Journal of Coastal Research | 7 | 3 | 895-921 | Fort Lauderdale, Florida | Summer 1991

Reports of Meetings

The Response of Beaches to Sea-Level Changes: A Review of Predictive Models

Scientific Committee on Ocean Research (SCOR) Working Group 89*

*Chairman—P.D. Komar (Oceanography, Oregon State University, Corvallis, Oregon, U.S.A.); Co-chairman—N. Lanfredi (Comisión de Investígaciones Ciantificas, Universidad de La Plata, La Plata, Argentina); M. Baba (Centre for Earth Science Studies, Cochin, India); R.G. Dean (Coastal and Oceanographic Engineering, University of Florida, Gainesville); K. Dyer (Institute of Marine Studies, Plymouth Polytechnic, England); T. Healy (Earth Sciences, University of Waikato, Hamilton, New Zealand); A.C. Ibe (Nigerian Institute for Oceanography and Marine Research, Lagos, Nigeria); J.H.J. Terwindt (Rijksuniversiteit te Utrecht, The Netherlands); B.G. Thom (Geography, The University of Sydney, Australia).

ABSTRACT

SCOR Working Group 89, 1991. The Response of Beaches to Sea-Level Changes: A Review of Predictive Models. *Journal of Coastal Research*, 7(3), 895–921.

Models are reviewed that have been proposed to predict beach-profile changes that result from a rise in water level, and include predictions of the resulting shoreline recession rates. The best-known model is that of Bruun (1962), while more-recently developed models include an entire barrier-island system or focus on the erosion response of beaches and dunes to the brief elevation of water levels associated with a storm surge. Testing and application of the models for beach responses to a long-term rise in sea level have been hampered by significant lag times of beach changes, amounting to months or years, and the importance of sediment-budget balances that can produce shoreline erosion or accretion irrespective of any sea-level rise. Profile changes assumed by the models have been reasonably well verified by laboratory and field studies, but the predictive equations are found to yield poor results when the effects of profile lag times and complete sediment budgets are not included in the analyses. Recommendations are made concerning additional field and laboratory studies that should be undertaken to improve our understanding of beach responses to elevated water levels.

ADDITIONAL KEY WORDS: *Bruun Rule, sea-level rise, shore erosion, storm surge.*

INTRODUCTION

Interest in the role of sea level as an agent in coastal erosion has increased in recent years as a result of predictions that the rise in ocean levels will accelerate in the next century due to greenhouse warming. Analyses by the Environmental Protection Agency in the United States have attempted to project the impact of greenhouse warming into the future, and have predicted sea-level rises of 50 to 340 cm by the year 2100, equivalent to average rates of 5 to 30 mm/year (Hoffman *et al.*, 1983). The Committee of the National Research Council on Carbon Dioxide Assessment suggests a rate of 7 mm/year by the year 2100 (Revelle, 1983). The recent estimates by Van der Veen (1988) are lower, 2.8 to 6.6 mm/year by 2085 A.D., rates that are still about 2 to 4 times the 1 to 2 mm/year rise that has prevailed during the last 100 years. Therefore, predictions of greenhouse-related sea-level rise vary considerably, but all agree that an acceleration is likely. Although such predictions remain controversial and have not been accepted by many scientists and engineers, it is still important to consider the potential consequences to our coastlines. Furthermore, irrespective of possibly accelerated increases in sea levels, the present rise amounting to 10 to 20 cm over a century is already significant to the erosion of many low-lying coasts. In addition, enhanced water levels that are shorter-term and more local, such as occurred along the west coast of the United States during the 1982-83 El Niño, can also induce beach erosion. The problem is not limited to the ocean. Roughly every ten to fifteen years excessive water levels in the Great Lakes of North America, produced by exceptional precipitation, have resulted in devastating erosion and property losses.

With a qualitative awareness that sea level is important to coastal erosion and shoreline changes, the question arises as to the status of models and analysis techniques for quantitative evaluations of the erosion response of beaches to increased water levels. SCOR Working Group 89 was brought into being in an attempt to answer that question. Related questions immediately come to mind. How does a beach change in its morphology when there is a higher water level? What process models are available to account for the observed morphological changes, and have those models been adequately tested? Does the beach response depend on the rate of water-level increase, or only on its total magnitude? Are laboratory-scale experiments, necessarily limited in duration, relevant to models that predict beach responses to long-term sea-level changes? Should monitoring programs be established on the world's coastlines, especially in those areas that presently lack relevant data and would be particularly vulnerable to projected sea-level increases? The present paper constitutes the report of SCOR Working Group 89 in its attempt to answer these questions, and to make suggestions for additional research. Recommendations will also be offered with respect to applications of the models in making coastal-zone management decisions.

Brief mention is needed as to what Working Group 89 has not included in its review. We recognize that increased sea levels, particularly of the predicted magnitudes for the next century, would have enormous consequences to estuaries, barrier islands, coral reefs, and other coastal environments. Previous committees have considered the broad consequences, so it was decided that the focus of Working Group 89 would be narrower in scope so as to permit a more detailed consideration. The primary objective, therefore, is limited to an examination of models of beach responses to water-level changes. We encourage the establishment of other committees to examine aspects of coastal impacts not considered by our group.

CAUSES AND MAGNITUDES OF SEA-LEVEL FLUCTUATIONS

During the past 3 million years, water has periodically been locked up within large continental glaciers and then released, producing cycles in the level of the sea. A timetable of the changes has been obtained by dating materials such as submerged peat beds, beach rock and fossil intertidal animals, material that has a known narrow relationship to past stands of the sea. A number of investigators have developed chronologies of sea-level variations extending over the past 50,000 years or more (SHEPARD, 1963; CURRAY, 1965; SHEPARD and CURRAY, 1967; MILLIMAN and EMERY, 1968; KRAFT *et al.*, 1973). The results generally agree that about 15,000 to 20,000 years ago, the sea was approximately 100 meters lower than at present. The curve established by Curray for the last 40,000 years is shown in Figure 1A, while Figure 1B includes the data compiled by Shepard and Curray for the last 8,000 years. The results indicate that with the melting of glaciers, there was initially a rapid rise in sea level, averaging about 8 mm/yr, until approximately 7,000 years ago when it slowed to 1 to 2 mm/yr.

Long-term tide-gauge records demonstrate that the global rise in sea level is continuing (HICKS, 1978; PIRRAZOLI, 1986; GORNITZ and LEBEDEFF, 1987; WYRTKI, 1990). Such records are particularly useful in examining the relative sea-level change at a specific site, the sum of the general rise in sea level (eustatic) due to glacial melting plus any local land-level change. It is, of course, this relative increase in water level that is important to erosion at the site. Examples of tide-gauge records are shown in Figure 2. The curve from New York is typical of those for much of the east coast of the U.S., and yields an average rise of approximately 3 mm/yr. That rate is due to the combined effects of a rising sea level with a nearly equal contribution from land subsidence. The curve for Galveston, Texas, indicates a much higher local

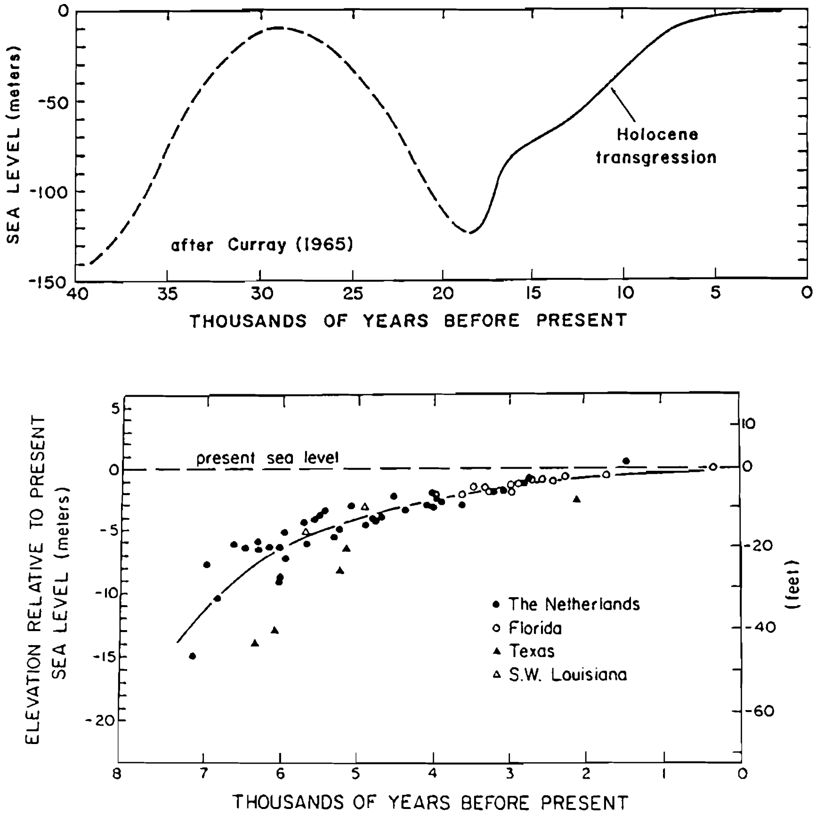


Figure 1. A. Curve for variations in sea level during the past 40,000 years, based on carbon-14 dates compiled by Curray (1965). The dashed curve is estimated from only limited data. B. Data and sea-level curve for the past 8,000 years based on a compilation by Shepard and Curray (1967) of data from "stable" areas of the world.

sea-level rise, averaging 6 mm/yr, produced by the rapid sinking of that portion of the Gulf Coast. There appears to be no relative rise in sea level at Astoria, Oregon, Figure 2—the land of that active continental margin is rising at approximately the same rate as the eustatic sea level. An extreme case is that of Juneau, Alaska, where the land is rising at such a rate that there is a net lowering of the ocean level relative to the land. Recent studies have examined spatial patterns in sea-level changes in attempts to distinguish between the portion due to isostatic and neotectonic movements versus the global eustatic rise [for example, AUBREY and EMERY (1986) and BRAATZ and AUBREY (1987)]. Due to the substantial effects of land-level changes on the records from tide gauges, it has been difficult to use that data to determine the world-wide eustatic component (a problem that is compounded by the uneven distribution of tide gauges, with most located in the northern hemisphere). Even when sites are eliminated that are obviously being greatly affected by anomalous localized subsidence or emergence, a wide range of estimates is derived for the eustatic rise: 1.5 ± 0.3 mm/yr (HICKS, 1978), 3 mm/yr (EMERY, 1980), 1.2 mm/yr (GORNITZ *et al.*, 1982), 2.3 ± 0.2 mm/yr (BARNETT, 1984), 1.2 ± 0.3 mm/yr (GORNITZ and LEBEDEFF, 1987), 1.0 ± 0.1 mm/yr (BRAATZ and AUBREY, 1987), 2.4 ± 0.9 mm/yr (PELTIER and TUSHINGHAM, 1989).

