORT (1983) showed that the response of a beach to a storm is dictated by the antecedent beach state. This is the explanation for the oft-observed phenomenon of the first storm of the season causing more erosion than subsequent storms, even if the storms are of the same magnitude. Maximum event signatures are most likely at the beginning of the storm season. Omission of beach state can be a critical shortcoming of short-term predictive models.

(17) Are the effects of engineering structures on the beach/shoreface considered?

Groins, seawalls, and beach nourishment impact strongly on sediment transport and beach behavior. The GENESIS and SBEACH models are designed specifically to take this into account, but other models basically assume the absence of beach engineering. Engineering events on adjacent shorelines may have a profound effect on sediment supply and rates of shoreline retreat, and produce unpredictable changes in sediment supply. For example, the engineered relocation of the Brazos rivermouth in Texas changed wave refraction patterns and created local reversals in longshore drift direction. This resulted in a cutoff of sand supply and increased shoreline retreat for the downdrift 80 km of shoreline (MORTON, 1975), threatening the Gulf Intracoastal Waterway and development at Sargent Beach (PILKEY and DIXON, 1996).

(18) Are variations in dune characteristics considered?

Extent of vegetation, slope, height, width, frequency of overwash gaps, *etc.* all play a role in the amount of sand that may be lost from the beach during a storm or returned to the beach during storm recovery. Barrier islands with low dunes and many dune gaps will receive much larger volumes of sand by overwash than islands with continuous dunes (GODFREY, 1977). Morphologic characteristics of dunes are ignored in all models. Yet, a number of studies have shown that dune characteristics can play an important role in event-scale beach response (*e.g.*, THIELER and YOUNG, 1991) as well as longer-term evolution of beaches and barrier islands. DAVIDSON-ARNOTT and LAW (1996), for example, found that variations in dune growth along a portion of the Lake Erie shoreline were most sensitive to changes in the width of the fronting beaches. This observation was true at both seasonal and interannual time scales, and over distances of only a few kilometers. DOLAN (1972) argued that the artificial dune ridge on the Outer Banks of North Carolina constructed in the 1930's narrowed the beach and increased the rate of shoreline retreat by preventing the release of energy by overwash and dissipation on a broad beach.

(19) Is the total amount of sediment transported uniform across the surf zone and shoreface?

Sediment transport both on the shoreface and in the surf zone is assumed to be uniform both across-shore and alongshore. For example, GENESIS assumes that the longshore transport is equal at all points across the surf zone (HANSON and KRAUS, 1989; YOUNG *et al.*, 1995). Sediment transport in the surf zone, however, is highly variable in an areal sense, and is controlled to a great extent by the presence of rip currents, bars, bedforms, *etc.*

Offshore sand transport is assumed to be sheet-like, as sand moves uniformly down the shoreface to closure depth. There is extensive evidence, based particularly on sidescan sonar records (CACCHIONE *et al.*, 1984; WRIGHT *et al.*, 1986; GAYES, 1991; THIELER *et al.*, 1995), that cross-shore sediment transport is often non-uniform or spatially heterogeneous.

(20) Is sediment transport seaward of the surf zone considered?

Neither the CERC longshore transport formula, the length equation for nourished beach durability, nor GENESIS consider sediment transport seaward of the surf zone. As described above, it has long been known that extensive sediment transport occurs seaward of the surf zone, and that the surf zone and the shelf are coupled (HAYES, 1967; MORTON, 1988; NIEDORODA *et al.*, 1985; WRIGHT, 1987; NUMMEDAL, 1991; among many others). JAFFE *et al.* (1997) proposed that sediment bypassing on the lower shoreface accounts for the majority of the sediment exchange between adjacent barrier islands on the Mississippi delta.

(21) Is the effect of the water table on sediment erodibility considered?

The effect of groundwater within the beach, which can have a negative or positive impact on the effective strength of beach sediment, is not a factor in any models. Such an impact varies over wave and tidal cycles, during storms, seasonally, and between different climatic zones. Several studies have documented the role of water table position on sediment erodibility (WADDELL, 1976; TURNER and LEATHERMAN, 1997; TURNER and NIELSEN, 1997). In fact, the perceived importance of the beach water table position on sediment erodibility (see in particular the review of TURNER and NIELSEN, 1997) forms the basis for at least one erosion control technology that utilizes beach dewatering (the *STABEACH* system).

(22) Is bed liquefaction or elevated pore water pressure in surf zone sediments considered?

Elevated pore water pressure in the surf zone seabed is not considered, although this is a phenomenon that should greatly affect the volume of surf zone transport. For example, underconsolidated sediment (*i.e.*, pore water pressure supports some of the weight of the overlying sediment) should be readily suspended by waves and transported by currents in the surf zone. Wave-generated stresses on the seafloor may induce liquefaction (HENKEL, 1970; LEE and FOCHT, 1976; SEED and RAHMAN, 1978), bed deformation (DALRYMPLE, 1979), and bed failure (MADSEN, 1978). CONLEY and INMAN (1992) have also shown that wave-induced excess pore pressure results in increased surf zone sediment mobility. They further suggest that this process is not represented in wave-tank experiments, which form the basis for many model assumptions discussed here. Liquefaction of shoreface sediments by cyclic wave loading is also the basis for a model of shallow-water turbidity currents that move sand offshore (WALKER, 1985) during storms.

Oceanographic Considerations

We divide this category into three parts: waves, currents, and water level. Some of the geologic considerations listed in Table 2 and discussed above (smooth profile, *etc.*) are repeated in the table since they also apply to how the models treat physical oceanographic parameters.

(1) Is a storm considered?

Lack of storm events may be one of the most important weaknesses in all of the models. None of the models except SBEACH consider storms. Yet, in many coastal systems, most profile changes, shoreline retreat and sediment transport occur during storms. Usually, an average wave climate (*e.g.*, GENESIS) or "design wave" derived from a WIS hindcast is used (*e.g.*, TRUITT *et al.*, 1993). Wave data for most study sites are largely non-existent (LARSON and KRAUS, 1989) or derived from offshore sources and must then be brought ashore in the model. Significant wave height is commonly used in models, but this does not resemble events during a real storm. The storm surf zone is extremely complex, often involving interacting waves from several directions. The models, however, assume waves coming from a single direction; beach response to such conditions is generally estimated from wave tank experiments. The lack of storm events in models is a particular weakness in modeling nourished beach evolution, since their durability may be highly dependent on the frequency and magnitude of storms (LEONARD *et al.*, 1990).

(2) Are multiple randomly occurring storm events considered?

Multiple, randomly occurring storms events do not exist in any of these models. This is a critical shortcoming. A more realistic view of storms can only come from probabilistic models, resulting in stochastic predictions. Predicted beach behavior must be described with statistical uncertainties or error bars to express randomly occurring storms.

(3) Is cross-shore sediment transport assumed to be caused only by waves?

The models uniformly assume that waves drive all cross-shore sediment transport in a uniform sediment blanket across the shoreface; the role of shoreward- or seaward-directed mean flows is not considered. In the models, sediment movement is typically achieved through a diffusion process due to wave energy gradients across the profile (*e.g.*, DEAN, 1991). Several types of currents, however, have been recognized (WRIGHT, 1995). There is also growing evidence that cross-shore flow is often channelized or spatially confined (REIMNITZ *et al.*, 1976; CACCHIONE and DRAKE, 1990; GAYES, 1991; THIELER *et al.*, 1995; ALLEN and NEWBERGER, 1997).

(6) Is frictional dissipation of wave energy across the shoreface considered?

Frictional dissipation of wave energy on the seafloor is not a factor in any of the models. Yet, it is well-established that bottom friction plays an important role on the wave characteristics reaching the surf zone. WRIGHT *et al.* (1987a) compared frictional and non-friction dissipative wave models on data from the Sandbridge, Virginia, inner shelf and found that frictional dissipation has a considerable impact on the wave energy reaching the surf zone, and thus on beach behavior.

(7) Does the model use monochromatic, unidirectional waves?

In actual application (HODGENS, 1993; TRUITT *et al.*, 1993), the models typically assume monochromatic, unidirectional waves. The interaction of simultaneous, multidirectional wave spectra, typical of storms, is not considered. These assumed wave properties reflect poorly the dynamics in a surf zone, especially during storms.

(9) Are the effects of offshore bars on surf zone waves and currents considered?

With the exception of SBEACH, the models do not consider the impact of offshore bars on the distribution of wave and current energy in the surf zone. Yet, it has been demonstrated that bars are very important in this regard. See the discussion above under geologic considerations.

(10) Are wave shape/breaker type considered?

It is well documented that surging, spilling and plunging breakers have different sediment-transporting capabilities. For example, plunging breakers are the most effective in suspending sand (MILLER, 1976). The models, however, all implicitly assume spilling breakers (typically via the assumptions made in utilizing a form of the equilibrium profile equation). Many factors determine breaker conditions, including the shape of the beach (WRIGHT and SHORT, 1983), wave steepness, and even local winds (PATTIARATCHI *et al.*, 1997). To describe wave characteristics only by some measure of wave height and period results in the omission of important sediment transport information.

(11) Is wave reflection considered?

Landward boundary conditions such as seawalls, bulkheads (KRAUS, 1988) and beach slope (WRIGHT and SHORT, 1983) may be responsible for significant wave reflection. This is a process that likely impacts the strength of longshore currents and the nature of wave energy dissipation in the surf zone (KRAUS and MCDOUGAL, 1996). Under certain conditions, this can be an important model omission (see also the discussion by MCDOUGAL *et al.*, 1996 regarding limitations of seawall impact modeling with SBEACH and similar models).

(12) Is linear wave theory used in wave transformations?

Linear theory is used for the wave transformation algorithms in the models. Linear theory also provides the underpinnings of the equilibrium profile model. In the real world, however, non-linear theory better expresses waveforms in the shoaling region, and the higher moments of these waveforms (*e.g.*, skewness) may be responsible for much of the sediment transport (GUZA and THORNTON, 1985b). GUZA and THORNTON (1980) long ago noted that "considering the widespread applications of these assumptions [of linear wave theory], there have been surprisingly few experiments to test them" (p. 1524). For the applied engineering models reviewed here, this statement remains true today.

(13) Are infragravity waves considered? Are the effects of forced long waves and/or groupy waves considered?

None of the models considers infragravity wave energy, or forced or bound long waves. A number of theoretical and field studies (HOLMAN, 1981; HOWD *et al.*, 1991; OLTMAN-SHAY *et al.*, 1989; HOLMAN and SALLENGER, 1993) suggest, however, that infragravity energy is a primary force in nearshore sediment transport and bar formation. Where infragravity waves are important, a significant component of sediment transport is missing in the models.

(14–21) Are turbidity currents considered? Are rip currents considered? Are storm surge ebb currents considered? Are gravity-driven currents considered? Are wind-driven up/downwelling currents considered? Are wind-driven longshore currents considered? Are wave setup/down-induced currents considered?

None of the models includes currents in any way. Yet, the scientific literature includes extensive references to a large variety of currents related to different forcing mechanisms (see the discussion above, and the review in WRIGHT, 1995). It is likely that this is a major weakness in the applied models used to describe beach behavior. Less is known about the generation of turbidity currents in the nearshore zone (MYROW and SOUTHARD, 1996); SEYMOUR (1990) suggested they may be important in the offshore transport of sand on the shoreface.

(22) Are the effects of wave-current interactions on cross-shore transport considered?

The importance of wave-current interaction lies in the fact that significant sediment transport can occur with weak mean flows if the sediment is suspended by wave activity (GRANT and MADSEN, 1986; GLENN and GRANT, 1987). Wave-current interactions on the shoreface are poorly understood at this time, but it is likely that this process is a major mover of sediment, rather than the simple diffusion process assumed by the models.

(24–25) Are tidal currents or the tidal range considered?

