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Author(s): Per Bruun
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# The Bruun Rule of Erosion by Sea-Level Rise: A Discussion on Large-Scale Two- and Three-Dimensional Usages

**Per Bruun**

34 Baynard Cove Road
Hilton Head Island SC 29928

## ABSTRACT

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This article reviews all basic assumptions for proper use of the Bruun-Rule of erosion by sea-level rise. It disproves misuses and discusses expansions of the rule's applicability in large-scale two and three dimensions.

**ADDITIONAL KEY WORDS:** *Bruun Rule, sea level rise, shore erosion, bottom profile development.*

## INTRODUCTION

The Bruun Rule of erosion, so named by American coastal geomorphologists (SCHWARTZ, 1967), was first published in 1962 (BRUUN, 1962). Concerning a long-term budget of onshore/offshore movement of material, the rule is based on the assumption of a closed material balance system between the (1) beach and nearshore and (2) the offshore bottom profile. Figure 1 is a schematic of the effect, a translation of the beach profile by a distance s following a rise a of the sea level, resulting in a shore erosion and a deposition of sediments. This topic is dealt with extensively in theory (HALLERMEIER, 1972; ALLISON, 1980; BRUUN, 1980, 1983) and through observations in the field (BRUUN, 1956 a, b, 1962, 1980, 1983; DUBOIS, 1976; ROSEN, 1978, 1980; WEGGEL, 1979; FISHER, 1980; HANDS, 1980; SCHWARTZ, 1965, 1967, 1979). Most lately the Rule has been used for various reports, *e.g.* the report on the erosion at Ocean City, Maryland, "Potential Impact of Sea Level Rise on the Beach at Ocean City, MD", published by the EPA, October 1985 and in a paper by EVERTS (1985).

The "rule" has sometimes been used rather indiscriminately without realizing its limitations. One should always remember that it is basically two-dimensional, but it is (almost) always applied three-dimensionally. This has caused a number of misinterpretations. Used objectively and correctly, the rule, however, offers several possibilities for better understanding of three-dimensional processes and for the explanation of three-dimensional large-scale coastal developments using the rule as a kind of "base-line" for whatever development that takes place (plus or minus) in relation to a basic profile of well defined geometry and to the observed relative sea level.

This paper discusses boundary conditions, deviations and adjustments which make the rule useful for interpretation of the observed phenomena in quantifiable terms.

## REVIEW OF BASIC ASPECTS OF PROFILE DEVELOPMENT IN RELATION TO SEA-LEVEL RISE

Consider a sea-level rise a in a theoretical profile with geometrical characteristics as shown in Figure 1. In a coastal geomorphological sense this corresponds to a lift of the profile of the value a. For a profile y = f(x), in order to re-establish the old profile one needs a deposition of:

$$\Delta = \int_0^l [f(x) + a]\,dx - \int_0^l f(x)\,dx = l \cdot a \qquad (1)$$

To establish quantitative equilibrium it is assumed that:

(1) Full profile equilibrium exists, which

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means the combined beach and offshore profile maintains an equilibrium shape, although seasonal fluctuations may occur. "Seasonal" means "short term" but eq. 1 refers to the long-term development. The outermost part of the profile Figure 1, is a "ramp".

(2) The shore or section of shore, to which the Rule is applied is in a quantitative materials-balance condition, or integrated over the profile equals zero, when $M = m_1 + m_2 \ldots + m_n$ is the total quantity of material moving in or out of the profile in all directions under the action of waves, currents and winds. To this man's activities in dredging could be added (ALLISON, 1981).

As the profile system is assumed to be in an overall cross-sectional equilibrium, the only way in which the material for deposition can be obtained is by a shoreward movement. In a practical close approximation such movement may be determined from the equation:

$$\Delta = \int_0^l f(x)dx + h \cdot s - \int_0^l f(x)dx = h \cdot s \qquad (2)$$

when h is "the maximum depth of exchange of material between the nearshore and the offshore", while l is the length of the profile of exchange. From eqs. 1 and 2 one has:

$$s = l \cdot a/h \qquad (3)$$

As pointed out by BRUUN (1962), neither the slope of the profile, nor the point of intersection of the new and the old profile, nor the position of, or the seaward slope angle of the offshore bar were used or needed for the derivation of the above simple formula. This is the "advantage" of the theory. As stated by ALLISON (1980), the exactness of the theory, however, depends upon the s/l ratio (Figure 1), but this ratio is always very small. Allison states:

> "For small ratio $s/l < 1$ there is, consequently, no need to know any detail of bottom profile at all and Bruun's Formula (1) correctly reflects this, not containing any parameters describing the shape of the bottom profile. Hence, the value h/l in formula (3) (having nothing to do with the slope of the bottom profile) is, to a zero order approximation, an invariant, valid for any profile shape for calculation of the ratio a/s. It is proposed, therefore, that this value h/l be known as "Bruun's Invariant."

The above, however, should not be interpreted too rigorously. It refers to simple profile geometries (BRUUN, 1954 a,b, 1962, 1980, 1983) and restrictions on materials, as mentioned later must also be accepted.

## RELATIVE MOVEMENTS OF PROFILES, INCLUDING SEA-LEVEL RISE AND FALL, TECTONIC, AND GLACIAL MOVEMENTS

Apparent sea-level rise varies in different parts of the world's oceans, influenced as they are by local trends of temperature, winds, and currents. Along the US eastern seaboard rises averaged about 3 millimeters per year during the last decades. Table 1 gives an impression of these movements. A very comprehensive work by LISLE (1982, sponsored by the Office of Naval Research) is mentioned in the latter part of this paper under "Latest Development in Research."

### Deviations from the Simple Rule: How to Interpret and Quantify Them Properly

In its simplest form the rule refers to a shore of infinite length and of neutrality of longshore movement of material. Consequently the beach and offshore bottom profiles maintain their geometrical shape which is solely a function of wave action, tides and sea level movements and materials. If wave action is always perpendicular to the shoreline there will be no resultant or predominant longshore drift. If the water table (apart from regular tidal action) stays constant, the profile develops an equilibrium shape with steepness corresponding to bottom material characteristics and wave action, as discussed in the following section.

Attempts have been made to compute the geometrical shape of such profiles based on idealized assumptions. There are basically two different approaches: one is of semi-theoretical "philosophical" nature using simplified, but still rational basic assumptions, and the other is a detailed hydrodynamic approach that considers the equilibrium condition for a single grain on the bottom, ignoring bottom configurations like ripple marks. The following discussion briefly explains both methods.

BRUUN's approach (1954, b, c, and 1985 with

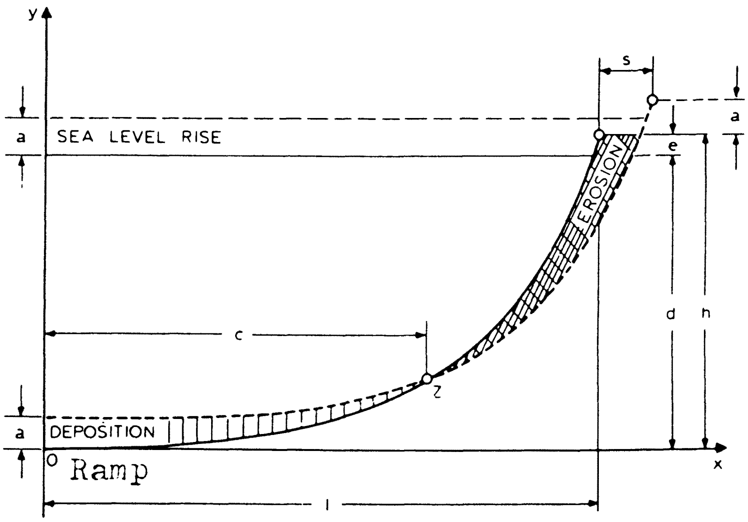

Figure 1. The Bruun Rule—translation of the beach and bottom profile resulting in shore recession and deposition of sediments (Bruun, 1983).