The predicted sea-level increase of 50 to 340 cm by the year 2100 (HOFFMAN *et al.*, 1983),

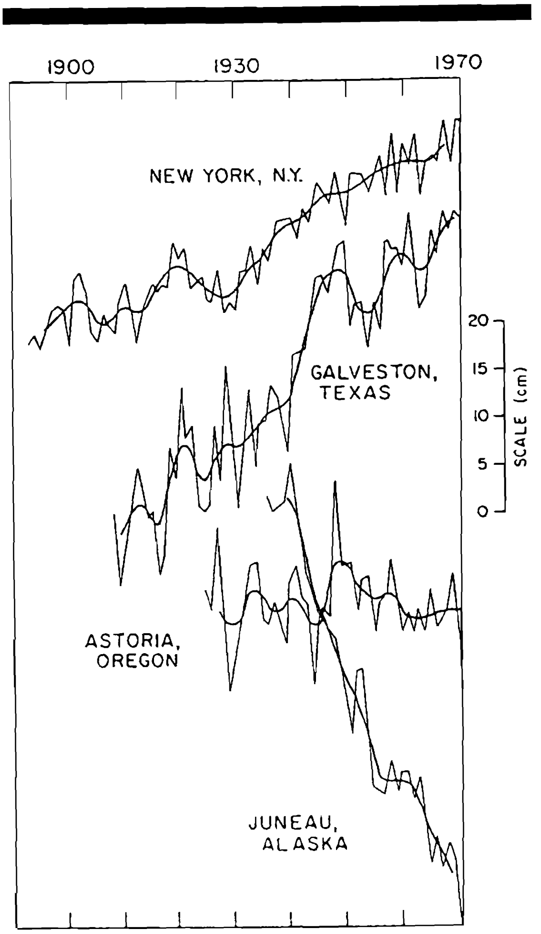


Figure 2. Yearly average sea levels as determined from tide-gauge records at various coastal sites, illustrating the effects of a slow eustatic rise in the water level of the oceans plus local changes in the levels of the land masses. [*from* Hicks (1972) and Komar (1983)].

rates averaging 5 to 30 mm/yr, would be substantially higher than those measured by tide gauges over the past century and possibly even greater than the 8 mm/yr rise during the stage of major glacial melting (Figure 1A). Most of this predicted increase in water levels in the next century would result from the thermal expansion of the ocean's waters accompanying greenhouse warming, as well as from additional melting of glaciers (GORNITZ *et al.*, 1982; VAN DER VEEN, 1988). Several studies have attempted to determine whether it is possible to identify in the tide-gauge records an increase in the rate of sea-level rise (an acceleration) that might be attributed to greenhouse warming. EMERY (1980) concluded that the available data do support an accelerated rise. Analyses by GORNITZ and LEBEDEFF (1987) for global sea level suggest an inflection in the trends in the mid-1930's, with a higher rate since that time. However, HICKS and HICKMAN (1988) concluded that rates for 1940-1962 versus 1962-1986 depend on regional groupings of tide gauges, and show no consistent acceleration. The consensus based on the aggregate of all analyses is that noise in the data precludes confident conclusions with regard to whether the global sea level is rising at accelerated rates in recent decades (WYRTKI, 1990). BARNETT (1984) has concluded that it is not possible to uniquely determine either a global rate of change in sea level or even the average rate of change from existing tide-gauge data, and that differences in analysis methods by themselves account for the large range of estimates noted above. Barnett went on to conclude that the detection of a response in sea level associated with greenhouse warming will be difficult due to the huge, natural variability in the data produced by glacial/tectonic processes.

Part of the difficulty in analyzing tide-gauge records for eustatic sea-level change results from the substantial variations in water levels from year to year, apparent in the curves of Figure 2. Differences in water levels in sequential years can be equivalent to the change produced by decades of glacial melting and tectonic subsidence or emergence. It is apparent at Astoria, Oregon, where there is minimal long-term sea-level change (Figure 2), that the yearly fluctuations would be those of primary significance to coastal erosion. These annual variations can be produced by a variety of oceanographic and atmospheric processes, including changes in water temperatures (local rather than global), variations in the strengths of coastal currents, atmospheric pressures, and winds blowing either in the longshore or cross-shore directions (KOMAR and ENFIELD, 1987). Many of these processes are seasonal, so that at most coastal sites there are annual sea-level variations typically on the order of 10 to 30 cm (achieving a maximum of about 100 cm in the Bay of Bengal). Variations in the magnitudes of these processes from year to year account for the fluctuations seen in the curves of Figure 2.

Particularly dramatic short-term sea-level changes are associated with the occurrence of an El Niño in the Pacific Ocean. An El Niño is triggered by the breakdown of the westward-directed trade winds along the equator, and one result is the release of setup of the sea level in the western Pacific normally established by those winds (WYRTKI, 1975). The released water moves eastward as a bulge in the sea level, held close to the equator by the Coriolis force. The movement of these sea-level "waves" has been documented in tide-gauge records from islands near the equator (WYRTKI, 1977, 1983), and has been shown to represent sea-level variations up to 40-50 cm in less than a year. On reaching the west coast of South America, the sea-level bulge splits with part of it moving south along the coast of Chile, and part moving north. The northward-moving bulge has been followed in tide gauges along the coasts of Mexico, the continental U.S., and has even been detected on the coast of Alaska (ENFIELD and ALLEN, 1980). The sea-level waves are held by refraction to the coastline due to the slope of the continental margin, and although some energy is lost offshore, the amplitude at the shoreline itself is enhanced by the increasing Coriolis force at higher latitudes. Such sea-level waves associated with an El Niño typically raise water levels along the west coast of the U.S. by 10 to 20 cm. The 1982-83 El Niño was exceptional in magnitude—on the coast of Oregon, the generated "wave" combined with the seasonal variations in water levels to produce a 60-cm rise within 12 months, 35-cm higher than average (HUYER, *et al.*, 1983; KOMAR, 1986).

Marked fluctuations in water levels also occur in lakes. This has been particularly significant in the Great Lakes of North America (HANDS, 1980, 1983). Figure 3 shows lake-level changes on the order of 1 meter, with submergence periods lasting for 5 to 10 years. The lake-level curves are compared in that diagram with sea-level curves for several coastal sites, illustrating the marked contrast in their magnitudes. In addition to the long-term trends of submergence and emergence, water levels on the Great Lakes also undergo annual cycles of 10s of centimeters, chiefly due to seasonal temperature differences.

This brief review has served to illustrate that there are many scales of water-level changes in the oceans and lakes. These are summarized in Figure 4, graphed as average amplitudes of water-level increases versus the time-scales of change (the corresponding rates are given in parentheses). For completeness and comparison purposes, approximate values have been plotted for average tidal cycles and for major storm surges. In considering potential impacts on coastlines, we have tended to focus on the long-term rise due to the melting of glaciers and thermal expansion of sea water. The associated eustatic rise has been estimated to be on the order of 1 to 2 mm/yr, but predictions suggest that it could increase to 5 to 30 mm/yr in the next century due to greenhouse warming. Whether those predictions come true or not, it has been seen that still higher rates have already been experienced due to established processes such as El Niño, seasonal and yearly fluctuations in sea levels, and variations in water levels in the Great Lakes.

THE COASTAL RESPONSE—GENERAL OBSERVATIONS

It is recognized, at least in general terms, that beaches and the overall coastal zone respond to the water-level changes discussed in the preceding section. The response to the long-term global rise in sea level due to melting of glaciers has been recognized primarily in the landward migration of barrier islands [see review by NUMMEDAL (1983)]. However, the response is not always simply one of a landward shift in the barrier island and a parallel retreat of the shoreline. Most barrier islands have accreted vertically during the past several thousand years, keeping pace with the increase in sea level. In a few of those examples, there has been some seaward advance of the ocean shoreline in spite of the sea-level rise. Important is the sediment availability, the overall budget of sediments. With a sufficient supply of sediments having appropriate sizes for the littoral zone, beach accretion can prevail over modest rates of sea-level rise.

The retreat of the shore due to a long-term increase in sea level is episodic rather than continuous. It depends on sediment movements produced by storm waves, and on associated processes such as storm surges and the creation of new inlets. Therefore, any satisfactory understanding of the long-term response of beaches to sea-level changes must come from the accumulated knowledge of nearshore processes including waves, currents and sediment

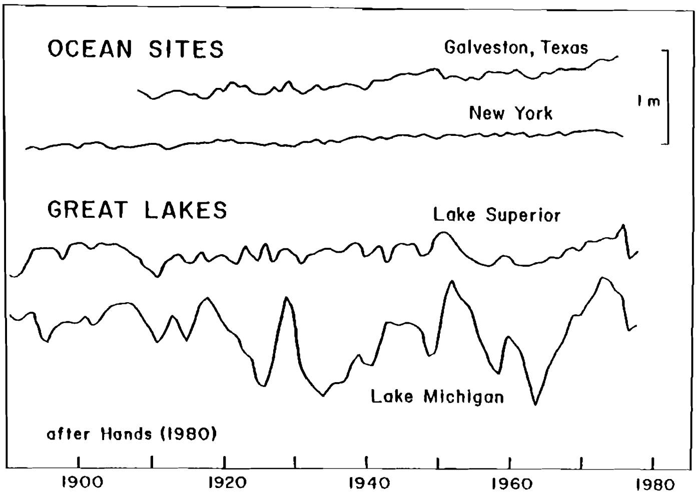


Figure 3. Annual mean water levels in the Great Lakes of North America, compared with sea-level variations for the same period at representative coastal sites. [*from* Hands (1980)].

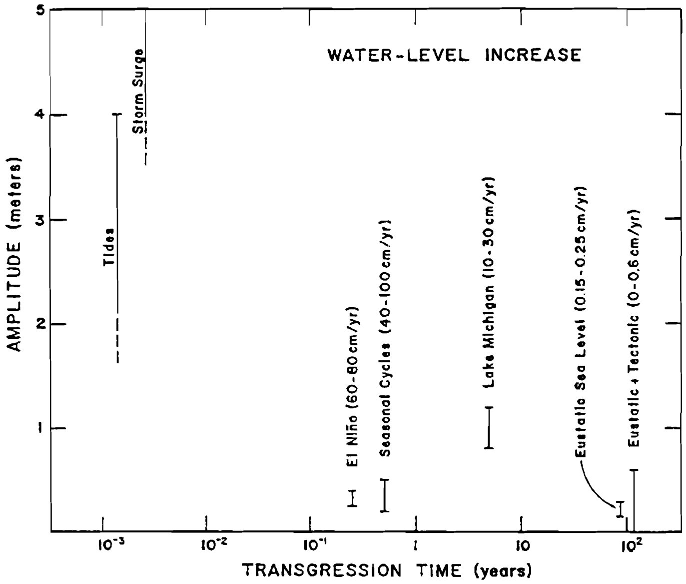


Figure 4. Average amplitudes of water-level increases versus their time scales of development. The long-term global rise associated with glacial melting is given as the change within 100 years, even though it can persist for much longer.

transport. This dependence on shorter-term processes introduces questions related to response times of the beach to a water-level increase. It can be expected that many storms will occur during the decades to centuries involved in the response of the coast to the global rise in sea level. Although the associated erosion would be episodic, the response of the beach should keep pace with the rising water level (and with the long-term budget of sediments). However, it is less clear that the coastal response rate will be sufficient to keep pace with shorter-term variations in sea level. For example, the water-level rise associated with the 1982-83 El Niño spanned only a few months. Although significant erosion resulted from the accompanying increased intensity of storm waves, it is uncertain that the beaches actually responded to the enhanced water levels to a sufficient extent that they achieved a new quasi-equilibrium. It will be seen in subsequent sections that the response time of beaches to changing water levels, the lag interval, is an important factor in testing theoretical models that predict beach responses.

BEACH RESPONSE MODELS—THEORY

The first and best-known model relating shoreline retreat to an increase in local sea level is that proposed by BRUUN (1962). BRUUN (1988) provides a recent rederivation as well as a discussion of the assumptions involved in the model and its uses and misuses. The analysis by Bruun assumes that with a rise in sea level, the equilibrium profile of the beach and shallow offshore moves upward and landward. The net change for a simple concave profile is illustrated in Figure 5A. The analysis is two-dimensional, and assumes: (1) the upper beach is eroded due to the landward translation of the profile; (2) the material eroded from the upper beach is transported immediately offshore and deposited, such that the volume eroded is equal to the volume deposited; and (3) the rise in the nearshore bottom as a result of this deposition is equal to the rise in sea level, thus maintaining a constant water depth in the offshore. Following these assumptions, Bruun derived the basic relationship for the shoreline retreat rate, R, due to an increase in sea level, S:

$$R = \frac{L_*}{B + h_*}S \tag{1}$$

where L_* is the cross-shore distance to the water depth h_* taken by Bruun as the depth to which nearshore sediments exist (as opposed to finer-grained continental shelf sediments). Those parameters are illustrated in Figure 5A where it is apparent that the depth h_* is that required to insure sediment continuity, that the two-dimensional volume of sand deposited in the offshore equals the eroded volume from the upper portion of the beach profile. The vertical dimension B in equation (1) represents the berm height or other elevation estimate of the eroded area. It is apparent that the relationship can also be expressed as

$$R = \frac{1}{\tan\theta}S \tag{2}$$

where $\tan\theta \approx (B + h_*)/L_*$ is the average slope of the nearshore along the cross-shore width L_*. In that $\tan\theta \approx 0.01$ to 0.02 for many coastal sites, equation (2) gives $R = 50S$ to $100S$, proportionalities that are commonly used as a "rule of thumb." The results demonstrate that a small increase in sea level (S) is predicted to cause a substantial shoreline retreat (R).