None of the models include tidal currents. The importance of tidal currents on beaches and shorefaces is highly variable, depending on inner shelf geometry, tidal amplitude and inlet frequency. Even low-velocity tidal currents can be important, provided that sand is being suspended by waves. Tidal currents can also enhance or retard other currents. Tidal range dictates the cross-shore limits of the beach profile exposed to waves, and determines the time span that a given location on the profile is exposed to waves. Tidal range also impacts on the frequency and extent of overwash, the position of the ground water table, the importance of eolian processes, and the magnitude of storm-induced changes (MASSELINK and SHORT, 1993). THORNTON and KIM (1993) found that longshore currents inside the surf zone can be forced at tidal frequencies, and that the tide is the dominant mechanism associated with longshore current variability at Duck, North Carolina.

DISCUSSION

The point of Table 2 is not to simply list a large number of variables that make the models look bad. Rather, the broad range of assumptions in the table reflects the fact that the assumptions made in the models are too simplified to deal with the complex, interacting processes that occur over the range of time and space scales important in their societally important predictions. The fact that some assumptions in a model are not satisfied is not necessarily a fatal blow to the predictive results. Some assumptions, variables and principles may have inconsequential bearing on the ultimate model output for a particular beach. Additionally, some considerations, such as beach state or storm surge ebb currents, may be critical on certain beaches and of no consequence whatsoever on others. In the case of the seven models examined here, however, each omits a number of critical, known processes, has unknown or poorly parameterized boundary conditions, and/or other problems that render them poorly suited to quantitative engineering prediction.

The major problems with the models reviewed here are shortcomings in their theoretical basis, the weak empirical foundation upon which they are built, and the demands placed by society for a level of certainty and exactitude in prediction that are unattainable. On the basis of the literature review that forms the foundation of this paper, we have identified five emergent themes that summarize why the applied coastal engineering models are at best only crude, qualitative approximations of beach behavior:

(1) poor assumptions are used in model formulation;
(2) relationships of questionable validity are used to express relationships between forcing and response;
(3) model calibration and verification are used incorrectly as an assertion of model veracity;
(4) hindsighting and objective evaluation of engineering projects that would enable model assessment are lacking; and
(5) model uncertainties exist that inhibit the ability to predict coastal evolution quantitatively at engineering time and space scales.

These problems are interrelated. For example, the use of poor assumptions (1 above) often stems from the fact that the process being modeled is not well understood, and is overly simplified. This leads to the use of questionable process-response relationships (2 above) that may not truly reflect the process being modeled. The later assurance of model veracity is often achieved through the incorrect application of the "calibration and verification" process (3 above). The lack of hindsighting model predictions (*i.e.*, 4 above—project monitoring) makes objective evaluation of model success or failure impossible, and virtually prevents model improvements based on real-world results. Finally, we may well be attempting to predict coastal evolution for engineering purposes at specific time and space scales that defy specific prediction. That is, we are asking the wrong (or inappropriate) questions of the models. These problems and relationships are discussed below.

Poor Assumptions

Most of the simplifying assumptions used in the "modern" (KOMAR, 1998a; 1998b) generation of applied coastal models are derived from principles that have been taken out of context, or if scrutinized individually, would be seen to have not passed the test of time (CARTER and WOODROFFE, 1994). The problem is that these faulty assumptions and principles are typically not examined with the same fervor used when critically reviewing new scientific concepts and ideas. As a result, the field of applied coastal modeling is out of date. An example of this is the R_A and R_J factors (KRUMBEIN and JAMES, 1965; JAMES, 1975) used in beach design and described in the Shore Protection Manual (USACE, 1984). These design parameters assume that the native beach sand size is the stable grain size on a beach in a given wave climate. Thus, nourishment sand will winnow preferentially to approach the native sand size distribution. The composition of native sediments, however, is determined by both wave climate and *availability.* The incorrect assumption that native sand size is important in determining nourishment longevity and beach fill volumes has probably introduced unnecessary costs into many beach nourishment projects.

The poor assumptions on which today's numerical models and engineering equations for beach nourishment are based is also well-illustrated by the evolution of the concept of "closure depth." Closure depth, or a seaward limit of significant sand transport, is an important assumption made in the design of beach nourishment projects and in sediment budget calculations. As described above, the concept was first suggested by BRUUN (1954, 1962). An interesting idea in its time, the concept of closure depth subsequently took on a life of its own, embedded in the application of the Bruun Rule and equilibrium beach profiles.

The Bruun Rule (BRUUN, 1954; 1962) provides the basis for most mathematical models used to predict the rate of shoreline retreat due to sea-level rise (*e.g.*, DEAN and MAURMEYER, 1983; DUBOIS, 1990; 1992; PILKEY and DAVIS, 1987), and is also the basis for the concepts of shoreface profile of equilibrium and closure depth (DEAN, 1977; 1991). This simple relationship was one of the first models of shoreface transgression, preceding even the classic geologic conceptualizations of CURRAY (1969) and SWIFT (1976).

The Bruun Rule, as originally conceived by Bruun, provided a strong conceptual basis for further thought about the nature of shoreface evolution. Subsequent work, however, sought to verify its basic principles (SCHWARTZ, 1965; 1967). Initial experiments by SCHWARTZ (1965) to examine the principles of the Bruun Rule were conducted in a "wave basin" that measured 81.25 cm wide, 115 cm long, and 5–10 cm deep. In this very small wave tank Schwartz ran several tests using waves created by an aquarium aerator that were 8 mm high, 15 cm long, and had a period of 0.33 sec. The "beach" material was Ottowa sand, of which 73 percent was in the 0.13–0.25 mm size range. In effect, Schwartz constructed a scale-model continental margin with prototype sediment. After a series of 10 trials in which the water level in the wave tank was raised 10 mm (a height equal to ~40 grain diameters in his experiment), Schwartz concluded that Bruun's proposition was correct because the profile appeared to reach an equilibrium after sediment eroded from the upper part of this tiny profile had moved "offshore" in the wave basin. Later, SCHWARTZ (1967) measured several beach profiles on Cape Cod over a single neap-spring tidal cycle, found that the profile appeared to move landward and upward over the period from neap to spring tide, and declared that "... the concept henceforth be known as 'Bruun's Rule.'" (SCHWARTZ, 1967, p. 90).

This example is not to say that Schwartz' experiments were poor science, but that scientists and engineers have never looked back and analyzed critically the original material underlying the concept. Anyone performing these experiments today would be roundly criticized for the crude experimental design, scaling inconsistencies, conceptual flaws, and drawing large-scale conclusions from a very limited dataset. In the decades since Schwartz' experiments, however, both engineers and geologists have embraced the Bruun Rule; the concept remains the basis for a number of quantitative models of coastal evolution (*e.g.*, DEAN, 1977; 1991; DUBOIS, 1976; 1990), and is used to predict coastal evolution in a variety of settings (*e.g.*, DUBOIS, 1975; 1976; 1992; ROSEN, 1978; BRAY and HOOKE, 1997).

There is no basis for using the Bruun Rule, as it is currently being used (*e.g.*, HOUSTON, 1996), to predict shoreline retreat rates or the behavior of nourished beaches. CARTER and WOODROFFE (1994) argue that the Bruun Rule, although initially interesting, has proved to be an inadequate oversimplification of nearshore evolution. Based on analysis of an extensive historical shoreface profile dataset for the Louisiana coast, a similar suggestion was made by LIST *et al.* (1997). Another problem with Bruun Rule application is illustrated by PILKEY and DAVIS (1987), who applied it at 1 km intervals along the entire North Carolina coastline. The Bruun Rule predicted 40–50 m yr^{-2} shoreline retreat for a 30 cm yr^{-2} sea-level rise. Since the average slope of the North Carolina coastal plain is 1:2000, and the Bruun Rule considers only the much steeper shoreface slope (see (1) above), not the coastal plain slope over which shoreline migration will occur, the Bruun Rule-predicted retreat simply does not make long-term sense.

Bruun (1962) estimated that the zone of active sand movement on the east coast of Florida extended to about 18 m water depth. This is probably the deepest water depth a coastal engineering model of the beach and shoreface zone has ever considered as a "closure depth." Later, closure depth was interpreted to correspond to the cross-shore point where repeated beach profiles intersect (BIRKEMEIER, 1985). In effect, the modern definition of closure depth as the seaward limit of significant sediment movement equates profile geometry with sediment transport process. Thus, the logic behind the closure depth concept is rooted in part in wave energy arguments (*e.g.*, BRUUN, 1962; DEAN, 1977), and also in profile geometry. It is widely assumed that since repeated cross-shore profiles (*e.g.*, the profile dataset presented by HOWD and BIRKEMEIER, 1987) often converge or "close" on the lower shoreface, no significant sedimentation occurs seaward of the geometric closure point. As noted earlier, however, on the low-gradient inner and mid-shelf, large volumes

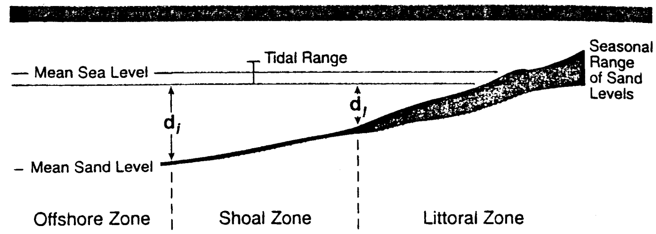

Figure 3. Limiting depths of sediment motion proposed by HALLERMEIER (1981a). He suggested that over centennial time scales the deeper limit (d_i) be used as the limit of significant sediment movement, and that sediment budgets and other predictions concerned with decadal time spans use the shallower depth limit, d_l. This recommendation was stated as specific beach nourishment design guidance by HALLERMEIER (1981a) and more recently by HOUSTON (1996). (After HALLERMEIER, 1981a.)

of sediment can be represented by a nearly imperceptible depth change.

Similar assumptions regarding the "geometry equals process" basis for a nearshore limit to sediment movement can be found in numerous recent technical papers and design documents (*e.g.*, HANSEN and SCHEFFNER, 1990; SMITH *et al.*, 1993; USACE, 1994; EBERSOLE *et al.*, 1996), and are found in the present generation of applied coastal engineering models such as GENESIS. In actual use, the assumed closure depth has decreased to between 4 and 8 m on East Coast shorefaces (*e.g.*, HODGENS, 1993).

HALLERMEIER (1981a; 1981b) used linear wave theory, annual wave climate statistics, and sediment grain size data to derive relationships for two "closure depths" (d_i and d_l) on the shoreface or "shoal zone" (Figure 3). He suggested that over the time scale of sea-level rise (*i.e.*, centuries to millennia) the deeper limit (d_i) be used as the limit of significant sediment movement. For Florida's east coast, d_i is about half the 18 m depth postulated by Bruun (see Hallermeier, 1981b, Table 2). Hallermeier further suggested that since depth changes are difficult to resolve between d_i and d_l, that sediment budgets and other predictions concerned with time spans of "a few decades" (HALLERMEIER, 1981b, p. 270) use the shallower depth limit, d_l. This recommendation was stated as specific beach nourishment design guidance by HALLERMEIER (1981a) and more recently by HOUSTON (1996).

A subsequent study by BIRKEMEIER (1985) reviewed the utility of Hallermeier's proposed depth limits for 10 erosion events over 17 months at Duck, North Carolina. In this paper, Birkmeier also substituted the terms "close-out depth" and "closure" for Hallermeier's term "seaward limit of significant sand transport," using the terms to include both profile geometry and the inferred process of sediment transport. Birkemeier's best-fit regression for the 10 data points yielded a closure depth somewhat shallower (an average of 0.4 m) than predicted by Hallermeier's d_l.

HOUSTON (1995; 1996) took the terminology and definition of closure depth one step further by reducing the relationship of BIRKEMEIER (1985)

$$d_l = 1.75H_e - 57.9\left(\frac{H_e^2}{gT_e^2}\right) \tag{7}$$

to

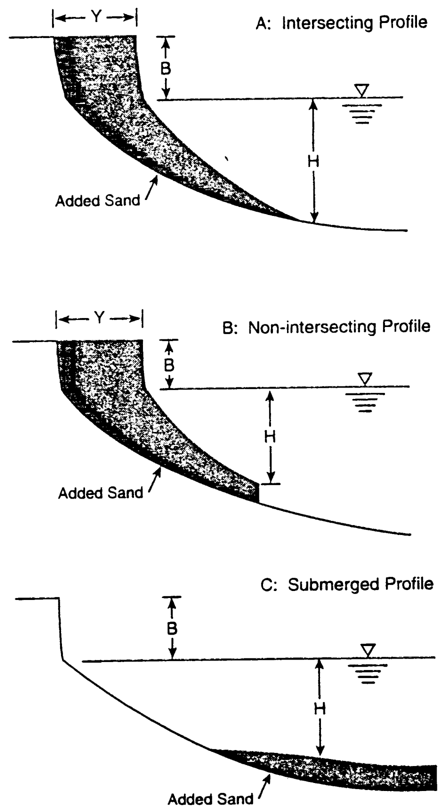

Figure 4. Three types of nourished beach profiles presented by HOUSTON (1996). (After HOUSTON, 1996.)

$$h_c = 1.5H_e = 6.75H_s \quad (8)$$

where h_c = closure depth in meters and H_s is the mean annual significant wave height. This relationship is presented by HOUSTON (1996) as the most current guidance for the design of beach nourishment projects.

Houston further suggests that for beach nourishment, the closure depth and other geometric profile properties can be used to implement a "'reverse' Bruun Rule" (HOUSTON, 1996, p. 30) whereby the shoreline is advanced seaward by beach nourishment. Figure 4 (from HOUSTON, 1996, which is adapted from DEAN, 1991) illustrates the unrealistic profile geometries, in particular Figure 4b, resulting from the application of closure-depth related concepts.

Relationships of Questionable Validity

The use of relationships of questionable validity to express relationships between forcing and response is commonplace in the coastal models reviewed here. The determination of k in the CERC longshore transport equation is one such example. KOMAR and INMAN (1970) summarized 14 four-hour experiments by KOMAR (1969) that measured swash zone sediment transport on El Moreno Beach in the Gulf of California and Silver Strand Beach on the Pacific Ocean. On the basis of these experiments, they suggest k = 0.77, which is the recommended value in the Shore Protection Manual (USACE, 1984) and the default value in the GENESIS model (GRAVENS et al., 1991). BODGE and KRAUS (1991), however, observed that there are a wide range of k values. They note field studies that place the value of k anywhere between 0.014 and 1.6. Recently, WANG et al. (1998) suggested that k should be 0.08 on low-energy coastlines. This value, however, is based entirely on short-term, 3–5 minute sediment trap surveys covering only a portion of the active surf zone during fair weather. The choice of k is problematic at best. WRIGHT et al. (1987) noted that there are many possible values of k, even for a single, specific field site. Many of the longshore transport volumes used routinely in the U.S. are based on k = 0.77, which is clearly not a universally applicable number (e.g., CIAVOLA et al., 1997). It may be legitimately argued that longshore transport rates are truly indeterminate for any given location.

To further illustrate the nature of the questionable relationships problem, we present an example that involves the development of the empirical relationship for distinguishing between beach erosion and accretion used in the SBEACH (LARSON and KRAUS, 1989) cross-shore transport model. In the development of SBEACH, LARSON and KRAUS (1989) used beach profile change data from wave tank experiments to derive a predictor of beach erosion and accretion. They found that a combination of wave steepness (H_o/L_o) and settling velocity and wave period (wT) plotted data in regions of a log-log plot that were separable by a straight line. Based on visual inspection of the plotted data, they drew a line and found a simple power-law expression

$$H_o/L_o = 0.00070(H_o/wT)^3 \quad (9)$$

for which the coefficient and exponent were determined by visual fitting (LARSON and KRAUS, 1989; KRAUS et al., 1991). This expression is used as an inequality in order to express profile behavior (erosion or accretion) and governs the application of sediment transport rules in SBEACH.

There are a number of problems inherent in the selection of this line as an erosion/accretion criterion. First, the subjective classification of erosion and accretion events in the dataset is neither reproducible nor necessarily correct. Second is the assumption that the variables used to define the criterion (H_o/L_o and wT) have a useful correspondence to the dynamics driving the observed changes in the wave tank, much less that these parameters apply to field conditions. These parameters certainly make intuitive sense, but their utility as guiding criteria has not been demonstrated. Third, and perhaps of greatest practical importance, is the method used to select the line itself (and its corresponding equation). Because the line was selected by eye, and its equation by trial-and error, it is not reproducible. While we certainly advocate the use of informed judgment in the decision-making process, LARSON and KRAUS (1989) fail to provide any substantiation of their choice of this line. To the extent that SBEACH is used to make specific beach design decisions, significant sediment volume (and therefore monetary) predictions depend on its correctness. Thus, we question the validity of this line, and ask: "How can we be sure it is the best possible line to choose?"

To provide insight into the answer to this question, we em-

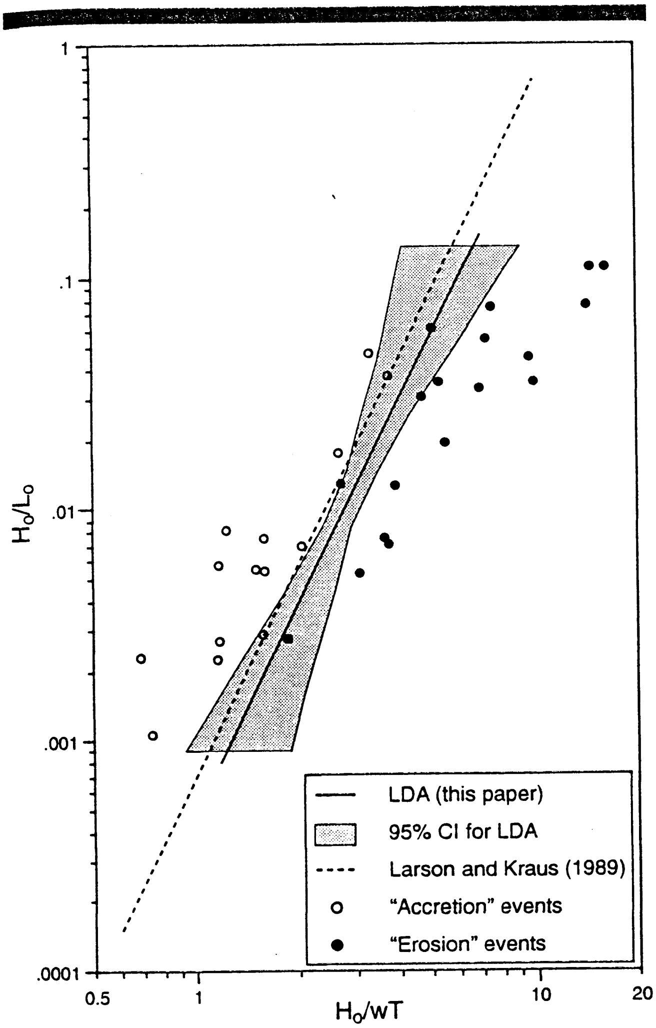

Figure 5. Plot of the beach erosion and accretion data used by LARSON and KRAUS (1989) in the development of cross-shore sediment transport rules used in SBEACH, showing the SBEACH-defined predictor line utilized by LARSON and KRAUS (1989), the line obtained by employing a Fischer linear discrimant analysis (LDA) to distinguish between erosion and accretion events (as opposed to the purely subjective method used by LARSON and KRAUS (1989)), and the 95 percent confidence interval for the LDA line. Note that: 1) there is a broad range of possible lines through the data that separate it equally well, including lines of both positive and negative slope; 2) the region encompassed by this family of lines embraces several orders of magnitude; and 3) portions of the line chosen by LARSON and KRAUS (1989) fall outside the 95 percent confidence limits of the dataset as defined by the LDA.

ployed a Fischer linear discriminant analysis (LDA; FISCHER, 1936) to determine the best-fit line that separates the data of KRAUS *et al.* (1991), and used bootstrap resampling to calculate a 95 percent confidence interval for the LDA line. Figure 5 shows the SBEACH-defined line, the LDA line, and the 95 percent confidence interval for the LDA line. Three conclusions are readily apparent: 1) there is a broad range of possible lines through the data that separate it equally well, including lines of both positive and negative slope; 2) the region encompassed by this family of lines embraces several orders of magnitude; and 3) portions of the line chosen by LARSON and KRAUS (1989) fall outside the 95 percent confidence limits of the dataset as defined by the LDA. The choice of a line is certainly problematic. Our results lead us to ask if there really is a relationship here that has sufficient predictive skill (or a sufficiently strong physical basis) to be used in multi-million dollar beach design decisions.

Misapplication of Calibration and Verification/ Validation

The use of deterministic numerical models in applied coastal studies typically involves a two-step process. First, the model, such as GENESIS or SBEACH, is "calibrated" by adjusting the various empirical constants in the model equations using a particular dataset such that the calibrated model reproduces the observed changes at the field site (*e.g.*, from an initial or pre-storm to a final or post-storm beach profile). Second, the model is run on another dataset from the same field site using the empirical constants determined during the calibration, and is considered "validated" or "verified" if it reproduces acceptably the measured data without further adjustment of the calibration parameters. This two-step approach been used extensively not only in field applications (*e.g.*, HODGENS, 1993; SMITH *et al.*, 1993; TRUITT *et al.*, 1993; EBERSOLE *et al.*, 1996), but also in the development and testing of the models themselves (*e.g.*, HANSON and KRAUS, 1989; LARSON and KRAUS 1989; WISE *et al.*, 1996). A similar approach is also used frequently in hydrology (MACANALLY, 1989; KONIKOW and BREDEHOEFT, 1992; YOUNG *et al.*, 1995).

In a review of modeling in the earth sciences, ORESKES *et al.* (1994) argue that "verification and validation of numerical models of natural systems is impossible" (p. 641). Their argument is based primarily on philosophical considerations concerning logic. The authors also provide numerous examples (from hydrology and geochemistry) of how the terms "verification" and "validation" have been misused in the course of public policy formulation (*e.g.*, siting of nuclear waste at Yucca Mountain, Nevada) using information furnished by numerical models. We examine below the usage of the terms "calibration," "validation" and "verification" as described by ORESKES *et al.* (1994) in the context of coastal engineering models.

Verification and validation are affirmative terms; in the strict sense, verification is an assertion of truth (ORESKES *et al.*, 1994). Thus, a verified model is useful for its intended predictive role because its "truth" has been demonstrated (ORESKES *et al.*, 1994). The same is true of "validation," a term that typically connotes legitimacy. In coastal engineering modeling, these terms are used in two incorrect ways: 1) in stating that the model reproduces observed data; and 2) that the model accurately represents physical reality. RECKHOW and CHAPRA (1983) and KONIKOW and BREDEHOEFT (1992) suggest a similar misuse of terminology in hydrology.

Because natural systems such as a beach or barrier island are not closed (unlike a statement of formal logic or mathematics), verification in the strict sense is impossible. The possibility of model verification is further precluded by the use of input parameters that are incompletely known, the scaling up of non-additive properties, assumptions about system behavior and/or what the input data represent, and the non-uniqueness of model results (ORESKES *et al.*, 1994). These attributes mean that models are open systems, and thus not susceptible to verification in the sense of truth, or validation in the sense of providing an accurate representation of physical reality. In the context of the coastal models reviewed here, for example, incomplete input parameters can range from the use of a single grain size (*e.g.*, d_{50}), to the selection of a constant for longshore energy flux (*e.g.*, k). These parameters are always based on limited data. The same is true of scaling up of system properties. Specification of the shear stress that results in sediment movement for a single grain is not directly applicable to the meter-scale evolution of a beach profile over a decade or even a day (HAFF, 1996).

Perhaps the most important attributes that make a model an open system, however, are the assumptions inherent in defining system behavior; that is, what the input data represent. For example, one of the many assumptions in the formulation of the SBEACH model (LARSON and KRAUS, 1989) is that profile change and bar formation are driven by breaking waves. In developing the mathematics behind the model, it is further assumed (both implicitly and explicitly) that the laboratory and field data showing beach profile change reflect this. Thus, the relationships between incident wave characteristics and beach erosion/accretion can be defined by specific empirical criteria and these criteria can be employed in the model.