The derivation of equation (1) is best approached by successive translations of the beach profile as illustrated in Figure 5B, first vertically by the distance S and then horizontally by the distance R to the point where the erosion represented by this horizontal movement equals the deposition required by the vertical translation. The volume per unit shoreline length represented by the vertical shift is L_*S, while that of the horizontal movement is $(B + h_*)R$. Equating these two volumes to insure continuity of sediment volume yields equation (1). This derivation ignores the cross-over point of the zones of offshore deposition versus onshore erosion, so that equations (1) and (2) contain no direct dependence on what would seem to be a critical depth and offshore distance. In some respects this is an advantage. It turns out that equations (1) and (2) hold irrespective of the shape of the beach profile, for example whether bars are present or not (ALLISON and SCHWARTZ, 1981). The shift of a profile with multiple bars is illustrated in Figure 6, which shows that there could be alternating zones of erosion and

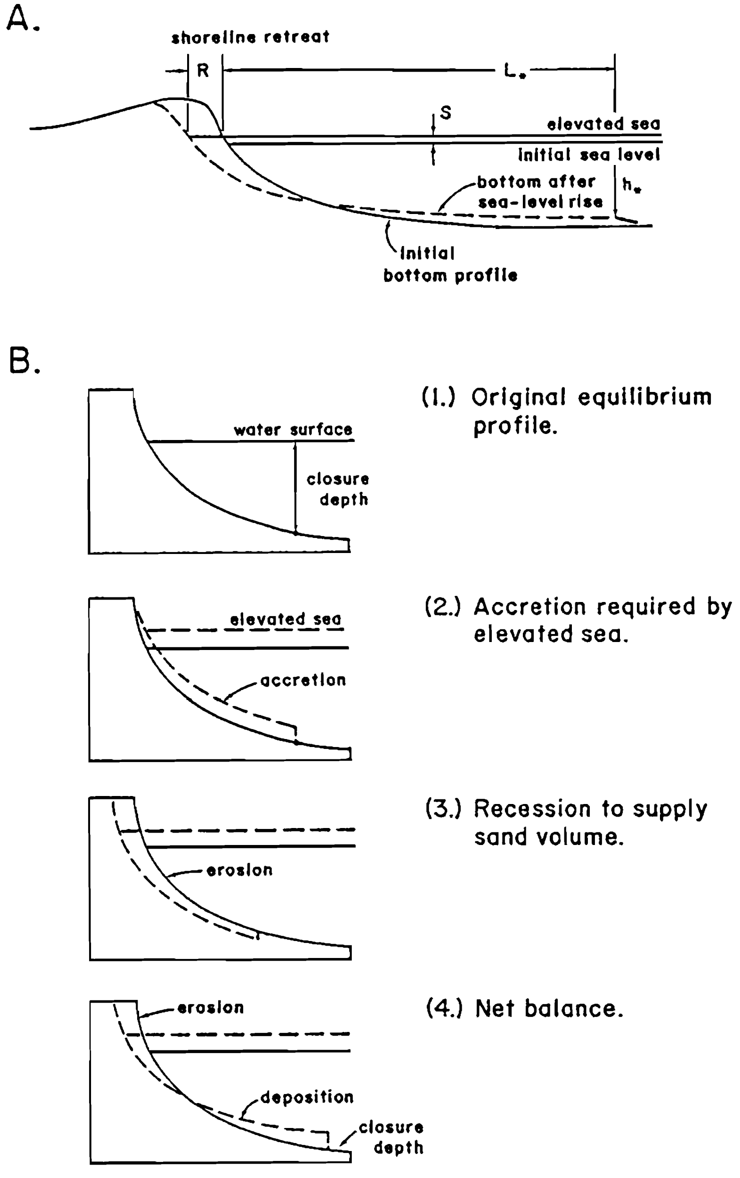


Figure 5. A. The net change in beach-profile position due to a rise in sea level, S, according to the Bruun model, resulting in a zone of offshore deposition and erosion of the upper beach, with an overall recession rate, R. B. Analysis leading to the Bruun rule, equation (1), initially involving an upward translation of the profile by the amount S, followed by its landward translation by the amount R.

accretion associated with bar migration in response to an increase in sea level—hence, there could be several depths and offshore distances of erosion versus deposition rather than the single critical point as illustrated in Bruun's simple concave profile (Figure 5A). Of importance is that the depth h_* and offshore distance L_* incorporate the entire nearshore zone so that conservation of sediment is maintained in spite of the complexity of local erosion versus

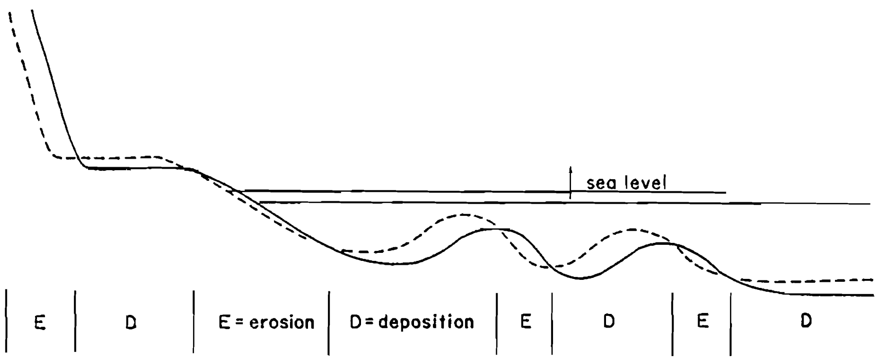


Figure 6. Alternating zones of erosion and accretion produced by the upward and landward shift of a profile having multiple bars.

deposition. Equations (1) and (2) also hold for the simple inundation of a coastline due to a rise in sea level, for example on a noneroding rocky shore of regional slope tanθ—this further illustrates the insensitivity of these relationships to the details of the profile, as well as to the nearshore processes.

Schwartz (1967) has proposed that this model of beach erosion be known as the "Bruun rule." Here we will use that term in direct reference to equations (1) and (2), as distinguished from the "Bruun model" which refers to his basic assumptions of nearshore changes resulting from an increase in sea level.

Dubois (1977) attempted to modify the Bruun model so as to better correspond to observed zones of beach-profile erosion versus deposition. The zone of erosion mainly involved an evenly-sloping beach face, Figure 7, while deposition occurred over the landward side of the offshore bar and intervening trough. The pattern corresponded with profile changes observed by Dubois (1975, 1976) in Lake Michigan. His attempt to test the Bruun rule and model with data collected from Lake Michigan will be discussed later. With respect to his suggested changes to the basic Bruun model, Dean and Maurmeyer (1983) concluded that they were already inherently present though not explicitly stated. This is apparent when one compares the shift in a multiple-bar profile, depicted in Figure 6, versus that proposed by Dubois in Figure 7. More specifically objectionable is the use by Dubois of θ as "the angle of the nearshore slope seaward from breaking waves," basically the lakeward face of the inner bar. Dean and Maurmeyer have criticized this choice, noting that in the derivation θ is clearly the average

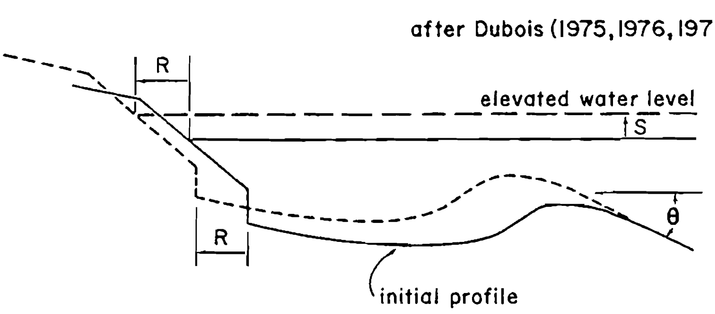


Figure 7. Proposed modification of the Bruun model by Dubois (1975, 1976, 1977) wherein erosion of the beach face due to rising water levels is balanced by deposition on the landward side of the offshore bar.

slope (= effective vertical dimension of the active profile divided by its effective horizontal dimension).

DEAN and MAURMEYER (1983) have generalized the Bruun rule to account for the landward and upward migration of an entire barrier-island system. This is depicted in Figure 8, where it is assumed that the barrier island accretes vertically at the same rate as the rise in sea level. The resulting derived relationship, with minor corrections (DEAN, 1991), is

$$R = \frac{L_{*o} + W + L_{*L}}{(h_{*o} - h_{*L})} S \qquad (3)$$

where L_{*o} and L_{*L} represent the widths of the active nearshore zones on the ocean and lagoon sides, and h_{*o} and h_{*L} are the associated water depths. W is the width of the barrier island, Figure 8, which is considered to remain constant in time. This equation reduces to the basic Bruun rule, equation (1), for the case of no deposition on the barrier island or in the lagoon (*i.e.*, when W, L_{*L} and $h_{*L} = 0$). Equation (3) for the entire barrier-island system always predicts a greater retreat rate R than does the Bruun rule. This is because sand is added to the island to maintain its vertical position relative to sea level, and also to the lagoon side to maintain its width. Furthermore, the net vertical dimension $h_{*o} - h_{*L}$ contributing sand during the island retreat is reduced compared with the Bruun rule which considers h_{*o} alone, also leading to a higher calculated retreat, R.

Several models have been developed for predicting the erosion of dunes or sediment bluffs during storms. These generally include the effects of a rise in water level associated with a storm surge, and accordingly are conceptually similar to the Bruun model. EDELMAN (1968, 1972) formulated a model for dune erosion based on numerous surveys of pre- and post-storm beach profiles along the coast of The Netherlands. His model is shown schematically in Figure 9A where sand eroded from the dunes is deposited as a wedge on the beach. The similarity to the Bruun model is apparent if one replaces the storm tide with a net sea-level rise. Edelman concluded that the equilibrium profile relative to the instantaneous sea level was approximately a constant and represented by a uniform slope that depends on sediment characteristics. He considered the depth of effective motion to be given by the wave-breaking depth. Assuming an idealized profile in which the dunes are represented by a vertical face and uniform crest elevation, Edelman developed generalized graphs that relate dune recession to the storm-tide water-level change (Figure 9B). This analysis approach has been improved upon by GRAAFF (1977) and VELLINGA (1982), based on results from large-scale wave-tank tests. While remaining conceptually similar to the model of Edelman as diagramed in Figure 9, Graff and Vellinga derived revised relationships for evaluating the shapes of beach profiles and for establishing depths of effective sediment motion.

DEAN (1982) has developed a series of beach-response models based on the beach-profile relationship $h(x) = Ax^{2/3}$ where h is the water depth at the offshore distance x [see summary in DEAN and MAURMEYER (1983)]. This relationship has been shown to agree reasonably well with natural profiles, where A is a scale factor

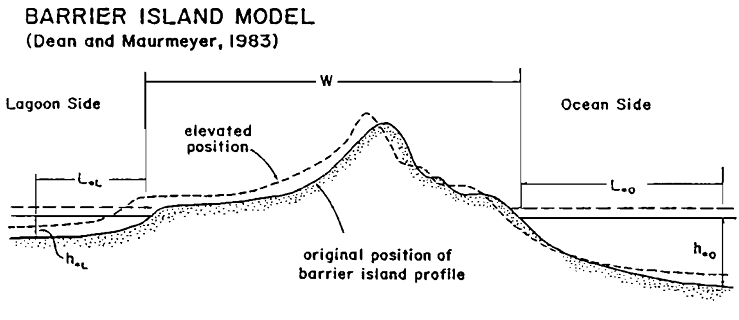


Figure 8. Model by Dean and Maurmeyer (1983) to account for the response of an entire barrier island system to a rise in sea level.

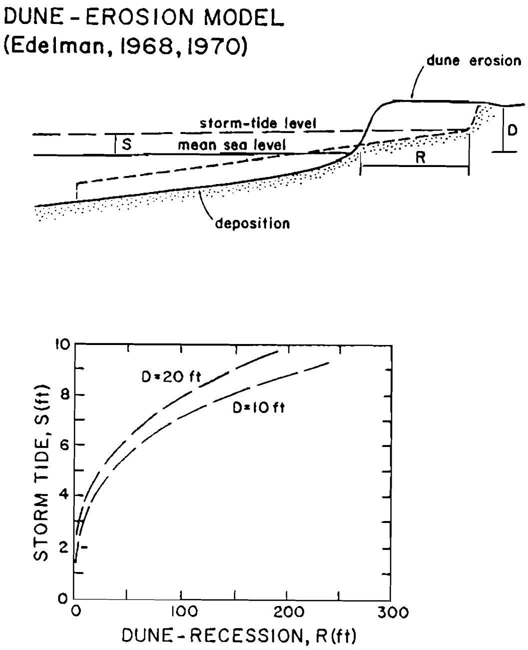


Figure 9. A. Conceptual basis of the dune-erosion model of Edelman (1968, 1970). B. Predictive curves for a specific example, relating the dune recession rate to the storm-tide elevation.

that depends primarily on sediment characteristics. Its chief failing occurs at the shoreline $(x = 0)$ where it predicts a profile slope $dh/dx = \infty$. Figure 10 illustrates the recession rate derived by Dean, expressed in dimensionless form, as a function of the storm-tide level and storm-wave breaker depth. Dean also provides a modified analysis to account for the presence of a seawall. In all of the analyses, there is again a balance between the volume of sand eroded from the upper beach and that deposited in the shallow offshore.

KRIEBEL and DEAN (1985) have developed a model that includes a computational procedure for predicting beach and dune erosion during severe storms and elevated water levels. As presented by Kriebel and Dean the analysis utilized the $h(x) = Ax^{2/3}$ equilibrium profile, but the most recent developments employ a modified profile having a uniform beachface slope within the inner surf zone (KRIEBEL, 1990). Their models represent a conceptual advance in that they include evaluations of cross-shore sediment transport due to the disequilibrium of wave-energy dissipation produced by the storm and higher water levels. The transport equation together with a relationship for sediment continuity are solved numerically to predict the time-dependent, two-dimensional beach and dune erosion. Since the analysis considers sediment-transport processes, the models can account for time variations in wave heights and water levels, and therefore can be used to examine response times of beaches. The models predict, for example, that for the same forcing conditions, beaches composed of fine sand respond with longer time scales and erode greater distances than do beaches formed of coarse sand. The results indicate that time scales of natural beaches may be on the order of 10 to 100 hours for storm conditions, and on the order of 1,000 to 10,000 hours when the effective limit of sediment motion is far offshore, as would be the case for erosion induced by a sea-level rise. The lag of the profile response can, therefore, be significant and in general results in the actual erosion during a storm surge being only 15 to 30% of the potential erosion predicted by equilibrium models based on simple shifts of beach profiles.

All of the above analyses are two dimensional treatments that conserve the quantity of sand within the cross-shore profile. The investigators were aware of this assumption, and most provide some discussion of potential longshore movements of sand that might affect the cross-shore balance. Such a consideration involves the development of a budget of sediment for the beach section being analyzed, with various potential sand gains and losses that can alter the total sand volume within the profile. The barrier-island model of DEAN and MAURMEYER (1983), discussed above, has already introduced two-dimensional components of the sediment budget in having accounted for island overwash and inlet processes removing sediments from the ocean beach. Considering the third dimension in the longshore, HANDS (1980, 1983) produced a modified Bruun rule that can be written as

$$R = \frac{L_* F_A}{B + h_*} S + \frac{\Sigma Q_S}{Y(B + h_*)} \qquad (4)$$

where $F_A > 1$ is the "overfill ratio," a factor to account for cases where some of the eroded shore deposits are too fine-grained to remain in the littoral zone (so that more erosion R is

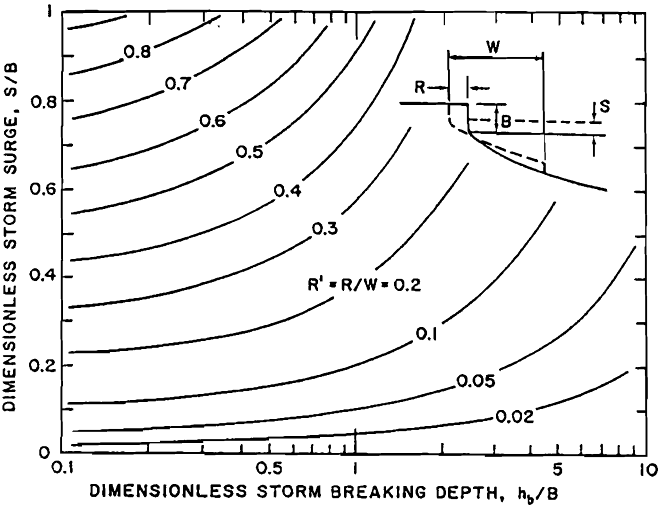


Figure 10. Model developed by Dean (1982) for the erosion induced by a storm tide. The solution is in dimensionless terms.

needed to maintain the offshore deposition). The second expression on the right of equation (4) accounts for a net longshore movement of sediment, ΣQ_s, out of or into the control volume of longshore length Y. DEAN and MAURMEYER (1983) have made comparable adjustments to the Bruun rule, expressing it as

$$R = \frac{L_*}{P(B + h_*)} S + \frac{(\partial Q_S/\partial y)\Delta t}{(B + h_*)} \qquad (5)$$

where P is the decimal fraction of eroded material that is compatible with the surf-zone sediment (the inverse of F_A in equation 4) and $\partial Q_S/\partial y$ is the longshore gradient of the littoral drift ($\partial Q_S/\partial y > 0$ indicates increasing transport in the longshore direction, which produces erosion and hence an increase in R beyond that due to a sea-level increase).

In more general terms, the relationship can be expressed as a complete budget of sediments,

$$P(B + h_*)R = L_*S + G_B \qquad (6)$$

where the left side of the equation evaluates the quantity of littoral sediment derived from shoreline recession (R), the term L_*S is the quantity required to maintain the equilibrium profile relative to a sea-level rise (S), and G_B are sediment-budget terms including contributions from rivers or the offshore, losses due to sediment being blown inland or transported offshore, as well as the longshore gradient of the littoral drift ($\partial Q_S/\partial y$) that was included in equation (5). Expressed as equation (6), it becomes apparent that in predictions of the shoreline recession R, it is extremely important to consider the G_B sediment-budget terms in that they will commonly be large in comparison with L_*S which tends to be small due to the low rates, S, of sea-level rise. This will be important both in testing the Bruun rule and related models summarized in this section, and in applications of those models to specific coastal sites.

DISCUSSION OF MODEL CONCEPTS

There are aspects of the models requiring brief discussion before we examine the studies that have attempted field or laboratory tests. The first is the development of a discontinuity in the offshore limit of the profile when it is translated upward and landward under a rising sea. This profile discontinuity is apparent in most of the figures illustrating the models (Figures 5, 6, 8, 9 and 10). BRUUN (1962) originally explained this discontinuity as the transition between nearshore sediments and deeper-water continental shelf sediments. Inherent in this division is the relative importance of sediment-transport processes and how they change with depth and distance offshore. The nearshore zone is viewed as dominated by surface waves producing cross-shore sediment movements and accompanying profile adjustments. Important to the models is the conservation of sand within the nearshore zone, with the net erosion close to the shore being balanced by deposition in the shallow offshore. The models tend to ignore the deeper offshore, the zone dominated by shelf currents. The assumption is that deposition on the shelf, principally of finer-grained sediments, will occur independently of sediment movements in the nearshore, but will have the overall effect of eliminating the profile discontinuity generated by the models.

Several studies have dealt with offshore limits of the models through considerations of closure depths of profile changes. This is illustrated in Figure 11 for a series of beach profiles from the east shore of Lake Michigan (HANDS, 1980), showing a wide envelope of profile changes in the shallower water of the nearshore but pinching out in the offshore. This defines the closure depth, and has been assumed to represent h* in the Bruun model (Figure 5) and that developed by DEAN and MAURMEYER (1983) (Figure 8). It might seem logical to equate this closure depth in the envelope of nearshore profiles to the water depth at which waves can entrain the bottom sediment. In some instances this assumption is probably reasonable, but at many locations it clearly is not. Oscillatory ripple marks generated by surface waves have been observed on the interface of continental-shelf sands to depths of 100 m, and as great as 200 m during storms (KOMAR, *et al.*, 1972), well beyond any reasonable closure depth of nearshore profile changes. The analysis procedures developed by HALLERMEIER (1981) and modified by BIRKEMEIER (1985), relating wave and sediment conditions to profile zonation, appear to provide a satisfactory methodology for selecting the closure depth. However, its evaluation is not necessarily critical to tests of the Bruun rule, equation (1), and in its potential applications. Identification of the closure depth determines the values of L_* (offshore distance) and h_* (depth). But these quantities are offsetting such that if h_* is overestimated, L_* will be overestimated in roughly the same proportion. This is apparent if we examine the equivalent equation (2) in terms of the average slope angle, θ. In testing or applying the Bruun rule, critical is the overall slope θ rather than some specific offshore depth. However, if the examination focuses more on the assumptions involved in the model, as opposed to a simple test of equa-

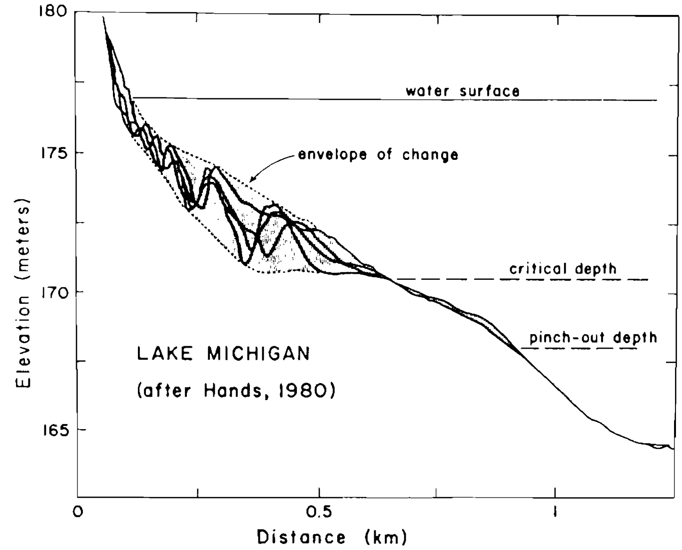


Figure 11. Envelopes of beach-profile variations on the eastern shore of Lake Michigan [Hands, 1980].

tion (1), then it would be important to evaluate the depth to which the nearshore sediments are shifted offshore during a rise in sea level, as well as evaluating the critical depth(s) in the transition(s) from onshore erosion versus offshore deposition.

A basic assumption of the models is the existence of an equilibrium beach profile, and that this profile is maintained or eventually achieved following a change in water level. It is clear from the derivations and accompanying discussions that the focus is a long-term equilibrium that recognizes the occurrence of seasonal, storm, or other temporary profile fluctuations. Furthermore, as noted in the previous section in connection with the derivation of the Bruun equation (1), the precise configuration of the profile is irrelevant so long as it is maintained as the water level changes. This assumption of maintenance of an equilibrium profile would appear to be necessary, first to permit derivations of equations relating shoreline recession rates to water-level changes, but also to prevent the nearshore profiles from becoming progressively steeper or achieving unreasonably low gradients. However, such progressive changes in profile gradients cannot be ruled out—for example, the series of profiles from Smith Island, Virginia, determined by EVERTS (1985, Figure 4), show progressive reductions in nearshore gradients as the island has eroded since 1852. A related uncertainty that could be critical is the response time of the beach profile to changes in water levels. If the water-level increase is rapid, such as occurs during an El Niño or is experienced in the Great Lakes, then the response of the beach profile may be too slow to maintain equilibrium. As will be seen in the next section, this is one factor that makes it difficult to test the models and especially the predictive equations.

FIELD AND LABORATORY TESTS

Nearly all studies involving data collection to test models relating shoreline erosion to a sea-level increase have focused on the Bruun rule. The first tests involved laboratory wave-basin investigations conducted by SCHWARTZ (1965), with additional results reported in SCHWARTZ (1967). Both studies involved small-scale basins (respectively 81 × 115 cm and 100 × 232 cm) and waves (periods 0.33, 0.75 and 1.25 sec; maximum heights of 3 cm). Sand with an average diameter of approximately 0.2 mm was used. The tests consisted of generating waves until an equilibrium profile developed, followed by an increase in water level and a renewal of wave activity until a new equilibrium was achieved. Water-level increases ranged from 1 to 6 cm. For the most part, the observations were qualitative. It was found that with a rise in water level, there is a shoreward displacement of the entire beach profile, with the upper beach eroding while deposition occurred on the adjacent offshore bottom. These changes conform with the profile modifications hypothesized by BRUUN (1962). The only quantitative measurements made by Schwartz were of the thickness of sand accumulation in the offshore and the change in water depth in that region. It was found that the thickness of sand accumulation equalled the increased water level, so that water depths in the shallow offshore remained constant. This again agrees with the basic premise of the Bruun model. In these tests, Schwartz did not attempt to substantiate the Bruun rule, the prediction of shoreline recession with equation (1).