As a result of these factors, model results are non-unique in that more than one set of model parameters can produce the same result. This has been observed in coastal modeling with GENESIS by KRAUS *et al.* (1988). Running the model with two radically different closure depths (1.35 m and 6.0 m) yielded three different sets of model calibration values, but all three produced similar shoreline configurations. Thus, there is no way to choose between these different conceptualizations, "other than to invoke extraevidential considerations like symmetry, simplicity, and elegance, or personal, political, or metaphysical preferences" (ORESKES *et al.*, 1994, p. 642).

As shown above, there are several problems with the two-step calibration-verification approach, both logical and practical. Perhaps the most significant problem, however, occurs in the so-called verification phase, when the model is declared a success. The problem is one of committing the logical error of affirming the consequent. ORESKES *et al.* (1994) call this a "fallacy" and describe it as follows (p. 643):

> To claim that a proposition (or model) is verified because empirical data match a predicted outcome is to commit the fallacy of affirming the consequent. If a model fails to reproduce observed data, then we know that the model is faulty in some way, but the reverse is never the case.

In other words, just because the model produces the expected answer does not mean it is correct.

Lack of Hindsighting and Objective Evaluation

Hardly a paper is written about beach nourishment that does not mention the need for monitoring, and criticize the fact that it hasn't been carried out in the past. A report by the NATIONAL RESEARCH COUNCIL (1995) is among the latest to do this. Without project monitoring, hindsighting and objective project evaluation, there can be no evaluation of the predictive success of models.

Typical problems with monitoring and evaluating project success have been illustrated by the experience of Folly Beach, South Carolina (HOUSTON, 1996; PILKEY *et al.*, 1996). When it is carried out, monitoring of most beach nourishment projects tends to be a scheduled process; profiles are taken at predetermined intervals. But in order to answer critical questions such as the impact of storms and the extent of post-storm nourished beach recovery, monitoring in the future must be much more flexible. Immediate pre- and post-storm profiles are essential.

Another problem that makes evaluation of model success difficult is the lack of objectivity of nourished beach success by the responsible state or Federal agencies. For example, the U.S. Army Corps of Engineers' (USACE) self-examination of nourished beach success (USACE, 1994) concluded that their cost performance has been excellent. A problem with this analysis, pointed out by PILKEY (1995), is that the USACE compared predicted and actual sand volumes and costs without considering whether the beach was still in place.

Model Uncertainties

HAFF (1996) reviewed critically the sources of uncertainty or error in predictive models of earth surface processes. These include:

(1) model imperfections;
(2) omission of important processes;
(3) lack of knowledge of initial conditions;
(4) sensitivity to initial conditions;
(5) unresolved heterogeneity;
(6) occurrence of external forcing; and
(7) inapplicability of the factor of safety concept.

Table 3 lists beach behavior prediction model uncertainties in five of Haff's categories. Most of the parameters listed in Table 3 are also listed in Table 2, the geologic and oceanographic assumptions behind the models. This is simply a means of recategorizing the assumptions in Table 2 into categories of model uncertainties.

Model imperfections refers to errors in the characterization or description of processes inherent in the model itself. The important factor k in the longshore transport equation was determined on two California beaches in a few hours of observations (KOMAR and INMAN, 1970) and is now assumed to be applicable universally to all beaches. It is a most likely candidate for a model imperfection.

Omission of important processes is a serious problem with coastal models. Perhaps foremost among these is the omission of currents and wave-current interactions on the shoreface. Haff notes that the larger the spatial scale of the system under study and the longer the time frame, the more likely that important processes will be omitted. HOLMAN (1995) concluded that this is a particularly significant problem in predictive coastal modeling. It is important to re-emphasize

Table 3. *Categorization of model uncertainties from Table 2 into five sources of model uncertainty identified by HAFF (1996).*

Model Imperfections	Unknown Initial Conditions and Sensitivity to Initial Conditions	External Forcing	Omission of Significant Processes
Assumption of an equilibrium shoreface profile	No (or poor) wave data	Multiple, randomly occurring storm events	Sediment transport beyond closure depth
Scaling up short-term relationships to long term (minutes to decades)	No (or poor) historical shoreline data	Areal and temporal variations in sediment supply	Offshore, onshore, or longshore loss or gain of sediment
Assumption of universal applicability of parameters	Degree of instability of nourished beaches	Storm surge	Variation in the cross-shore distribution of sediment transported alongshore
Use of linear theory in wave characterization	Permeability of engineering structures		Water table effects on sediment erodibility
Use of poorly known parameters as adjustable constants	Geology underlying the surface		Bed liquefaction or elevated pore water pressure in surf zone sediments
Use of wave tank data for modeling the prototype	Areal and temporal grain size variability		Wave refraction/diffraction effects
	Offshore bars and bedform configuration		Frictional dissipation of wave energy across the shoreface
	Beach state		Random waves and wave–wave interactions
	Shoreface bathymetry		Wave shape/breaker type
	Shoreline stabilization structures		Infragravity waves
			Turbidity currents
			Rip currents
			Storm surge ebb currents
			Gravity-driven currents
			Wind-driven up/downwelling currents
			Wind-driven longshore currents
			Wave setup/down-induced currents
			Forced long waves and/or groupy incident waves
			Wave–current interactions
			Tidal currents

here that, as in the case of Table 2, the assumptions in Table 3 will vary greatly in importance from beach to beach, and from time to time on a single beach. Many process or beach attribute assumptions will be of no consequence on some beaches and of great importance on others.

Unknown initial conditions refers to lack of knowledge about components of the coastal environment that must be well known before the model run begins. Unknowns could include beach state and offshore bar configuration (WRIGHT and SHORT, 1983). Nourished beaches, which are likely to be unstable relative to natural beaches (LEONARD *et al.*, 1990), are another example.

Sensitivity to initial conditions. According to HAFF (1996, p. 346) "in non-linear systems like those that characterize sediment transport there can exist a sensitivity to initial conditions that effectively prohibits detailed prediction of system evolution. A strong dependence on initial conditions is a highlight of chaotic behavior (LORENZ, 1963)." Beach state is certainly an initial condition on which some beaches are strongly dependent. Perhaps an even better example may be the formation of or the presence of shell and gravel lags, formed in the initial stages of a storm or present when a storm strikes a sandy shoreline. The lags will delay the response of the shoreface to storm conditions resulting in an overall storm response considerably different than would have occurred if the affected sediment body was uniform, well-sorted sand. Bio-stabilization and de-stabilization by organic mats and animal tubes may have the same effect (*e.g.*, EKMAN *et al.*, 1981).

External forcing according to HAFF (1996, p. 351) "arises in an open system where mass, energy and momentum can enter and be discharged through the system boundaries." Haff also notes that external forcing becomes an increasingly important issue in prediction as the size of the natural system increases. The random occurrence of storms is perhaps the most important form of external forcing in coastal modeling.

Inability to Predict Coastal Evolution at Engineering Time and Space Scales

It is critical to understand that even if a particular model did take into account the various parameters listed in Table 2, this alone does not necessarily make the model useful. Even the most "complete" model will suffer from a variety of limitations. Given the uncertainties involved, specific "when, where, and how much" model predictions of the kind society demands today may be an impossibility. This situation places predictive engineering modelers in a most unenviable position that is quite different from that of the scientist. For example, BAKER (1994, p. 147) states

> Science uses prediction as a tool to test explanations built upon its temporary state of understanding. Engineering assumes that temporary state of understanding in proceeding directly to a useful prediction. The engi-

neer must always be concerned that the basis in understanding is inadequate, while the scientist must always strive to elucidate the inadequacy of that understanding.

As opposed to predictive mathematical modeling based on some combination of idealized laboratory data applied to field conditions, an approach based on the examination of system history could be employed. For example, the past behavior of the coastal area in question can be studied to yield clues about process-response relationships. Such an approach is advocated by BAKER (1994) for the evaluation of riverine flood hazards. He suggests that field study of paleofloods yields two important results: 1) information regarding the past behavior of an actual system (*e.g.,* floods on a specific river) that can be used to ground theoretical and analytical models, and 2) tangible physical evidence of paleofloods, which impact directly on the perceptions of society. Regarding the former, BAKER (1994, p. 139) asserts that "... flood 'science' is increasingly becoming the mathematical manipulation of idealized parameters that are assumed to have flood-like properties." Thus, geomorphological studies of paleofloods allow models to be tested and modified using the geological indices (sedimentary deposits, erosion scars, *etc.*) of past floods. He further argues that since perceptions of risk guide societal action, physical evidence of paleofloods can be used to guide action or public policy. Baker states (p. 152–153):

> Showing where floods once coursed across the landscape shows the long-term extent of the river. Those who construct valuable entities within the paleoflood limits are not doing so in some idealized regulatory zone defined by scientific experts. They are constructing in the river as nature has defined it.

Certainly this approach is and can be used in the management of beaches. On barrier islands, for example, the delineation of pre-historic and historical inlet locations (*e.g.,* HERON *et al.,* 1984), overwash zones (CLEARY and HOSIER, 1979), erosion-prone areas (DEKIMPE *et al.,* 1991), *etc.* can form the basis for coastal development guidelines, hazard disclosure laws, and for building permits for specific structures.

ALTERNATIVES TO MODELS

In our previous reviews (PILKEY *et al.,* 1993; YOUNG *et al.,* 1995) we have often been faced with the criticism, "If the models do not work, what do we do now? What new approach do you have to offer?" (*e.g.,* DUBOIS, 1993; HOUSTON, 1996; BODGE, 1997). One response is that our criticisms constitute a purely scholarly endeavor; it is not incumbent upon us to offer any solutions at all. It is clear, however, that the models are being asked questions that exceed their ability to answer. It is equally clear that there will be no universal model for coastal evolution. A local to regional approach is needed.

If we are not to use numerical models for predicting beach behavior or designing nourishment projects, then what are the alternatives? We believe that an empirical approach based on local or regional experience is perhaps the most viable alternative. An excellent framework for such an approach is provided by the Universal Soil Loss Equation (USLE) (WISCHMEIER and SMITH, 1978). The USLE is an empirically-based equation used to estimate soil erosion losses due to climate, soil characteristics, topography, crop and tillage practices. The USLE for estimating average annual soil erosion is

$$A = RKLSCP \tag{10}$$

where A is the average annual soil loss in tons ac^{-1} yr^{-1}, R is a rainfall erosivity index, K is a soil erodibility factor, L is a slope length factor, S is a slope steepness factor, C is a crop or cover factor, and P is a tillage type or conservation practice factor. Both the USLE and its successor, the Revised USLE, are fundamentally statistical in nature. The various factors in the equation are based on over 10,000 plot-years of natural rainfall/runoff data collected under carefully monitored field conditions. To use it, one simply needs to know the soil type, topography, planned crop, and tillage practice to be used. The model usually yields a useful estimate that provides a basis for comparing erosion losses due to different farming scenarios.

While an approach similar to the USLE would certainly be viable for predicting such things as nourished beach life span, there is a major obstacle to this approach. Namely, the USLE is based on vast amounts of carefully recorded and reported observations. As several previous studies (*e.g.,* PILKEY and CLAYTON, 1987; PILKEY and CLAYTON, 1989; LEONARD *et al.,* 1990) and reports (*e.g.,* NATIONAL RESEARCH COUNCIL, 1990; 1995) have pointed out, monitoring and record-keeping of beach nourishment has been uniformly poor (at least the U.S. experience). We agree with the NRC report (NATIONAL RESEARCH COUNCIL, 1995) that beach monitoring must be improved, and that objective measures of beach "success" must be developed.

PILKEY *et al.* (1994) suggested three alternatives to equilibrium profile-based models for the design of beach nourishment projects:

(1) determine beachfill requirements by measuring volume loss and profile shape changes on the natural beach over a period of years, and assume similar behavior for future nourishments (VERHAGEN, 1992) ("imitate nature");
(2) place sand on the beach without design predictions and monitor the beach for volume loss and sediment dispersal ("see what happens"); and
(3) design beaches based on past experience on the same, neighboring or regional beaches (PILKEY, 1989) ("past experience").

We believe the third approach, described below, is probably the most broadly applicable.

In their studies of the U.S. nourishment experience, PILKEY and CLAYTON (1989), LEONARD *et al.* (1990), and CLAYTON (1991) observed strong regional differences in subaerial nourished beach durability. This is especially true on the Atlantic coast. Nourished beaches in southern Florida, south of Cape Canaveral, have typical life spans of 7–9 years. North of Cape Canaveral, through North Carolina, beach life spans range from 3–5 years. In New Jersey, life spans of nourished beaches are almost always less than 3 years. Within a given region, however, there may be a wide range in the durability of nourished beaches. For example, south of Cape Canaveral, beach durabilities range from the experience of Miami Beach which has lasted more than 15 years without major renourishment to that of nearby Jupiter Island which typically needs extensive renourishment approximately every 3 years (PILKEY and CLAYTON, 1989).

The regional differences in beach durability on the East Coast appear to be very generally related to average wave energy and frequency of storms, both of which generally increase from south to north along this shoreline reach (DOLAN *et al.*, 1988; 1992). Higher wave energies and more frequent storms lead to shorter nourished beach life spans. Other factors, however, are clearly involved. For example, the 1978 nourished beach on Tybee Island Georgia, a shoreline reach tucked within the low wave energy Georgia Bight, was largely lost within a year (PILKEY and CLAYTON, 1987).

PILKEY (1989) proposed a "thumbnail method" for use in estimating beach durability on the U.S. East Coast. This is a purely empirical approach based on the regional beach durability experience from past nourishment projects. PILKEY (1989) suggested using the following empirical relationship to obtain a rough estimate of the volume of sand required for initial nourishment:

$$V = \left(\frac{X}{n}\right)v_i \qquad (11)$$

where V is the total volume of sand required to maintain a design beach of a given length, n is the assumed interval of required major restoration (for Florida, n = 9 years, for New Jersey, n = 3 years, and for the remaining East Coast barriers, n = 5 years), X is the desired project life or design life, and v_i is the volume of initial fill placed along the beach.

The factor n in (11) is based on Table 2 in PILKEY (1989), which is a summary of beach nourishment performance on U.S. East Coast beaches. With increased experience in nourishment on the same and/or neighboring beaches, the factor should be adjusted accordingly.

Equation (11) integrates the nourishment experience over reaches of hundred of kilometers. Alternatively, one can use strictly local beach durability experience if such is available. Local could be defined as beaches separated by a few tens of kilometers. In general, this may be more accurate than the regional approach, but local factors such as proximity to an inlet or variations in local sediment supply could result in large differences in nourished beach behavior on adjacent shoreline reaches. Previous experience on the same beach should provide the most accurate barometer of all for prediction of beach response and life span; the more nourishments the more useful. The success in using previous experience as a design guide, however, will depend in large part on the quality and extent of physical monitoring of beaches.

CONCLUSIONS

We believe that the applied engineering models currently being used to predict the behavior of beaches in the U.S. are at best poorly founded and at worst invalid. We have listed a number of geologic and oceanographic assumptions that are not satisfied by the models. The importance of these assumptions may vary widely from beach to beach, but in all the models examined, important principles are not addressed.

We have also noted a number of model imperfections, including their presumed universal applicability and the establishment of model parameters based on very restricted and localized observations (*e.g.*, k in the longshore transport equation). Initial conditions such as wave and shoreline behavior data, offshore bars and bedforms and underlying geology are seldom known in sufficient detail. Perhaps the most important "unknown" external forcing factor in these deterministic models is the occurrence of multiple, randomly occurring storms.

The validity of the calibration and verification process employed for models of beach behavior is questionable.

The success of model predictions is difficult to gauge because of a lack of monitoring and even a lack of definition of success for certain projects, including nourished beaches.

Commonly, once a simplified assumption or principle is incorporated into a model it is not reexamined by most model users. But this paper demonstrates the importance of objectively examining, one by one, the assumptions in models before their application to the solution of important societal problems. If an important assumption proves questionable when examined in isolation, incorporating it into a model certainly does not improve its validity.

The listing of assumptions in Tables 2 and 3 should not be construed as an appeal to make the models more complex by including more variables. To include all variables that affect beach behavior (assuming that we knew them) would clearly increase model complexity and uncertainty beyond reason. What we suggest is a re-examination of beach behavior models. This could include a realistic examination of the variables such as we have attempted herein, and a careful and objective survey of modeling results on real-world projects. Most important, however, is a reconsideration of whether we are asking the right questions of models. In other words, is it feasible to model beach behavior within the time and space constraints required by most coastal engineering projects?

We believe that we have demonstrated the need for a thorough re-examination of mathematical models used to predict the behavior of beaches. Until mathematical models can be shown to have meaningful application to applied beach engineering problems, there are alternative approaches to solving societally important shoreline problems. For example, a reasonable first estimate for predicting the behavior of a new nourished beach can be made by examining the life span of nearby nourished beaches.

ACKNOWLEDGMENTS

This paper is, in part, the product of a series of formal and informal geology classes over the past several years at Duke University that involved a number of students and visiting scientists. The diverse graduate and undergraduate members of these classes are thanked for their diligent work in finding relevant papers, stimulating discussions, and providing a fresh perspective on the topics we discussed. Vic Baker, Peter Haff, and Cathy Rigsby are thanked for leading class discussions and suggesting new ways of thinking about the modeling of earth surface processes. William Ascher is thanked for his insight into similar model-related issues in economics. Helpful reviews and discussions were provided by Jeff List, Bill Schwab, and several anonymous reviewers.

LITERATURE CITED

ALLEN, J.S. and NEWBERGER, P.A., 1996. Downwelling circulation on the Oregon continental shelf. Part I: response to forcing. *Journal of Physical Oceanography,* 26, 2011–2035.

AUBREY, D.G.; TWICHELL, D.C., and PFIRMAN, S.L., 1982. Holocene sedimentation in the shallow nearshore zone off Nauset Inlet, Cape Cod, Massachusetts. *Marine Geology,* 47, 243–259.

BAILARD, J.A., 1981. An energetics total load sediment transport model for a plane sloping beach. *Journal of Geophysical Research,* 86, 2035–2043.

BAKER, V.R., 1994. Geomorphological understanding of floods. *Geomorphology,* 10, 139–156.

BIRKEMEIER, W.A., 1985. Field data on seaward limit of profile change. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 111, 598–602.

BODGE, K.R., 1997. Discussion of: Young, R. S.; Pilkey, O. H.; Bush, D. M., and Thieler, E. R., 1995. A discussion of the Generalized Model for Simulating Shoreline Change (GENESIS). *Journal of Coastal Research,* 13, 953.

BODGE, K.R. and KRAUS, N.C., 1991.Critical examination of longshore transport rate magnitude. *Coastal Sediments '91.* New York: ASCE, pp. 139–155.

BRAY, M.J. and HOOKE, J.M., 1997. Prediction of soft-cliff retreat with accelerating sea-level rise. *Journal of Coastal Research,* 13, 453–467.

BRUUN, P., 1954. *Coastal erosion and development of beach profiles.* Washington: U.S. Army Corps of Engineers, Technical Memorandum No. 44, 75p.

BRUUN, P., 1962. Sea-level rise as a cause of shore erosion. Proceedings of the American Society of Civil Engineers, *Journal of the Waterways and Harbors Division,* 88, 117–130.

CACCHIONE, D.A. and DRAKE, D.E., 1982. Measurements of storm-generated bottom stresses on the continental shelf. *Journal of Geophysical Research,* 87, 1952–1960.

CACCHIONE, D.A. and DRAKE, D.E., 1990. Shelf sediment transport: An overview with applications to the northern California continental shelf. *In:* LEMEHAUTE, B. and HANES, D. (Editors), *The Sea.* Volume 9. New York: Wiley-Interscience, pp. 729–773.

CACCHIONE, D.A.; DRAKE, D.E.; GRANT, W.D., and TATE, G.B., 1984. Rippled scour depressions on the inner continental shelf of central California. *Journal of Sedimentary Petrology,* 54, 1280–1291.

CACCHIONE, D.A.; GRANT, W.D.; DRAKE, D.E., and GLENN, S., 1987. Storm-dominated bottom boundary layer dynamics on the northern California continental shelf: Measurements and predictions. *Journal of Geophysical Research,* 92, 1817–1827.

CARTER, R.W.G. and WOODROFFE, C.D., 1994. Coastal evolution: an introduction. *Coastal evolution: Late Quaternary Shoreline Morphodynamics.* Cambridge: Cambridge University Press, pp. 1–31.

CIAVOLA, P.; TABORDA, R.; FEREIRA, O., and DIAS, J.A., 1997. Field measurements of longshore sand transport and control processes on a steep meso-tidal beach in Portugal. *Journal of Coastal Research,* 13, 1119–1129.

CLAYTON, T.D., 1991. Beach replenishment activities on the U.S. Continental Pacific Coast. *Journal of Coastal Research,* 7, 1195–1210.

CLEARY, W.J. and HOSIER, P.E., 1979. Coastal geomorphology, washover history, and inlet zonation: Cape Lookout to Bird Island, North Carolina. *In:* LEATHERMAN, S.P. (Editor), *Barrier Islands: From the Gulf of St. Lawrence to the Gulf of Mexico.* New York: Academic Press, pp. 237–262.

CONLEY, D.C. and INMAN, D.L., 1992. Field observations of the fluid-granular boundary layer under near-breaking waves. *Journal of Geophysical Research,* 97, 9631–9643.

COWELL, P.J.; ROY, P.S., and JONES, R.A., 1995. Simulation of large-scale coastal change using a morphological behaviour model. *Marine Geology,* 126, 45–61.

CURRAY, J.R., 1969. Shore zone sand bodies—barriers, cheniers, and beach ridges. *In:* STANLEY, D.J. (Editor), *The New Concepts of Continental Margin Sedimentation.* Washington: American Geological Institute, pp. JCII-1–JCII-18.

DALRYMPLE, R.W., 1979. Wave-induced liquefaction: a modern example from the Bay of Fundy. *Sedimentology,* 26, 835–844.

DAVIDSON-ARNOTT, R.G.D. and LAW, M.N., 1996. Measurement and prediction of long-term sediment supply to coastal foredunes. *Journal of Coastal Research,* 12, 654–663.

DAVIS, R.A., (Editor), 1985. *Coastal Sedimentary Environments.* New York: Springer-Verlag, 716p.

DAVIS, R.A. and KUHN, B.J., 1985. Origin and development of Anclote Key, west-peninsular Florida. *Marine Geology,* 63, 153–171.

DEAN, R.G., 1977. *Equilibrium beach profiles: U.S. Atlantic and Gulf coasts.* Department of Civil Engineering, University of Delaware, Technical Report No. 12, 45p.

DEAN, R.G., 1983. Principles of beach nourishment. *In:* KOMAR, P.D. (Editor), *CRC Handbook of Coastal Processes and Erosion.* Boca Raton, Florida: CRC Press, Inc., pp. 217–231.

DEAN, R.G., 1987. Coastal sediment processes: Toward engineering solutions. *Coastal Sediments '87.* New York: ASCE, pp. 1–24.

DEAN, R.G., 1991. Equilibrium beach profiles: Characteristics and applications. *Journal of Coastal Research,* 7, 53–84.

DEAN, R.G., 1996. Beach nourishment performance: planform considerations. *Shore and Beach,* 64(3), 36–39.

DEAN, R.G. and PERLIN, M., 1977. Coastal engineering study of Ocean City Inlet, Maryland. *Coastal Sediments '77.* New York: ASCE, pp. 520–544.

DEAN, R.G. and MAURMEYER, E.M., 1983. Models for beach profile responses. KOMAR, P.D. (Editor), *CRC Handbook of Coastal Processes and Erosion.* Boca Raton, Florida: CRC Press, Inc., pp. 151–166.

DEIGAARD, R.; HEDEGAARD, I.; ANDERSON, O., and FREDSOE, J., 1989. Engineering models for coastal sediment transport. *International Symposium for Sediment Transport Modeling,* New York: ASCE, pp. 172–177.

DEKIMPE, N.M.; DOLAN, R., and HAYDEN, B.P., 1991. Predicted dune recession on the Outer Banks of North Carolina, USA. *Journal of Coastal Research,* 7, 451–463.