In addition to the laboratory experiments, SCHWARTZ (1967) collected field data from two beaches on Cape Cod, Massachusetts. The hypothesis was that the beach profiles would change during the period between neap and spring tidal ranges, and that the response would be comparable to those induced by variations in mean sea levels. This assumption is questionable, so there are immediate uncertainties as to whether the study actually provided a test of the Bruun model. Five profiles were obtained at each field site, including three during spring tides and two at neap tides. Schwartz concluded that "a recognizable upward and landward translation of the profile was noted in the intervals between neap and spring tides." However, the series of profiles reveal that landward translation also occurred during some intervals between spring and neap tides, opposite to that thought by Schwartz to conform with the Bruun model. Therefore, there are both conceptual and observational uncertainties regarding the field investigations conducted by Schwartz, so that conclusions with respect to the validity of the Bruun model are questionable.

DUBOIS (1975) reported on a field study at

Terry Andrae State Park on the western shore of Lake Michigan. The characteristics of two beach profiles were measured on a weekly basis over a 35-week period during which the mean lake level increased by approximately 0.3 m as part of the normal seasonal cycle. It was found that the shoreline recession due to that rise amounted to 7.0 m, of which 1.8 m were attributed by Dubois as being due to the direct effect of inundation of the sloped profile. Dubois undertook a correlation analysis between the water-level increase and wave conditions, versus various features of the two profiles. It was found that elements of the beach profiles, such as the base of the foreshore slope and the crest elevation of the inner bar, maintained their positions relative to the rising water level, moving both landward and upward. Dubois concluded that this provided a qualitative validation of the Bruun model of profile shifts under a rising sea. This conclusion has been criticized by ROSEN (1977), who noted that other studies of bar movement in the Great Lakes found that the inner bar actively shifts position in response to changing wave conditions, a factor largely ignored by Dubois. Rosen also raised questions concerning the expected response time of the beach profiles to a change in mean water level, a response time that appears to span at least several months in the Great Lakes. This slow response time may have been reflected in the movement of the outer bar, which according to the profile measurements of Dubois, shifted landward with a rise in lake level but did not correspondingly move upward. Rosen argued that verification of the Bruun model should have included consideration of the complete barred profile, not simply the inner bar and foreshore. In a subsequent analysis, DUBOIS (1977) used the same field data in an attempt to provide a quantitative verification of the Bruun rule in the form of equation (2). However, Dubois took θ as the angle of the lakeward slope of the inner bar. As noted above, DEAN and MAURMEYER (1983) have criticized this choice, indicating that in the derivation θ is clearly the average slope. In summary, the main contribution of the studies by Dubois relevant to the Bruun model is the partial confirmation that, with a rise in water level, the beach profile does tend to shift landward while maintaining something of an equilibrium form. The study also served to focus attention on the potential problems involved in response times of the beach and to the selection of parameters such as θ and offshore distances for application of the Bruun rule.

ROSEN (1978) evaluated the Bruun rule as a predictor of shoreline recession along the Virginia coast of the lower Chesapeake Bay. Within that 336-km length of shoreline there is a considerable variation in sea-level rise recorded from tide gauges, ranging from -0.46 to $+5.43$ mm/yr. The break in offshore slope at a depth of 3.6 m was used to define the width of the beach profile and depth of effective sediment motion. A total of 146 beach units were included in the evaluation, but these were combined by county (10) and then into the eastern versus the western shore, and finally for the bay as a whole. For the entire bay, the measured erosion differed by only 3% from that predicted by Bruun's equation (1) for a 100-year time span. However, on the eastern shore the difference was +58% and on the western shore it was −7% (the + percentage indicates that the predicted erosion exceeded the measured). Individual counties ranged from +224% to −68%, but Rosen noted that such extreme differences between predicted and measured rates resulted in many instances from the presence of marshes along the shoreline.

The results from the study of ROSEN (1978) demonstrate that the Bruun rule, equations (1) and (2), can be seriously in error when used for site-specific estimates. The approximate agreement between predicted and measured rates, when averaged for the bay as a whole, might be taken to indicate that the Bruun rule can be applied on a more regional than site-specific basis. However, the results from other studies demonstrate that this is not necessarily the case. The graph in Figure 12 from DEAN (1990) shows state-wide averaged erosion rates measured by DOLAN *et al.* (1983) versus the average sea-level rise determined from tide-gauges within the boundaries of the state. The data scatter is large, and accretion is found in three states (New York, Delaware and Georgia) even though relative sea level has been rising. The "rule of thumb" proportionalities $R = 50S$ and $R = 100S$ from the Bruun rule are seen to be poor predictors of state-wide erosion. This suggests that the agreement (within 3%) found by ROSEN (1978) in Chesapeake Bay as a whole, was likely fortuitous. It is uncertain what

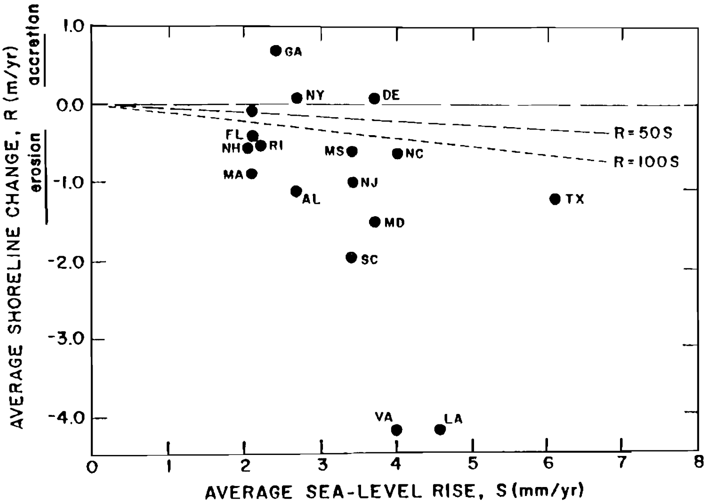


Figure 12. State-wide shoreline-change rates versus average local sea-level changes for the east coast and Gulf coast of the United States [Dean (1990)].

causes the large scatter seen in Figure 12, and the poor predictive capability of the Bruun rule in state-wide comparisons. It likely results from the other factors in the overall budget of sediments, the G_B terms of equation (6). These could create considerable variability in shoreline changes beyond those predicted as a response to an increase in sea level, and would account for net accretion in spite of the sea-level rise as found in New York, Delaware and Georgia. It might have been expected that in considering a broad area rather than being site specific, the G_B terms would have tended to cancel or would at least be reduced so that they no longer overwhelm the L_*S sea-level term in equation (6). However, the data scatter in Figure 12 suggests that the G_B sediment budget terms remain important even when grouping regional data.

EVERTS (1985) has made the most concerted effort to account for the sediment-budget terms in a study of shoreline recession along Smith Island, Virginia, and along the barrier islands of North Carolina. On Smith Island, sediment moves landward from the littoral zone by overwash and ephemeral inlet processes, and significant volumes of sand are removed from the island due to longshore transport. It was found that such sediment-budget factors account for 47% of the shore retreat, with the remainder attributed to the sea-level increase. Having made sediment-budget corrections, the calculated shoreline recession due to sea level (-5.5 m/yr) was almost exactly the same as the actual change (-5.6 m/yr). However, a similar analysis for the North Carolina barrier islands found that the predicted shoreline change (-1.7 m/yr) is about 121% of the measured rate. Even with that amount of disagreement, it is apparent that inclusion of the overall budget of sediments permits improved comparisons between predicted and measured shoreline recession rates.

The study of PILKEY and DAVIS (1987) also compared measured recession rates along the North Carolina barrier islands with the predictive models, those of BRUUN (1962), EDELMAN (1972) and DEAN and MAURMEYER (1983). Overall, the measured recession values had minimal correspondence with the rates predicted by the models. Of special interest in the study of Pilkey and Davis was their consideration of the choice of θ to be used in the predictive models. Figure 13 from their study, showing the reaches over which the various migration slopes might be averaged, illustrates the potential θ selections. The narrow range C would be applicable to the original Bruun rule in that it covers only

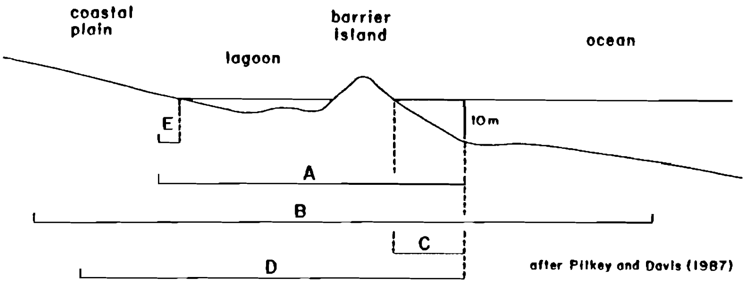


Figure 13. A diagrammatic cross section of the lower coastal plain and barrier-island system, showing the reaches over which the various migration slopes and associated angle θ in the BRUUN-rule relationship, equation (2), might potentially be evaluated [Pilkey and Davis (1987)].

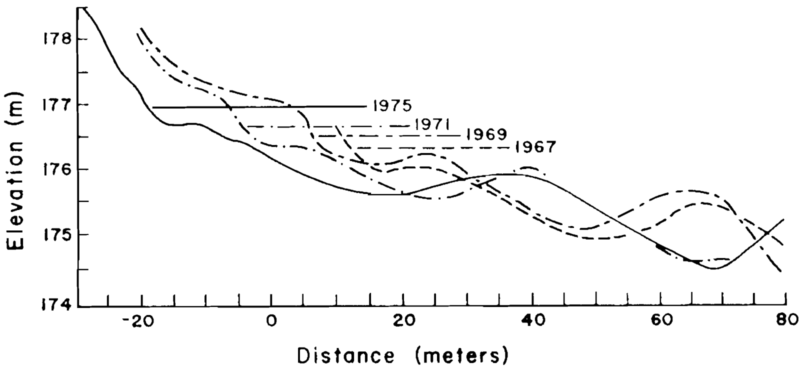
the shoreface zone. This would appear to be appropriate if the erosion was in response to only a small increment of sea-level rise and was confined to this shoreface zone. On the other hand, if the migration of the complete barrier island system is considered, as in the model of Dean and Maurmeyer, then the horizontal ranges A, B or D would be more appropriate. Any of these ranges would yield a substantially lower θ migration angle than does the C range, and accordingly would yield much higher predicted shoreline recession rates than obtained with the Bruun rule. Unfortunately, the scatter of the measured recession rates determined by Pilkey and Davis was sufficiently great that comparisons with the model predictions did not result in conclusions as to the best choice of a migration slope and θ value.

The study undertaken by HANDS (1979, 1980, 1983) utilized the long-term water-level variations in Lake Michigan (Figure 3) to investigate beach responses. Twenty-five beach profiles spread over 50 km of shore were monitored for 8 years. Four of the survey series occurred during a period of increasing lake levels, while the last two took place during declining levels. The maximum water-level change between surveys was 0.39 m. Figure 14 illustrates the observed profile changes. In keeping with the equilibrium assumption, the bars migrated landward and maintained a nearly constant depth beneath the gradually rising lake level. Due to the pronounced bars and troughs, the landward migration created shore-parallel bands of alternating erosion and deposition like those illustrated schematically in Figure 6. Hands did confirm that deposition balanced the erosion, verifying the conservation of sediment volume required by the model.

The observed shoreline retreat distances are compared in Figure 15A with those predicted by the Bruun rule, equation (1). The comparisons span three time intervals determined by surveys: 1969-1971, 1969-1975 and 1969-1976. The lake-level hydrograph for the study period is given in Figure 15B, which shows a gradual rise to a high stand during 1973-74, followed by a more rapid drop in lake level. The water levels in 1971, 1975 and 1976 were all higher than during the 1969 base survey, but the surveys of 1975 and 1976 occurred during the period of subsiding lake levels. It is seen in Figure 15A that the calculated shoreline retreats were substantially higher than those measured for the 1969-1971 and 1969-1975 comparisons, but good agreement was achieved for the 1969-1976 total span represented by the surveys. Hands noted that the shoreline recession rates had dramatically decreased as lake levels declined after 1974, and the beach prograded for the first time at 12 of 34 survey sites. Hands attributed the higher calculated than measured shoreline erosion to the profile retreat lagging behind the lake-level rise. By this interpretation, the rising water levels established a potential for erosion, but realization of that potential required cross-shore sediment redistributions that are dependent on storm-wave energy. The eventual convergence of measured and predicted retreat, 3 years after annual lake levels had peaked, suggested that several storm seasons may be required before beach profiles are able to adjust

LAKE MICHIGAN (after Hands, 1983)

A. Shore Retreat, 1967-1975



B. Shore Recovery, 1975-1976

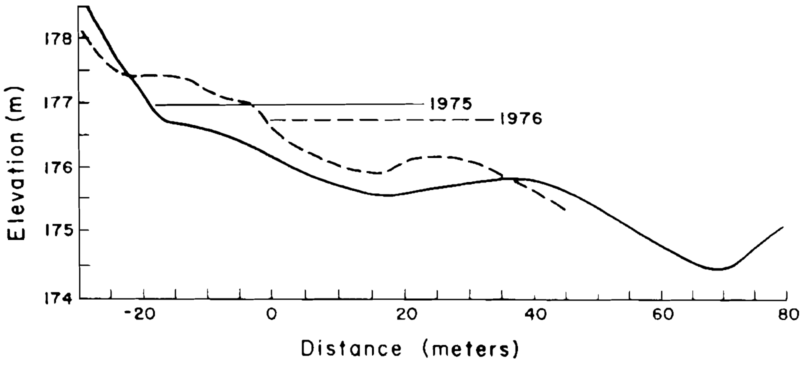


Figure 14. Measured profile adjustments on a Lake Michigan beach determined by Hands (1980, 1983), showing that the bars and shoreline shifted landward during a period of rising lake levels.

to significant changes in mean-water levels. Evidence for this lag is that shoreline recession persisted after the lake level peaked. Hands felt that the crucial proof of the Bruun rule and evidence of its usefulness lay in the 1976 final agreement between predicted and measured shoreline recession distances.

A lag time of the beach response as suggested by Hands (1979, 1980, 1983) likely does account for part of the disagreement between the measured recession and that predicted by the Bruun rule. The profile shifts on Lake Michigan beaches involve the migration of very large bars (Figure 14) with appreciable sand move-

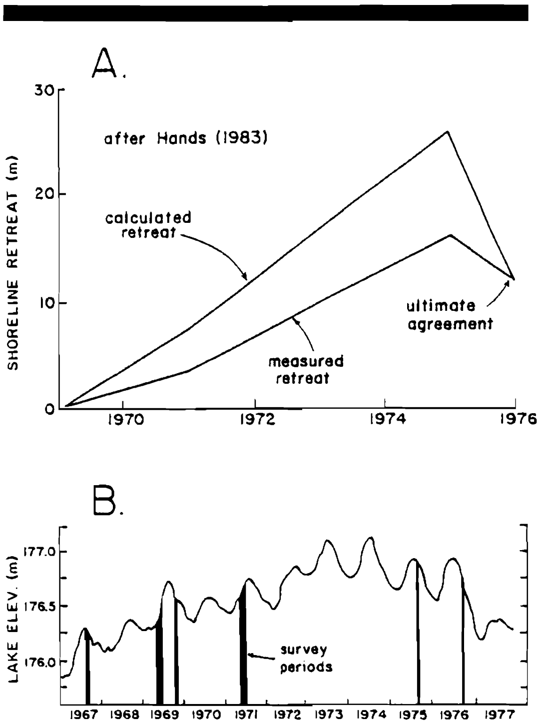


Figure 15. A. Calculated versus measured shoreline retreat distances determined by Hands (1980, 1983) on Lake Michigan beaches. B. Hydrograph showing lake-level changes and survey periods.

ments, occurring under limited wave-energy conditions. However, it is unclear whether a lag on the order of 3 years is reasonable, or whether part of the disagreement between the measured and computed recession distances represents a partial failure of the Bruun rule. The ultimate agreement, after 6 years of profile surveys, between the measured and computed distances is more likely to have resulted from the reduced lake levels in the last 2 years of the study than to any basic validity of the Bruun rule. It is probable that had the lake levels continued to rise during the time-frame of the study, the disagreement between measured recession and that predicted by the Bruun rule would have persisted, and might have continued to diverge as suggested by the trends seen in Figure 15A.

The most-recent investigations of beach responses on the Great Lakes due to elevated water levels are those reported by Weishar and Wood (1983) and Wood and Weishar (1984). A four-year set of profiles, measured at monthly intervals, was submitted to empirical eigenfunction analysis to determine time variations in morphology. It was found that the inner bar moves actively under the influence of waves, but lacks a well-defined seasonal or longer-term response to lake-level variations. In contrast, the outer bar and the beach-and-berm region exhibit migration patterns in direct response to lake levels as proposed by the Bruun model. No attempt was made to compare the beach recession with the erosion rate predicted by the Bruun rule, equation (1).

Another study that has examined long-term changes of beach profiles is that of Clarke and Eliot (1983) in western Australia. Although their study did not specifically address the Bruun rule or related models, the results obtained by Clarke and Eliot appeared to show, at least initially, a strong correlation between beach-width variations and sea-level fluctuations. The analyses involved a sixteen-year record of beach-width changes at six profiles measured monthly on Scarborough Beach, Perth. The measurements revealed a trend of long-term beach progradation, apparently resulting from littoral drift accumulation. However, a time-series analysis of the beach-width data identified cycles having periods of 0.5, 1.0, 3.5 and 7.0 years. Comparable periodicities were found in time-series analyses of sea levels measured on a nearby tide gauge. The annual cycles of each mode responded in an inverse manner such that a 1-cm rise in mean sea level corresponded to a 1-m decrease in beach width—this would conform with the Bruun rule, equation (2), if $\tan\theta = 0.01$ (*i.e.*, to the rule of thumb, $R = 100S$). It was found that the sea-level rise leads the beach-width retreat. For the 1-year cycle the lead time was about 2.6 months, while for the 3.5-year cycle the lead time was about 4 months. Unfortunately, this apparent demonstration of the beach response to fluctuations in sea levels was later brought into question through additional analyses reported by Clarke and Eliot (1987). It was found that the beach-width changes corresponded more closely to groundwater levels measured within the dunes backing the beach, than to sea levels. The groundwater level is a function of precipitation as well as sea-level variations. The annual oscillation of the groundwater table was found to be 180 degrees out of phase with the shoreline fluctuation, and the beach width responded to a three-year drought in the area. Although these latter analyses appear to have negated the earlier conclusions regarding the response of the beach to sea-level fluctuations, it is still worthwhile to consider these studies in reference to Bruun-type models. First of all, they demonstrate that long-term data obtained from monthly beach profiles are amenable to time-series analyses that could potentially demonstrate responses to sea-level fluctuations. On the other hand, the studies also serve to illustrate potential hazards in any long-term studies of natural beaches that might be undertaken to investigate the response to sea level changes. It is apparent that the full environment would have to be monitored, even groundwater levels.

Considerable attention has been devoted to verification of the storm-tide dune-erosion models summarized in the preceding section. These models tend to be semi-empirical, so that data collection and comparisons have been an integral part of their development. For example, the models of Edelman (1968, 1972) were based on empirical beach profiles measured following major storms on the coast of The Netherlands. It was observed that during a storm, the beach change is mainly a result of sand transport perpendicular to the shore, with erosion of the berm and dune, and deposition within the outer surf zone to the depth of the breaking waves. Using actual and idealized pre-storm profiles, Edelman established the known post-storm profile relative to the level of the peak storm surge, and then shifted the profile landward to conserve sand volumes. In being based on field measurements, while at the same time being conceptually similar to the Bruun model, the studies by Edelman provide at least partial confirmation of sediment-movement patterns predicted by the Bruun model. Graaff (1977) and Vellinga (1982) have provided additional confirmation of the dune-erosion models, and hence indirectly of the Bruun model, through a series of large-scale wave-tank tests. The results of a representative test are illustrated in Figure 16, an example that employed a time-varying storm surge level that simulated a major surge experienced on the coast of The Netherlands in 1953. It is seen in this example that the elevated water levels resulted in erosion of the dunes and retreat of the shore, with offshore transport and deposition of the sand.

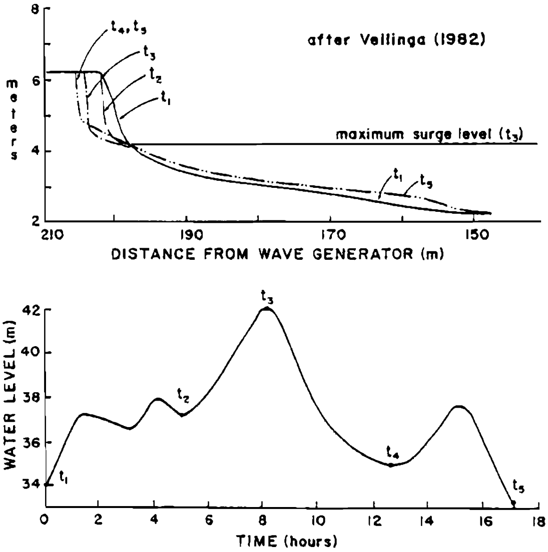


Figure 16. The erosion-profile development in a large-scale wave tank resulting from storm-surge elevated water levels. The water elevations employed in the model simulate those experienced during a major storm (1953) on the coast of The Netherlands [Vellinga (1982)].

As noted in the section on model development, the dune-erosion analysis of Kriebel and Dean (1985) and Kriebel (1990) incorporated an evaluation of the cross-shore sediment transport responsible for the profile changes. The model becomes semi-empirical in that the proportionality coefficient in that transport equation is calibrated by comparisons with measured profile changes. Kriebel and Dean compared their model with dune recession along the Florida coast resulting from Hurricane Eloise in 1975. Kriebel (1986) provided additional tests of a slightly modified model with data from large-scale wave basin experiments as well as more detailed comparisons with measured erosion during Hurricane Eloise. One comparison of profile changes during the hurricane with those predicted by the model is shown in Figure 17. The agreement is very good, the main difference being the presence of a small offshore bar in the observed post-storm profile, a recovery feature that may actually have formed following the storm but before profiling was undertaken.

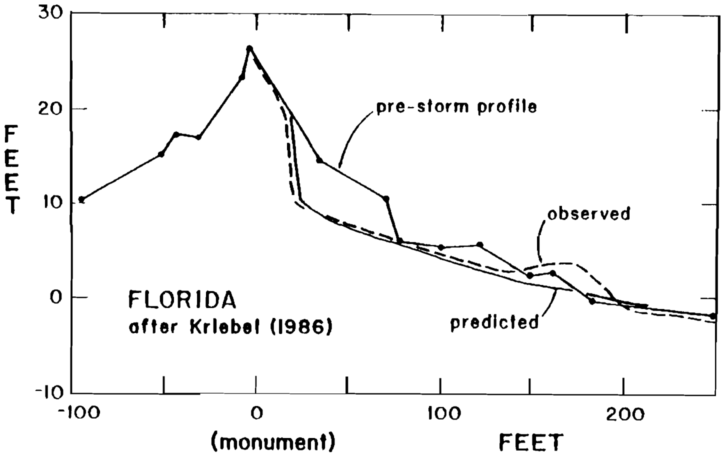


Figure 17. The dune erosion and profile development predicted by the storm-surge model of Kriebel and Dean (1985), compared with an actual erosion profile experienced on the Florida coast during Hurricane Eloise [Kriebel (1986)].

DISCUSSION OF MODEL TESTING AND APPLICATIONS

In assessing the status of research into the response of beaches to sea-level changes, it is best to differentiate between the models of sediment movement and accompanying profile changes versus predictive equations such as the Bruun rule, equation (1). The Bruun model, illustrated in Figure 5, involves the upward and landward translation of an equilibrium profile to maintain its position relative to the higher water level. The barrier island model of Dean and Maurmeyer (1983), Figure 8, and the storm-surge erosion models of Edelman (1968, 1972), Graaff (1977) and Vellinga (1982) are comparable in that they also involve geometric arguments of shifting profiles. There are clear inferences as to net sediment-transport patterns required to bring about the profile shifts, but little is said about the nature of the transport processes and their evaluations are not required in applications of the geometric models. This can be viewed as an advantage, considering how poorly we understand the processes of cross-shore sediment transport. On the other hand, it limits the flexibility of the models and in some applications could be a factor in erroneous assessments of coastal retreat. One major limitation noted in the above review is the inability of the geometric models to deal with any time lag of the beach response to an increase in water level. Without an assessment of the processes involved and the time required for sediment redistribution, geometric models such as that of Bruun can only predict the ultimate profile and extent of shoreline retreat expected for a specified rise in sea level. This may be satisfactory in assessing the expected shoreline retreat due to a long-term global rise in sea level, but limits its application in evaluations of the impact of shorter-term water-level increases such as those associated with an El Niño or in the Great Lakes. It is also an important factor in limiting our ability to adequately test the models over a reasonable time period, and especially of their predictive capabilities such as provided by the Bruun rule. This was demonstrated by the study of Hands (1979, 1980, 1983) on the Great Lakes where it appeared that a significant lag in beach response hindered comparisons between model predictions and measured shoreline recession rates. Such criticisms can be made of all of the models that are based solely on geometric arguments, those which do not incorporate considerations of sediment-transport processes.