DELANGE, W. and HEALY, T., 1994. Assessing the stability of inner shelf dredge spoil mounds using spreadsheet applications on personal computers. *Journal of Coastal Research,* 10, 946–958.

DEVRIEND, H.J., 1991a. Mathematical modelling and large-scale coastal behaviour; Part 1, physical processes. *Journal of Hydraulic Research,* 29, 727–740.

DEVRIEND, H.J., 1991b. Mathematical modelling and large-scale coastal behaviour; Part 2, predictive models. *Journal of Hydraulic Research,* 29, 741–753.

DOLAN, R., 1972. Barrier dune system along the Outer Banks of North Carolina: a reappraisal. *Science,* 176, 286–288.

DOLAN, R.; LINS, H., and HAYDEN, B., 1988. Mid-Atlantic coastal storms. *Journal of Coastal Research,* 4, 417–433.

DUBOIS, R.N., 1975. Support and refinement of the Bruun Rule on shore erosion. *Journal of Geology,* 83, 651–657.

DUBOIS, R.N., 1976. Nearshore evidence in support of the Bruun Rule on shore erosion. *Journal of Geology,* 84, 485–491.

DUBOIS, R.N., 1990. Barrier-beach erosion and rising sea level. *Geology,* 18, 1150–1152.

DUBOIS, R.N., 1992. A re-evaluation of Bruun's rules and supporting evidence. *Journal of Coastal Research,* 8, 618–628.

DUBOIS, R.N., 1993. The concept of shoreface profile of equilibrium: A critical review—Discussion. *Journal of Coastal Research,* 9, 1146–1148.

EBERSOLE, B.A.; NEILANS, P.J., and DOWD, M.W., 1996. Beach-Fill Performance at Folly Beach, South Carolina (1 Year After Construction) and Evaluation of Design Methods. *Shore and Beach,* 64, 11–26.

ECONOMIST, 1998. The risk business. *The Economist,* 17 October 1998, p. 21ff.

EKMAN, J. E.; NOWELL, A. R. M., and JUMARS, P. A., 1981. Sediment destabilization by animal tubes. *Journal of Marine Research*, 39, 361–374.

EVANS, M.W.; HINE, A.C.; BELKNAP, D.F., and DAVIS, R.A., 1985. Bedrock controls on barrier island development: West-central Florida coast. *Marine Geology*, 63, 263–283.

FIELD, M.E. and ROY, P.S., 1984. Offshore transport and sand-body formation: evidence from a steep, high-energy shoreface, southeastern Australia. *Journal of Sedimentary Petrology*, 54, 1292–1302.

FISCHER, R. A., 1936. The use of multiple measurements in taxonomic problems. *Annals of Eugenics*, 7, 179–188.

FLETCHER, C.H. and WEHMILLER, J.F., (Editors), 1992. *Quaternary Coasts of the United States: Marine and Lacustrine Systems*. Tulsa, Oklahoma: SEPM (Society for Sedimentary Geology) Special Publication No. 48, p.

FRENCH, J.R.; SPENCER, T., and REED, D.J., 1995. (Editorial) Geomorphic response to sea-level rise: Existing evidence and future impacts. *Earth Surface Processes and Landforms*, 20, 1–6.

GADD, P.E.; LAVELLE, J.W., and SWIFT, D.J.P., 1978. Estimates of sand transport on the New York Shelf using near-bottom current meter observations. *Journal of Sedimentary Petrology*, 48, 239–252.

GAYES, P.T., 1990. Post-Hurricane Hugo nearshore sidescan sonar survey; Myrtle Beach to Folly Beach, South Carolina. *In:* FINKL, C.W. and PILKEY, O.H. (Editors), *Journal of Coastal Research*, Special Issue No. 8, pp. 95–111.

GLENN, S.M. and GRANT, W.D., 1987. A suspended sediment stratification correction of combined wave and current flows. *Journal of Geophysical Research*, 92, 8244–8264.

GODFREY, P.J., 1977. Comparative ecology of East Coast barrier islands: Hydrology, soil, vegetation. *1976 Barrier Island Workshop*. Washington: The Conservation Foundation, pp. 5–31.

GRANT, W.D. and MADSEN, O.S., 1979. Combined wave and current interaction with a rough bottom. *Journal of Geophysical Research*, 84, 1797–1808.

GRANT, W.D. and MADSEN, O.S., 1986. The continental-shelf bottom boundary layer. Annual *Review of Fluid Mechanics*, 18, 265–305.

GRAVENS, M.B.; KRAUS, N.C., and HANSON, H., 1991. *GENESIS: Generalized Model for Simulating Shoreline Change. Report 2, Workbook and System User's Manual*. Vicksburg, Mississippi: U.S. Army Corps of Engineers, CERC, Technical Report CERC-89-19, 431p.

GREENWOOD, B. and OSBORNE, P.D., 1991. Equilibrium slopes and cross-shore velocity asymmetries in a storm-dominated, barred nearshore system. *Marine Geology*, 96, 211–235.

GUILLEN, J. and HOEKSTRA, P., 1996. The equilibrium distribution of grain-size fractions and its implications for cross-shore sediment transport—A conceptual model. *Marine Geology*, 135, 15–33.

GUZA, R.T. and THORNTON, E.B., 1980. Local and shoaled comparisons of sea surface elevations, pressures, and velocities. *Journal of Geophysical Research*, 85, 1524–1530.

GUZA, R.T. and THORNTON, E.B., 1985a. Observations of surf beat. *Journal of Geophysical Research*, 90, 3161–3172.

GUZA, R.T. and THORNTON, E.B., 1985b. Velocity moments in the nearshore. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 111, 235–256.

HAFF, P., 1996. Limitations on predictive modeling in geomorphology. *In:* RHOADS, B.L. and THORN, C.E. (Editors), *The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology*. New York: Wiley, pp. 337–358.

HALLERMEIER, R.J., 1981a. A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering*, 4, 253–277.

HALLERMEIER, R.J., 1981b. *Seaward limit of significant sand transport by waves: an annual zonation for seasonal profiles*. Fort Belvoir, Virginia: U.S. Army Corps of Engineers, CERC, Coastal Engineering Technical Aid No. 81-2, 23p.

HANDS, E.B., 1980. *Prediction of shore retreat and nearshore profile adjustments to rising water levels on the Great Lakes*. Fort Belvoir, Virginia: U.S. Army Corps of Engineers, CERC, Coastal Engineering Technical Paper No. 80-7, 119p.

HANSEN, M. and SCHEFFNER, N., 1990. *Coastal engineering studies in support of Virginia Beach, Virginia, beach erosion and hurricane protection project*. Vicksburg, Mississippi: U.S. Army Corps of Engineers, CERC, Technical Report CERC-88-1.

HANSON, H., 1989. Genesis—A generalized shoreline change numerical model. *Journal of Coastal Research*, 5, 1–27.

HANSON, H. and KRAUS, N.C., 1989. *Genesis: Generalized Model for Simulating Shoreline Change*. Vicksburg, Mississippi: U.S. Army Corps of Engineers, CERC, Technical Report CERC-89-19, 185 p.

HAYDEN, B.P.; FELDER, W.; FISHER, J.; RESIO, D.; VINCENT, L., and DOLAN, R., 1975. *Systematic variations in inshore bathymetry*. University of Virginia, Department of Environmental Sciences, Charlottesville, Virginia, Technical Report 10.

HAYES, M., 1967. Hurricanes as geological agents, south Texas coast. *AAPG Bulletin*, 51, 937–956.

HAYES, M.O., 1979. Barrier island morphology as a function of tidal and wave regime. *In:* LEATHERMAN, S.P. (Editor), *Barrier Islands: From the Gulf of St. Lawrence to the Gulf of Mexico*. New York: Academic Press, pp. 1–27.

HENKEL, D.J., 1970. The role of waves in causing submarine landslides. *Geotechnique*, 20, 75–80.

HEQUETTE, A. and HILL, P.R., 1993. Storm-generated currents and offshore sediment transport on a sandy shoreface, Tibjak Beach, Canadian Beaufort Sea. *Marine Geology*, 113, 283–304.

HERON, S.D.; MOSLOW, T.F.; BERELSON, W.M.; HERBERT, J.R.; STEELE, G.A., and SUSMAN, K.R., 1984. Holocene sedimentation of a wave-dominated barrier-island shoreline: Cape Lookout, North Carolina. *Marine Geology*, 60: 413–434.

HODGENS, E., 1993. Engineering application: Generalized Model for Simulating Shoreline Change Canaveral Harbor, Florida, *Proceedings of the 6th Annual National Conference on Beach Preservation Technology*. Florida Shore and Beach Preservation Association, pp. 144–160.

HOLMAN, R.A., 1981. Infragravity energy in the surf zone. *Journal of Geophysical Research*, 86, 6442–6450.

HOLMAN, R.A., 1995. Nearshore processes. *Reviews of Geophysics*, Supplement, U.S. National Report to International Union of Geodesy and Geophysics, 33, Part 2, 1237–1247.

HOLMAN, R.A. and SALLENGENER, A.H., 1993. Sand bar generation: A discussion of the Duck experiment series. *Journal of Coastal Research*, Special Issue 15, 76–92.

HOLMAN, R.A. and STOCKDON, H.F., 1994. Why doesn't Scripps Beach have sand bars? *Eos*, 75(44), 336.

HOUSTON, J.R., 1995. *Beach-fill volume required to produce specified dry beach width*. Vicksburg, Mississippi: U. S. Army Corps of Engineers, CERC, Coastal Engineering Technical Note CETN II-32, 8p.

HOUSTON, J.R., 1996. Engineering practice for beach-fill design. *Shore and Beach*, 64(3), 27–35.

HOUSTON, J.R., 1996. Discussion of Young et al., 1995, A discussion of the Generalized Model for Simulating Shoreline Change (GENESIS). *Journal of Coastal Research*, 12, 1038–1043.

HOUSTON, J.R., 1997. Simplified Dean's method for beach-fill design. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 122, 143–146.

HOWD, P.A. and BIRKEMEIER, W.A., 1987. *Beach and nearshore survey data: 1981–1984, CERC Field Research Facility*. Vicksburg, Mississippi: U. S. Army Corps of Engineers, CERC, Technical Report No. 87-9, 139p.

HOWD, P.; BOWEN, T.; HOLMAN, R., and OLTMAN-SHAY, J., 1991. Infragravity waves, longshore currents and linear sand bar formation. *Coastal Sediments '91*. New York: ASCE, pp. 72–84.

IPCC (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE), 1996. *Climate Change 1995: The Science of Climate Change*. Cambridge: Cambridge University Press, 584p.

JAFFE, B.E.; LIST, J.H., and SALLENGER, A.H., 1997. Massive sediment bypassing on the lower shoreface offshore of a wide tidal inlet; Cat Island Pass, Louisiana. *Marine Geology*, 136, 131–149.

JAMES, W.R., 1975. *Techniques in evaluating suitability of borrow material for beach nourishment*. Fort Belvoir, Virginia: U.S. Army Corps of Engineers, CERC, Technical Memorandum No. 60, 81p.

JARRETT, J.T., 1977. Sediment budget analysis, Wrightsville Beach to Kure Beach, North Carolina. *Coastal Sediments '77*. New York: ASCE, pp. 986–1005.

KEEN, T. and SLINGERLAND, R., 1993. A numerical study of sediment transport and event bed genesis during tropical storm Delia. *Journal of Geophysical Research,* 98, 4775–4792.

KOMAR, P.D., 1969. The longshore transport of sand on beaches. Ph.D. dissertation, University of California, San Diego, 143p.

KOMAR, P.D., 1998a. *Beach Processes and Sedimentation.* Upper Saddle River, New Jersey: Prentice-Hall, 544p.

KOMAR, P.D., 1998b. The modeling of processes and morphology in the coastal zone—reflections on the maturity of our science. *Shore and Beach,* 66(1), 10–22.

KOMAR, P.D. and INMAN, D.L., 1970. Longshore sand transport on beaches. *Journal of Geophysical Research,* 75, 5914–5927.

KONIKOW, L.F. and BREDEHOEFT, J.D., 1992. Ground-water models cannot be validated. *Advances in Water Resources,* 15, 75–83.