The profile shift of the Bruun model requires that sediment be eroded from the upper beach, and from any dunes, sea cliffs, *etc.*, backing the beach (Figure 5). Considering for the moment only the two-dimensional aspects of the model, it infers that the eroded sediment is transported to the immediate offshore and deposited so as to maintain the profile relative to the rising sea. Several of the studies reviewed above offer confirmation of the profile adjustment assumed in the Bruun model. The general offshore shift of sand from the eroded upper beach and dunes, with deposition offshore, was found in the laboratory wave-flume experiments of SCHWARTZ (1965, 1967), GRAAFF (1977) and VELLINGA (1982). The studies by DUBOIS (1975, 1976, 1977), HANDS (1979, 1980, 1983) and WEISHAR and WOOD (1983) in Lake Michigan found a landward and upward shift of profile elements in response to elevated water levels, agreeing with the expected trends of the Bruun model, although the details of the erosion/deposition patterns were complex due to the multiple-bar profiles. Although these studies tended to confirm the assumptions made by Bruun and others concerning the upward and landward shift of the profile, they have been unable to convincingly demonstrate that the models can serve to predict shoreline recession rates. There are several reasons for this, including the apparent existence of a considerable lag time of the beach response behind the water-level rise, uncertainties in the selection of the parameters in the predictive equations (such as h_*, L_* and θ), and the local importance of sediment-budget G_B terms in the sand balance.

In spite of the guidelines offered by the studies of HALLERMEIER (1981) and BIRKEMEIER (1985) in selecting the offshore critical depth for closure of profile changes (h^* and L^*), enough uncertainty remains to hinder quantitative comparisons between measured recession rates and those predicted by relationships such as the Bruun rule. There is a similar uncertainty in the selection of the angle θ in equation (2), evident in the different ways studies have assessed its value. As stated in the simple proportionality of equation (2), with an inherent flexibility in how θ is selected, the relationship seems self-evident and almost certain of "proof" if the comparison between R and S spans a sufficient time to remove time lags in profile responses. Indeed, the best proof of equation (2) would come from a non-eroding rocky coast with a fixed θ regional slope, the relationship then being one of simple inundation. In that the derivations of equations (1) and (2) do not depend on the form of the beach profile, applications on sandy coasts still simply involve the migration of the nearshore zone or barrier-island complex up the regional slope (PILKEY and DAVIS, 1987). For such reasons, studies examining the validity of the Bruun model need to focus on the assumed shifts of the profile and inferred sediment movements, rather than simply involving attempts to confirm equations (1) and (2).

The study by ROSEN (1978) of R versus S in Chesapeake Bay further demonstrates problems inherent in field tests of the predictive equations, and in potential applications of those relationships. Extreme disagreement existed between predicted and measured recession rates for specific coastal sites, and reasonable agreement resulted for the Bruun rule only when the results for the entire region were averaged. However, DEAN (1990) found no clear relationship for R versus S when averaged on a state-wide basis. As noted earlier, the G_B sediment-budget terms of equation (6) can easily overwhelm the L_*S contribution to shoreline recession. Accordingly, the shoreline could very well advance in spite of a rise in sea level, as found for New York, Delaware and Georgia, due to sediment contributions from rivers, the offshore, from biogenic production, or from littoral drift accumulation. The problem in many field tests would be to evaluate the G_B terms with sufficient precision to permit their inclusion in equation (6). The study by EVERTS (1985) has demonstrated the importance of the G_B terms, and showed that if they are included, a more reasonable assessment of the shoreline response to a sea-level increase can be achieved. Unfortunately, the development of a full sediment budget for open coastlines is difficult. One solution might be to locate a study to test Bruun-type models in an isolated pocket beach where most of the G_B terms are absent, and those remaining are small. This would enhance the response of R to S alone. Alternatively, DEAN (1991) has suggested that a study of time variations in R would tend to eliminate the G_B terms, assuming that their changes with time are small. Using the subscripts 1 and 2 to denote successive time intervals, equation (6) can be written as

$$P(B + h_*)R_1 = L_*S_1 + G_B$$
$$P(B + h_*)R_2 = L_*S_2 + G_B$$

Subtraction yields

$$R_2 = R_1 + (S_2 - S_1)\frac{L_*}{P(B + h_*)} \qquad (7)$$

The "constant" G_B sediment-budget terms have dropped out of the equation. In requiring a change in the rate of water-level rise, $S_2 - S_1$, use of this approach to test the model would most effectively be applied in locations that experience reasonably rapid water-level fluctuations. In addition, there should be short lag times in profile responses since the derivation of equation (7) does not account for any lag. The relationship could also be used in applications to assess changes in the rate of shoreline recession that might occur in response to accelerated water-level increases such as those predicted for the next century.

The Bruun-type models focus in their derivations on a single profile, assuming continuity of sediment volumes which constitutes a local budget of sediments. The general factors in the sediment budget (river input, etc.) are included in the G_B terms of equation (6). However, if the testing or application of the models is restricted to one or only a few beach profiles, then relatively localized sediment shifts can also influence the results. For example, beach systems that include crescentic bars or rip-current embayments typically show marked longshore variations in beach profiles. If the testing is too restricted in longshore extent, then fluctuations due to shifting bars and rip currents will adversely affect comparisons and predictions (acting like localized G_B budget factors). Depending on the variability of the beach under investigation, it is important that a series of beach profiles be monitored and averaged in order to remove such effects.

Although there are many inherent difficulties in field investigations to detect beach responses to water-level changes, it is important that additional studies be undertaken. The research by CLARKE and ELIOT (1983, 1987) demonstrated that time-series analyses of a long-term series of beach profiles can detect cycles of beach-width variability, even though in their study it was uncertain whether the response was due to sea-level changes or to fluctuations in ground-water elevations. Their study in western Australia involved a beach location that was less than ideal in that marked shifts in the beach profiles occurred due to rip-current embayments and other processes, and there is a long-term accumulation of littoral drift. It might be expected that comparable studies at other coastal sites would be fruitful. This would require a long-term commitment, including the collection of weekly or monthly beach profiles over a significant length of shore, with the profiles extending to sufficient depths to reach the profile-envelope closure point. The wise selection of the study site(s) would enhance the expected return—a relatively simple system with small or known G_B sediment-budget terms, and a coastal site that has a large local rise in sea level due to subsidence plus a well-defined seasonal variability in water levels. It would also be preferable that the site have a moderately large wave-energy level so as to reduce response times of the beach profiles, but sufficiently low that wave conditions do not inhibit acquisition of the beach profiles. In addition to these long-term measurements, the site should become the focus for short-term studies into waves, currents and sediment movements so that the processes involved in profile changes are better understood and data are acquired that can serve as inputs to models that are process oriented. Several coastal sites are already being monitored for long-term profile changes and erosion assessments (Rhode Island and Florida in the U.S., Perth in Australia, Denmark, The Netherlands, the Nile-Delta coast of Egypt, and the southwest coast of India). It is important to continue these established series, although they should be reviewed to ensure their usefulness in future assessments of coastal responses to sea level. If possible, a uniformity of measurement techniques and data reporting should be established. It was the opinion of this committee that such a worldwide program would be enhanced if there were a central repository of the accumulated nearshore measurements, comparable to the role played by the Bidston Observatory in England for the collection of tide-gauge data.

Additional laboratory wave-flume experiments can also be expected to increase our understanding of the response of a beach to increased water levels. Since such experiments must necessarily be of short duration, they should focus mainly on the storm-surge erosion models, and especially on increasing our understanding of the physical processes involved in cross-shore transport and the beach response, and on time-lags between beach responses and changes in the forcing parameters. Although the storm-surge models differ somewhat from those developed for predicting the long-term response to sea-level changes, it is apparent that a better understanding of the former will contribute to our knowledge of expected beach changes resulting from a global increase in sea level.

In addition to the need for more field and laboratory research to better establish the response of beaches to a rise in sea level, there is a need for conceptual advances in the theoretical models. For example, the Bruun model is based on the assumption that with a rise in water level, the upper beach erodes and the sediment is transported to the immediate offshore where it is deposited. Arguing against this pattern of sand movement is the well-documented evidence that there must be a substantial onshore transport of sediment with a rise in sea level—beach sand compositions that result from offshore rather than landward sources, the existence of cross-shore grain-size variations, and the maintenance of an intact beach deposit during a transgression. Cross-shore sorting processes tend to concentrate the coarser grain sizes in the littoral zone, while moving finer grain sizes to the offshore. This sorting pattern should be maintained, even during a rise in sea level (so long as the rates are modest). The picture that emerges is that with a rise in sea level, there is a transgression of the beach deposit as a whole, involving a net onshore transport. Newly eroded material from sea cliffs, dunes, *etc.*, is processed by the nearshore waves and currents, with appropriate grain sizes retained in the nearshore while fine material is transported offshore. Depending on the balance of grain sizes derived from the eroded materials, it is possible that the volume of the littoral sand deposits will increase as a result of the rise in the level of the sea. This pattern is considerably different and more complex than that inferred by the Bruun model with its direct offshore transport of what would appear to be primarily littoral sediments.

CONCLUSIONS AND RECOMMENDATIONS

The principal objective of SCOR Working Group 89 has been to assess the status of the models and analysis techniques for quantitative evaluations of the erosion response of beaches to increased water levels. Such analyses still focus mainly on the Bruun model and predictive rule, equations (1) and (2). Modifications of that basic analysis include its adaptation to the response of an entire barrier-island system (Dean and Maurmeyer, 1983), and the inclusion of sediment-budget factors that can alter the total volume of sand in the beach section involved in the analysis (Hands, 1983; Dean and Maurmeyer, 1983; Everts, 1985). The present report also reviewed the models and predictive equations developed to assess beach and dune erosion resulting from storm surges (Edelman, 1968, 1972; Vellinga, 1982; Dean, 1982; Kriebel and Dean, 1985), models that have a close similarity to the sea-level response analyses.

The principal conclusions reached in our review include:

(1) The Bruun model, which assumes an upward and landward translation of an equilibrium profile in response to a rise in sea level, inferring a net offshore transport of sediment, has been confirmed in its basic patterns by both laboratory and field experiments.

(2) The Bruun rule, equations (1) and (2), depends on parameters (h_*, L_* or θ) that are difficult to evaluate, hindering quantitative testing of the relationships as well as their applications. In that the derivation of the Bruun rule is independent of the nearshore profile configuration, the resulting equations constitute little more than a landward migration of the nearshore zone up the regional slope, and accordingly can be expected to be correct within one's ability to choose the appropriate θ value.

(3) There may be a significant time lag of the beach response to an elevated water level. This will not be important to predictions of beach erosion resulting from a long-term global increase in sea level, but could be important to shorter-term increases such as those experienced during an El Niño or in the Great Lakes. The time lag can also be important in tests of the models if the experiments are to be limited to reasonable time spans.

(4) The principal hinderance in achieving acceptable predictions of shoreline reces-

sion rates with the basic Bruun rule is that it does not include other sediment-budget components that can result in shoreline recession or accretion. The barrier-island model of DEAN and MAURMEYER (1983) represents an improvement in that it includes sand removal from the beachface due to overwash and inlet processes, those that account for the landward migration of the island. It is important to assess other sediment-budget contributions and losses at the study site—these are accounted for by the G_B term in equation (6).

(5) As a result of the difficulties in selecting h_*, L_*, or θ in equations (1) and (2), and due to problems with beach-response lag times and sediment contributions/losses that also cause shoreline changes, the existing laboratory and field studies have not convincingly demonstrated the validity of the Bruun rule. Even though the rule can be expected to be basically correct, studies to date suggest that predicted recession rates can differ from measured rates by factors of 2 to 5. It appears that predictions are greatly improved if the full budget of sediments is included in the analysis (EVERTS, 1985).

In view of the above conclusions, we offer the following recommendations:

(1) The Bruun rule be used only for order-of-magnitude estimates of potential shoreline recession rates. Large error bars should be included with any calculated estimates as a reminder of the approximate nature of the analysis procedure. If possible, the full budget of sediments should be developed for the study site so that these factors can be included in predictions of the shoreline changes. Alternately, where the interest is in evaluating additional erosion tendencies in response to augmented sea-level rise rates, equation (7) can be utilized so long as the sediment-budget terms are nearly constant with time.

(2) Field studies be undertaken, committed to the long-term (decades) surveying of beach profiles at select coastal sites. The sites should be chosen on the basis of small or known sediment-budget factors, and with a reasonable wave-energy level to reduce the beach response lag time. One site should be located in an area of significant subsidence so as to provide a large relative sea-level rise, and possibly where there is a well-defined seasonal cycle in the water level. Shorter-term studies of waves, nearshore currents and sediment transport should also be undertaken at the sites.

(3) Laboratory wave-flume studies should focus mainly on the storm-surge models of dune erosion, and include considerations of the processes of wave transformation and cross-shore sediment transport. Important is an increased understanding of the development of an equilibrium profile, and the lag in response time of the profile to a change in water level.

Coastal erosion in response to elevated water levels is already a significant problem, and could become substantially greater if predictions of accelerated sea-level increases due to greenhouse warming are correct. Unfortunately, the status of models for the beach response to elevated water levels is far from satisfactory, and predictions of the associated shoreline recession rates yield uncertain results. There is a clear need for substantial research efforts in this area.

LITERATURE CITED

ALLISON, H. and SCHWARTZ, M.L., 1981. Bruun Rule: A phenomenological theory of shore erosion. *Technical Memorandum 81/3*, CSIRO, Division of Land Resources Management, Perth, Australia. 52 pp.

AUBREY, D.G. and EMERY, K.O., 1986. Relative sea levels of Japan from tide-gauge records. *Geological Society American Bulletin*, 97, 194-205.

BARNETT, T.P., 1984. The estimation of "Global" sea level change: A problem of uniqueness. *Journal of Geophysical Research*, 89(C5), 7980-7988.

BIRKEMEIER, W.A., 1985. Field data on seaward limit of profile change. *Journal of Waterway, Port, Coastal and Ocean Engineering*, American Society Civil Engineers, 111 (No. 3), 598-602.

BRAATZ, B.V. and AUBREY, D.G., 1987. Recent relative sea-level change in eastern North America. *In:* Nummedal, D.; Pilkey, O.H., and J. Howard, (eds.), *Sea-level Fluctuations and Coastal Evolution*, S.E.P.M. Special Publication No. 41, pp. 29-46.

BRUUN, P., 1962. Sea-level rise as a cause of shore erosion. *Journal Waterways and Harbors Division*, American Society Civil Engineers, 88 (WW1), 117-130.

BRUUN, P., 1988. The Bruun Rule of erosion by sea-level rise: A discussion of large-scale two- and three-dimensional usages. *Journal of Coastal Research*, 4, 627-648.

CLARKE, D.J. and ELIOT, I.G., 1983. Mean sea-level and beach-width variation at Scarborough, Western Australia. *Marine Geology*, 51, 251-267.

CLARKE, D.J., and ELIOT, I.G., 1987. Groundwater-level changes in a coastal dune, sea-level fluctuations and shoreline movement on a sandy beach. *Marine Geology*, 77, 319-326.

CURRAY, J.R., 1965. Late Quaternary history, continental shelfs of the U.S. *In: The Quaternary of the United States*, H.E. Wright and D.G. Frey, (Eds.), Princeton, N.J.: Princeton University Press, pp. 723-735.

DEAN, R.G., 1982. *Models for Beach Profile Response.* Technical Report No. 30, University of Delaware, Newark.

DEAN, R.G., 1990. Beach response to sea level change. *In: Le Méhauté, B. and Hanes, D.M. (eds.) Ocean Engineering Science*, v. 9 of *The Sea.* New York: Wiley, Inc., pp. 869-887.

DEAN, R.G., 1991. Equilibrium beach profiles: Characteristics and applications. *Journal of Coastal Research*, 7(1), 53-84.

DEAN, R.G. and MAURMEYER, E.M., 1983. Models for beach profile response. *In: Komar, P.D., (ed.), Handbook of Coastal Processes and Erosion.* Boca Raton, Florida: C.R.C. Press, pp. 151-166.

DOLAN, R.; HAYDEN, B., and MAY, S., 1983. Erosion of the United States shorelines. *In:* Komar, P.D., (ed.), *Handbook of Coastal Processes and Erosion.* Boca Raton, Florida: C.R.C. Press, pp. 285-299.

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

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

DUBOIS, R.N., 1977. Predicting beach erosion as a function of rising water level. *Journal of Geology*, 85, 470-476.

EDELMAN, T., 1968. Dune erosion during storm conditions. *Proceedings of the 11th Conference of Coastal Engineering*, ASCE, 719-722.

EDELMAN, T., 1972. Dune erosion during storm conditions. *Proceedings of the 13th Conference of Coastal Engineering*, ASCE, 1305-1312.

EMERY, K.O., 1980. Relative sea levels from tide-gauge records. *Proceedings of the National Academy of Sciences*, 77(12), 6968-6972.

ENFIELD, D.B. and ALLEN, J.R., 1980. On the structure and dynamics of monthly mean sea level anomalies along the Pacific coast of North and South America. *Journal of Physical Oceanography*, 10, 557-578.

EVERTS, C.H., 1985. Sea level rise effects. *Journal Waterway, Port, Coastal and Ocean Engineering, (American Society of Civil Engineers)*, 111 (no. 6), 985-999.

GORNITZ, V.; LEBEDEFF, S., and HANSEN, J., 1982. Global sea level trend in the past century. *Science*, 215, 1611-1614.

GORNITZ, V. and LEBEDEFF, S., 1987. Global sea-level changes during the past century. *In:* Nummedal, D.; Pilkey, O.H., and J. Howard, (eds.), *Sea-level Fluctuations and Coastal Evolution*, S.E.P.M. Special Publication No. 41, pp. 3-16.

GRAAFF, J. VAN DE, 1977. Dune erosion during a storm surge. *Coastal Engineering*, 1, 99-134.

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

HANDS, E.B., 1979. Changes in rates of shore retreat, Lake Michigan, 1967-1976. *Coastal Engineering Research Center, Technical Memorandum No. 79-4*, 71p.

HANDS, E.B., 1980. Prediction of shore retreat and nearshore profile adjustments to rising water levels on the Great Lakes. *Coastal Engineering Research Center, Technical Memorandum No. 80-7*, 119p.

HANDS, E.B., 1983. The Great Lakes as a test model for profile responses to sea level changes. *In:* Komar, P.D., (ed.), *Handbook of Coastal Processes and Erosion.* Boca Raton, Florida: C.R.C. Press, pp. 176-189.

HICKS, S.D., 1978. An average geopotential sea level series for the United States. *Journal of Geophysical Research*, 83 (no. C3): 1377-1379.

HICKS, S.D. and HICKMAN, L.E., 1988. United States sea level variation through 1986. *Shore & Beach*, 56, 3-7.

HOFFMAN, J.; KEYES, D., and TITUS, J.G., 1983. *Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs.* U.S. Environmental Protection Agency, Washington, D.C.

HUYER, A.; GILBERT, W.E., and PITTOCK, H.L., 1983. Anomalous sea levels at Newport, Oregon during the 1982-83 El Niño. *Coastal Oceanography and Climatology News*, 5, 37-39.

KOMAR, P.D., 1986. The 1982-83 El Niño and erosion on the coast of Oregon. *Shore and Beach*, 54, 3-12.

KOMAR, P.D.; NEUDECK, R.H., and KULM, L.D., 1972. Observations and significance of deep-water oscillatory ripple marks on the Oregon continental shelf: *In: Shelf Sediment Transport*, Duane and Pilkey (eds.), Stroudsburg, PA: Dowden, Hutchinson & Ross, pp. 601-619.

KOMAR, P.D. and ENFIELD, D.B., 1987. Short-term sea-level changes and coastal erosion. *In:* Nummedal, D.; Pilkey, O.H., and J. Howard, (eds.), *Sea-level Fluctuations and Coastal Evolution*, S.E.P.M. Special Publication No. 41, 17-27.

KRAFT, J.C.: BIGGS, R.B., and HALSEY, S.D., 1973. Morphology and vertical sedimentary sequence models in Holocene transgressive barrier systems. *In: Coastal Geomorphology*, D.R. Coates (ed.), Binghamton: State University of New York, pp. 321-354.

KRIEBEL, D.L., 1986. Verification study of a dune erosion model. *Shore and Beach*, 54, 13-21.

KRIEBEL, D.L., 1990. Advances in numerical modelling of dune erosion. *Proceedings 22nd International Conference on Coastal Engineering.*

KRIEBEL, D.L. and DEAN, R.G., 1985. Numerical simulation of time-dependent beach and dune erosion. *Coastal Engineering*, 9, 221-245.

MILLIMAN, J.D. and EMERY, K.O., 1968. Sea levels during the past 35,000 years. *Science*, 162, 1121-1123.

NUMMEDAL, E., 1983. Barrier islands. *In:* Komar, P.D., (ed.) *Handbook of Coastal Processes and Erosion.* Boca Raton, Florida: C.R.C. Press, pp. 77-121.

PELTIER, W.R. and TUSHINGHAM, A.M., 1989. Global sea level rise and the greenhouse effect: Might they be connected? *Science*, 244, 806-810.

PILKEY, O.H. and DAVIS, T.W., 1987. An analysis of coastal recession models: North Carolina coast. *In:* Nummedal, D.; Pilkey, O.H., and J. Howard, (eds.), *Sea-level Fluctuations and Coastal Evolution*, S.E.P.M. Special Publication No. 41, pp. 59-68.

PIRRAZOLI, P.A., 1986. Secular trends of relative sea level (RSL) changes indicated by tide-gauge records: *Journal of Coastal Research*, Special Issue No. 1, 1-26.

REVELLE, R.R., 1983. Probable future changes in sea level resulting from increased atmospheric carbon dioxide. *Changing Climate*, National Research Council Report, National Academy Press, Washington, D.C., pp. 433-448.

ROSEN, P.S., 1977. Discussion {of Dubois (1976)}. *Journal of Geology*, 85, 491-492.

ROSEN, P.S., 1978. A regional test of the Bruun Rule on shoreline erosion. *Marine Geology*, 26, M7-M16.

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

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

SHEPARD, F.P., 1963. Thirty-five thousand years of sea level. *In: Essays in Marine Geology in Honor of K.O. Emery*, University of Southern California Press, Los Angeles, pp. 1-10.

SHEPARD, F.P. and CURRAY, J.R., 1967. Carbon-14 determination of sea level changes in stable areas. *Progress in Oceanography, The Quaternary History of the Ocean Basins*. Oxford: Pergamon Press, Vol. 4, 283-291.

VAN DER VEEN, C.J., 1988. Projecting future sea level. *Surveys in Geophysics*, 9, 389-418.

VELLINGA, P., 1982. Beach and dune erosion during storms. *Coastal Engineering*, 6, 361-387.

WEISHAR, L.L. and WOOD, W.L., 1983. An evaluation of offshore and beach changes on a tideless coast. *Journal of Sedimentary Petrology*, 53, 847-858.

WOOD, W.L. and WEISHAR, L.L., 1984. Beach response to long period lake-level variation. *Proceedings of the 19th Coastal Engineering Conference*, (American Society of Civil Engineers), pp. 1571-1583.

WYRTKI, K., 1975. Fluctuations of the dynamic topography in the Pacific Ocean. *Journal of Physical Oceanography*, 5, 450-459.

WYRTKI, K., 1977. Sea level during the 1972 El Niño. *Journal of Physical Oceanography*, 7, 779-787.

WYRTKI, K., 1983. Sea level in the equatorial Pacific in 1982. *Tropical Ocean-Atmosphere Newsletter*, No. 16, 6-7.

WYRTKI, K., 1990. Sea level rise: The facts and the future. *Pacific Science*, 44, 1-16.