KRAFT, J.C.; CHRZASTOWSKI, M.J.; BELKNAP, D.F.; TOSCANO, M.A., and FLETCHER, C.H., 1987. The transgressive barrier-lagoon coast of Delaware: Morphostratigraphy, sedimentary sequences and responses to relative rise in sea level. *In:* NUMMEDAL, D.; PILKEY, O.H., and HOWARD, J.D. (Editors), *Sea-Level Fluctuation and Coastal Evolution.* Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists, pp. 129–143.

KRAUS, N. LARSON, M., and KRIEBEL, D., 1991. Evaluation of beach erosion and accretion predictors. *Coastal Sediments '91.* New York: ASCE, pp. 572–587.

KRAUS, N.C., 1988. The effects of seawalls on the beach: an extended literature review. *Journal of Coastal Research,* Special Issue 4, 1–28.

KRAUS, N.C. and MCDOUGAL, W.G., 1996. The effects of seawalls on the beach: part I, an updated literature review. *Journal of Coastal Research,* 12, 691–701.

KRAUS, N.C.; SCHEFFNER, N.W.; HANSON, H.; CHOU, L.W.; CIALONE, M.A.; SMITH, J.M., and HARDY, T.A., 1988. *Coastal processes at Sea Bright to Ocean Township, New Jersey.* Vicksburg, Mississippi: U.S. Army Corps of Engineers, CERC, Miscellaneous Paper CERC-88-12, 140p.

KRUMBEIN, W.C. and JAMES, W.R., 1965. *A lognormal size distribution model for estimating the stability of beach fill material.* Washington: U.S. Army Corps of Engineers, CERC, Technical Memorandum No. 16, 17p.

KUNZIG, R., 1995. Twilight of the cod. *Discover,* 16(4), p. 44ff.

LARSON, M., 1991. Equilibrium profile of a beach with varying grain size. Coastal Sediments '91. New York: ASCE, pp. 905–919.

LARSON, M. and KRAUS, N.C., 1989. SBEACH: Numerical Model for Simulating Storm-Induced Beach Change. Vicksburg, Mississippi: U.S. Army Corps of Engineers, CERC, Technical Report CERC-89-9, 256p.

LARSON, M. and KRAUS, N.C., 1992. *Analysis of cross-shore movement of natural longshore bars and material place to create longshore bars.* Vicksburg, Mississippi: U.S. Army Corps of Engineers, WES, Technical Report DRP-92-5, 115p.

LAVELLE, J.W.; YOUNG, R.A.; SWIFT, D.J.P., and CLARKE, T.L., 1978. Near-bottom sediment concentration and fluid velocity measurements on the inner continental shelf. *Journal of Geophysical Research,* 83, 6052–6062.

LEATHERMAN, S.P., 1984. Shoreline evolution of North Assateague Island, Maryland. *Shore and Beach,* 52, 3–10.

LEE, G. and BIRKEMEIER, W.A., 1993. *Beach and nearshore survey data: 1985–1991 CERC Field Research Facility.* Vicksburg, Mississippi: U.S. Army Corps of Engineers, CERC, Technical Report CERC-93-3.

LEE, K.L. and FOCHT, J.A., 1976. Cyclic testing of soil for ocean wave loading problems. *Marine Geotechnology,* 1, 305–325.

LEONARD, L.; CLAYTON, T.D.; DIXON, K., and PILKEY, O.H., 1989. U.S. beach replenishment experience: a comparison of the Atlantic, Pacific, and Gulf coasts. *Coastal Zone '89.* New York: ASCE, pp. 1994–2006.

LEONARD, L.; CLAYTON, T., and PILKEY, O., 1990. An analysis of replenished beach design parameters on U.S. East Coast barrier islands. *Journal of Coastal Research,* 6, 15–36.

LIST, J.H.; SALLENGER, A.H.; HANSEN, M.E., and JAFFE, B.E., 1997. Accelerated relative sea-level rise and rapid coastal erosion: testing a causal relationship for the Louisiana barrier islands. *Marine Geology,* 140, 347–365.

LIST, J.H. and TERWINDT, J.H.J, 1995. Large-scale coastal behavior. *Marine Geology,* 126, 331p.

LORENZ, E.N., 1963. Deterministic nonperiodic flow. *Journal of the Atmospheric Sciences,* 20, 130–141.

MADSEN, O.S., 1978. Wave-induced pore pressures and effective stresses in a porous bed. *Geotechnique,* 28, 377–394.

MASSELINK, G. and SHORT, A.D., 1993. The effect of tide range on beach morphodynamics and morphology; a conceptual beach model. *Journal of Coastal Research,* 9, 785–800.

MCANALLY, W.H., 1989. Lessons from ten years experience in 2D sediment modeling. *In:* WANG, S.S.Y. (Editor), *Proceedings of the International Symposium on Sediment Transport Modeling.* New York: ASCE, pp. 350–355.

MCDOUGAL, W.G.; KRAUS, N.C., and AJIWIBOWO, H., 1996. The effects of seawalls on the beach: part II, numerical modeling of SUPERTANK seawall tests. *Journal of Coastal Research,* 12, 702–713.

MILLER, R.L., 1976. Role of vortices in surf zone prediction: Sedimentation and wave forces. *In:* DAVIS, R.A. and ETHINGTON, R.L. (Editors), *Beach and Nearshore Sedimentation.* Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists, Special Publication No. 24, pp. 92–114.

MOORE, B.D., 1982. *Beach profile evolution in response to changes in water level and wave height.* M.S. thesis, University of Delaware, Newark, Delaware, 164p.

MORANG, A. and MCMASTER, R.L., 1980. Nearshore bedform patterns along Rhode Island from side-scan sonar surveys. *Journal of Sedimentary Petrology,* 50, 831–839.

MORTON, R.A., 1975. Shoreline changes in the vicinity of the Brazos River delta (San Luis Pass to Brown Cedar Cut); an analysis of historical changes of the Texas Gulf shoreline. Texas Bureau of Economic Geology, *Geological Circular 75-4,* 47pp.

MORTON, R.A., 1988. Nearshore responses to great storms. Boulder: Geological Society of America, *Special Paper 229,* pp. 7–22.

MURRAY, A.B. and REYDELLET, G., submitted. A rip current model based on a newly hypothesized interaction between waves and currents, *Journal of Fluid Mechanics.*

MYROW, P.M. and SOUTHARD, J.B., 1996. Tempestite deposition. *Journal of Sedimentary Research,* 66, 875–887.

NATIONAL RESEARCH COUNCIL, 1990. *Managing Coastal Erosion.* Washington: National Academy Press, 163p.

NATIONAL RESEARCH COUNCIL, 1995. *Beach Nourishment and Protection.* Washington: National Academy Press, 334p.

NIEDORODA, A.W.; SWIFT, D.J.P., and HOPKINS, T.S., 1985. The shoreface. *In:* DAVIS, R. A. (Editor), *Coastal Sedimentary Environments.* New York: Springer-Verlag, p. 533–624.

NIELSEN, P., 1988. Three simple models of wave sediment transport. *Coastal Engineering,* 12, 43–62.

NIELSEN, P., 1992. *Coastal Bottom Boundary Layers and Sediment Transport.* World Scientific, Singapore, 324 pp.

NUMMEDAL, D., 1991. Shallow marine storm sedimentation—the oceanographic perspective. *In:* EINSELE, G.; RICKEN, W., and SEILACHER, A. (Editors), *Cycles and Events in Stratigraphy.* New York: Springer-Verlag, pp. 227–248.

OLTMAN-SHAY, J.; HOWD, P.A., and BIRKEMEIER, W.A., 1989. Shear instabilities of the mean longshore current 2. Field observations. *Journal of Geophysical Research,* 94, 18031–18042.

ORESKES, N.; SHRADER-FRECHETTE, K., and BELITZ, K., 1994. Verifcation, validation, and confirmation of numerical models in the earth sciences. *Science,* 263, 641–646.

PATTIARATCHI, C.; HEGE, B.; GOULD, J., and ELIOT, I., 1997. Impact of sea-breeze activity on nearshore and foreshore processes in southwestern Australia. *Continental Shelf Research,* 17, 1539–1560.

PELNARD-CONSIDÈRE, R., 1956. Model tests confirm the theory of the changing shapes of sand and stone beaches—Essai de theorie de l'evolution des formes de rivage en plages de sable et de galets. *Quatriemes journees de l'hydraulique,* 13, 289–298.

PILKEY, O.H., 1988. A "Thumbnail Method" for beach communities:

Estimation of long-term beach replenishment requirements. *Shore and Beach*, 23–31.

PILKEY, O.H., 1995. The fox guarding the hen house. *Journal of Coastal Research*, 11(3), iii–v.

PILKEY, O.H. and CLAYTON, T.D., 1987. Beach replenishment: The national solution? *Coastal Zone '87*. New York: ASCE, pp. 1408–1419.

PILKEY, O.H. and CLAYTON, T.D., 1989. Summary of beach replenishment experience on U.S. East Coast barrier islands. *Journal of Coastal Research*, 5, 147–159.

PILKEY, O.H. and DAVIS, T.W., 1987. An analysis of coastal recession models: North Carolina coast. *In:* D. NUMMEDAL, PILKEY, O. H. and HOWARD, J.D. (Editors), *Sea-Level Fluctuation and Coastal Evolution*. Society of Economic Paleontologists and Mineralogists, pp. 59–68.

PILKEY, O.H. and DIXON, K.L., 1996. *The Corps and the Shore*. Washington: Island Press, 272p.

PILKEY, O.H. and FIELD, M.E., 1972. Onshore transportation of continental shelf sediment: Atlantic Southeastern United States. *In:* SWIFT, D.J.P.; DUANE, D.B., and PILKEY, O.H. (Editors), *Shelf Sediment Transport: Process and Pattern*. Stroudsburg, Pennsylvania: Dowden, Hutchinson and Ross, Inc., pp. 429–446.

PILKEY, O.H.; YOUNG, R.S.; RIGGS, S.R.; SMITH, A.W.; WU, H., and PILKEY, W.D., 1993. The concept of shoreface profile of equilibrium: A critical review. *Journal of Coastal Research*, 9, 255–278.

PILKEY, O.H.; YOUNG, R.S.; BUSH, D.M., and THIELER, E.R., 1994. Predicting the behavior of beaches: Alternatives to models. *In:* DE CARVALHO, G.S. (Editor), *Littoral 94, Procs. of the 2nd International Symposium*. Lisbon: Association EUROCOAST—Portugal, Lisbon, Portugal, pp. 53–60.

PILKEY, O.H.; YOUNG, R.S.; THIELER, E.R.; JACOBS, B.S.; KATUNA, M.P.; LENNON, G., and MOELLER, M.E., 1996. Reply to: Houston, J. R., 1996, Discussion of Young *et al.*, 1995, A discussion of the Generalized Model for Simulating Shoreline Change (GENESIS). *Journal of Coastal Research*, 12, 1044–1050.

PLAG, H.P.; AUSTIN, W.E.N.; BELKNAP, D.F.; DEVOY, R.J.N.; ENGLAND, J.; JOSEHANS, H.; PEACOCK, J.D.; PETERSEN, K.S.; ROKOENGEN, K.; SCOURSE, J.D.; SMITH, D.E., and WINGFIELD, R.T.R., 1996. Late Quaternary relative sea-level changes and the role of glaciation upon continental shelves. *Terra Nova*, 8, 213–222.

RECKHOW, K.H. and CHAPRA, S.C., 1983. *Engineering Approaches for Lake Management*. Boston: Butterworth-Heinemann, 358p.

REIMNITZ, E.; TOIMIL, L.J.; SHEPARD, F.P., and GUTIERREZ-ESTRADA, M., 1976. Possible rip current origin for bottom ripple zones to 30-m depth. *Geology*, 4, 395–400.

RIGGS, S.R.; CLEARY, W.J., and SNYDER, S.W., 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. *Marine Geology*, 126, 213–234.

RIGGS, S.R.; SNYDER, S.W.; HINE, A.C., and MEARNS, D.L., 1996. Hardbottom morphology and relationship to the geologic framework: mid-Atlantic continental shelf. *Journal of Sedimentary Research*, 66, 830–846.

ROELVINK, J.A. and STIVE, M.J.F., 1989. Bar-generating cross-shore flow mechanisms on a beach. *Journal of Geophysical Research*, 94, 4785–4800.

ROSEN, P., 1978. A regional test of the Bruun Rule of shoreline erosion. *Marine Geology*, 26, 7–16.

SCHWAB, W.C.; RODRIGUEZ, R.W.; DANFORTH, W.W., and GOWEN, M.H., 1996. Sediment distribution on a storm-dominated insular shelf, Luquillo, Puerto Rico, USA. *Journal of Coastal Research*, 12, 147–159.

SCHWAB, W.C.; ALLISON, M.A.; CORSO, W.; LOTTO, L.L.; BUTMAN, B.; TEN BRINK, M.; DENNY, J.F.; DANFORTH, W.W., and FOSTER, D.S., 1997. Initial results of high-resolution sea-floor mapping offshore of the New York—New Jersey metropolitan area using side-scan sonar. *Northeastern Geology and Environmental Sciences*, 19, 243–262.

SCHWARTZ, M., 1965. Laboratory study of sea-level rise as a cause of shore erosion. *Journal of Geology*, 73, 528–534.

SCHWARTZ, M., 1967. The Bruun theory of sea-level rise as a cause of shore erosion. *Journal of Geology*, 75, 76–92.

SEED, H.B. and RAHMAN, M.S., 1978. Wave-induced pore pressure in relation to ocean floor stability of cohesionless soils. *Marine Geotechnology*, 3, 123–150.

SEYMOUR, R.J., 1990. Autosuspending turbidity flows. *In:* LE-MEHAUTE, B. and HANES, D. (Editors), *The Sea*, Volume 9. New York: Wiley-Interscience, pp. 919–940.

SHEPARD, F.P., 1950. *Beach cycles in southern California*. Washington: U.S. Beach Erosion Board, Technical Memorandum, 26p.

SMITH, W.G.; ROSATI, J.D., and LEMIRE, A., 1993. Revere Beach and Point of Pines, Massachusetts, Shore Front Study. *In:* STAUBLE, D.K. and KRAUS, N.C. (Editors), *Beach Nourishment Engineering and Management Considerations*. New Orleans: ASCE, pp. 118–132.

SNEDDEN, J.W.; NUMMEDAL, D., and AMOS, A.F., 1988. Storm- and fair-weather combined flow on the central Texas continental shelf. *Journal of Sedimentary Petrology*, 58, 580–595.

STERNBERG, R.W. and LARSEN, L.H., 1975. Threshold of sediment movement by open ocean waves: Observations. *Deep-Sea Research*, 22, 299–309.

STIVE, M.J.F. and DEVRIEND, H.J., 1995. Modeling shoreface profile evolution. *Marine Geology*, 126, 235–248.

SWIFT, D.J.P., 1976. Continental shelf sedimentation. *In:* STANLEY, D.J. and SWIFT, D.J.P. (Editors), *Marine Sediment Transport and Environmental Management*. John Wiley and Sons, New York, pp. 311–350.

TAIT, J.; ANIMA, R.J., and GRIGGS, G.B., 1992. Shoreface storage and transport of littoral sediments along the Central California coast. *Eos*, 73 (Supplement), 302.

THIELER, E.R.; BRILL, A.L.; HOBBS, C.H., and GAMMISCH, R., 1995. Geology of the Wrightsville Beach, North Carolina shoreface: Implications for the concept of shoreface profile of equilibrium. *Marine Geology*, 126, 271–287.

THIELER, E.R. and YOUNG, R.S., 1991. Quantitative evaluation of coastal geomorphological changes in South Carolina after hurricane Hugo. *Journal of Coastal Research*, Special Issue No. 8, 187–200.

THORNTON, E.B. and KIM, C.S., 1993. Longshore current and wave height modulation at tidal frequency inside the surf zone. *Journal of Geophysical Research*, 98, 16509–16519.

TRUITT, C.L.; KRAUS, N.C., and HAYWARD, D., 1993. Beach fill performance at the Lido Beach, Florida, groin. *In:* STAUBLE, D.K. and KRAUS, N.C. (Editors), *Beach Nourishment Engineering and Management Considerations*. New Orleans: ASCE, pp. 31–42.

TURNER, I.L. and LEATHERMAN, S.P., 1997. Beach dewatering as a 'soft' engineering solution to coastal erosion—a history and critical review. *Journal of Coastal Research*, 13, 1050–1063.

TURNER, I.L. and NIELSEN, P., 1997. Rapid water table fluctuations within the beach face: implications for swash zone sediment mobility? *Coastal Engineering*, 32, 45–59.

USACE, 1984. *Shore Protection Manual*. Vicksburg, Mississippi: U.S. Army Corps of Engineers, 2 vols.

USACE, 1989. *Atlantic Coast of Maryland Hurricane Protection Project, Final General Design Memorandum*. Baltimore: U.S. Army Corps of Engineers, 3 vols.

USACE, 1994. *Shoreline protection and beach erosion control study, Phase I: cost comparison of shoreline protection projects of the U.S. Army Corps of Engineers*. Alexandria, Virginia: U.S. Army Corps of Engineers, IWR Report 94-PS-1, 135p.

USACE, 1991. *Folly Beach General Design Memorandum*. Charleston: U.S. Army Corps of Engineers, 2 vols.

USACE, 1999. Manteo (Shallowbag) Bay North Carolina, Supplement No. 2 General Design Memorandum, Draft Supplement No. III Environmental Impact Statement. Wilmington, NC: U.S. Army Corps of Engineers, 1 vol., variously paginated.

VERHAGEN, H., 1992. Method for artificial beach renourishment. *Proceedings of the 23rd International Conference on Coastal Engineering*, Venice, Italy, pp. 2474–2485.

VINCENT, C.E. and GREEN, M.O., 1990. Field measurements of the suspended sand concentration profiles and fluxes and of the resuspension coefficient g0 over a rippled bed. *Journal of Geophysical Research*, 95, 11,591–11,601.

VINCENT, C.E.; YOUNG, R.A., and SWIFT, D.J.P., 1982. On the relationship between bedload and suspended sand transport on the inner shelf, Long Island, New York. *Journal of Geophysical Research,* 87, 4163–4170.

WADDELL, E., 1976. Swash-groundwater-beach profile interactions. *In:* DAVIS, R.A. and ETHINGTON, R.L. (Editors), *Beach and Nearshore Sedimentation.* Society of Economic Paleontologists and Mineralogists, Tulsa, Oklahoma, pp. 115–125.

WALKER, R. G., 1985. Geological evidence for storm transportation and deposition on ancient shelves. *In:* TILLMAN, R.W.; SWIFT, D.J.P., and R.G. WALKER, (Editors), *Shelf Sands and Sandstone Reservoirs.* Tulsa, Oklahoma: SEPM Short Course Notes No. 13, p. 243–301.

WANG, P.; KRAUS, N.C., and DAVIS, R.A., 1998. Total longshore sediment transport rate in the surf zone: field measurements and empirical predictions. *Journal of Coastal Research,* 14, 269–282.

WEHMILLER, J.F.; YORK, L.L., and BART, M.L., 1995. Amino-acid racemization geochronology of reworked Quaternary mollusks on US Atlantic coast beaches: Implications for chronostratigraphy, taphonomy, and coastal sediment transport. *Marine Geology,* 124, 303–337.

WERNER, B.T., 1995. Eolian dunes: computer simulations and attractor interpretation. *Geology,* 23, 1107–1110.

WERNER, B.T. and FINK, T.M., 1993. Beach cusps as self-organized patterns. *Science,* 260, 968–971.

WIBERG, P.L., 1995. A theoretical investigation of boundary layer flow and bottom shear stress for smooth, transitional, and rough flow under waves. *Journal of Geophysical Research,* 100, 22,667–22,679.

WIBERG, P.L., DRAKE, D.E., and CACCHIONE, D.A., 1994. Sediment resuspension and bed armoring during high bottom stress events on the northern California inner continental shelf: measurements and predictions. *Continental Shelf Research,* 14, 1191–1219.

WIBERG, P.L. and HARRIS, C.K., 1994. Ripple geometry in wave-dominated environments. *Journal of Geophysical Research,* 99, 775–789.

WIBERG, P.L. and SMITH, J.D., 1983. A comparison of field data and theoretical models for wave-current interactions at the bed on the continental shelf. *Continental Shelf Research,* 2, 147–162.

WILLIAMS, S.J. and MEISBURGER, E.P., 1987. Sand sources for the transgressive barrier coast of Long Island, New York: Evidence for landward transport of shelf sediments. *Coastal Sediments '87.* New York: ASCE, pp. 1517–1532.

WISCHMEIER, W.H. and SMITH, D.D., 1978. *Predicting rainfall erosion losses—a guide to conservation planning.* Washington: U.S. Department of Agriculture, Agriculture Handbook 537, 58p.

WISE, R.A.; SMITH, S.J., and LARSON, M., 1996. *SBEACH: Numerical Model for Simulating Storm-Induced Beach Change.* Vicksburg, Mississippi: U.S. Army Corps of Engineers, CERC, Technical Report CERC-89-9, Report 4, Cross-Shore Transport Under Random Waves and Model Validation with SUPERTANK and Field Data, 140p.

WISE, R.A. and SMITH, S.J. Numerical modeling of storm-induced beach erosion. *The CERCULAR,* v. CERC-96-1, pp. 1ff.

WRIGHT, L.D., 1987. Shelf-surfzone coupling: diabathic shoreface transport. *Coastal Sediments '87.* New York: ASCE, pp. 25–40.

WRIGHT, L.D., 1989. Benthic boundary layers of estuarine and coastal environments. *Aquatic Sciences,* 1, 75–95.

WRIGHT, L.D., 1995. *Morphodynamics of Inner Continental Shelves.* Boca Raton, Florida: CRC Press, 241p.

WRIGHT, L.D.; BOON, J.D.; GREEN, M.O., and LIST, J.H., 1986. Response of the mid-shoreface of the southern Mid-Atlantic Bight to a "Northeaster." *Geo-Marine Letters,* 6, 153–160.

WRIGHT, L.D.; BOON, J.D.; KIM, S.C., and LIST, J.H., 1991. Modes of cross-shore sediment transport on the shoreface of the Middle Atlantic Bight. *Marine Geology,* 96, 19–51.

WRIGHT, L.D.; KIM, S.C.; HARDAWAY, C.S.; KIMBALL, S.M., and GREEN, M.O., 1987. *Shoreface and beach dynamics of the coastal region from Cape Henry to False Cape, Virginia.* Gloucester Point, Virginia: Virginia Institute of Marine Sciences, 116p.

WRIGHT, L.D.; SCHAFFNER, L.C., and MAA, J.P.-Y., 1997. Biological mediation of bottom boundary layer processes and sediment suspension in the lower Chesapeake Bay. *Marine Geology,* 141, 27–50.

WRIGHT, L.D. and SHORT, A.D., 1983. Morphodynamics of beaches and surf zones in Australia. *In:* KOMAR, P.D. (Editor), *CRC Handbook of Coastal Processes and Erosion.* Boca Raton, Florida: CRC Press, pp. 35–64.

WRIGHT, L.D.; XU, J.P., and MADSEN, O.S., 1994. Across-shelf benthic transports on the inner shelf of the Middle Atlantic Bight during the "Halloween storm" of 1991. *Marine Geology,* 118, 61–77.

YOUNG, R.S.; PILKEY, O.H.; BUSH, D.M., and THIELER, E.R., 1995. A discussion of the Generalized Model for Simulating Shoreline Change (GENESIS). *Journal of Coastal Research,* 11, 875–886.

YOUNG, R.S.; PILKEY, O.H.; BUSH, D.M., and THIELER, E.R., 1997. Reply to: Bodge, K. R., 1997. Discussion of: Young, R. S., Pilkey, O. H., Bush, D. M., and Thieler, E. R., 1995. A discussion of the Generalized Model for Simulating Shoreline Change (GENESIS). *Journal of Coastal Research,* 13, 954–955.