Table 1. *Average sea-level rises, 1940–1970 on the US east coast (Bruun, 1973, after compilation by Hicks)*

| Location | | Rate (cm/yr) |
|---|---|---|
| Eastport, Maine | 1930–1969 | 0.338 |
| Portsmouth, New Hampshire | 1927–1970 | 0.165 |
| Woods Hole, Massachusetts | 1933–1970 | 0.268 |
| Newport, Rhode Island | 1931–1970 | 0.210 |
| New London, Connecticut | 1939–1970 | 0.229 |
| New York, New York | 1893–1970 | 0.287 |
| Sandy Hook, New Jersey | 1933–1970 | 0.457 |
| Baltimore, Maryland | 1903–1970 | 0.259 |
| Washington, D.C. | 1932–1970 | 0.244 |
| Portsmouth, Virginia | 1936–1970 | 0.341 |
| Charleston, South Carolina | 1922–1970 | 0.180 |
| Fort Pulaski, Georgia | 1936–1970 | 0.198 |
| Mayport, Florida | 1929–1970 | 0.155 |
| Miami Beach, Florida | 1932–1970 | 0.192 |
| Pensacola, Florida | 1924–1970 | 0.040 |
| Eugene I., Louisiana | 1940–1970 | 0.905 |
| Galveston, Texas | 1909–1970 | 0.430 |

The trend after 1970 has generally been up but with no definite sign of acceleration (Pirazzoli, 1986).

SCHWARTZ), an example of the former, is as follows:

(a) The profile is formed by shear stress due to wave action and is at right angles to the shoreline. The material detached by the oscillating water is removed by longshore currents. As the shear stress due to wave action in general—and particularly during storms—is far greater than the shear stress originating from the longshore currents, this assumption seems logical.

(b) In the equilibrium profile the shear stress per unit bottom area may be assumed to be constant, *i.e.* the "condition" at the bottom is the same ($d\tau/dx = d\tau/dt = 0$). Confirmation of this assumption only can be attained by experiments. One obtains $\tau = K\rho\mu^2_{ave}$, where $\rho$ is the density, K the resistance coefficient and u the water velocity. If $\tau$ is assumed a constant, then $\mu_{ave} \sim H\pi/T \sinh 2\pi y/L$ is also constant where T is the wave period; $H_1$ the wave height; L, the wave length, and y, the water depth.

(c) $dE_1/dx$ = constant, where $E_1$ is the transported wave energy per unit area of the wave, and x is the distance from the shoreline. The loss of energy is mainly by bottom friction, a loss by spilling of the wave and a loss by internal friction are very small. The correctness of this assumption can only be proven by experiments. Calcuations give:

$$x = L_o\sqrt{2\pi y}\,\{2\left(\frac{2\pi y}{L_o}\right) + \frac{1}{3}\left(\frac{2\pi y}{L_o}\right)^2 + \frac{43}{180}\left(\frac{\pi y}{L_o}\right)\ldots\}$$

where y is the water depth and $L_o$ the deep water wave length. The series is convergent for

$y < Lo/8$, *i.e.*, for storm waves on the Danish west coast out to depths of about 12 m (40 feet) where $L_o$ = 100 m (300 feet). Since $y << L_o$ the equation may be reduced to

$$y^{3/2} = px \qquad (4)$$

where p is a "constant" related to exposure and bottom materials. If it now is assumed that the loss of energy is due only to bottom friction and that this loss per unit area $e_t$ is constant, then

$$\tau = K\rho\mu^2_{ave} \qquad (5)$$

where K is a constant times $(a/R)^{3/4}$, a is the length of the ripple marks and R is the half amplitude of the oscillating water motion at the bottom ($R >> a$, BAGNOLD, 1946). Calculations similar to those described above then give:

$$y^{3/2} = \frac{p_1 \cdot x}{T^{2/3}} \quad (y < \text{about } L_o/8) \qquad (6)$$

This profile is similar to the one above (eq. 4). Certainly the profile depends on the wave period T, but as the profile is shaped mainly by storm waves and as the variation in T for these is small, the profile in reality will be the same as that given by (4). BRUUN (1954b, 1954c) found confirmation of this profile geometry on the Danish North Sea Coast as well as in southern California. $p_1$ is calibrated to local environmental conditions (waves, materials).

For the area inside the breaker zone BRUUN (1987–88) developed the equation

$$y^{5/4} = p_2 \cdot x \qquad (7a)$$

That was based on model research by VELLINGA (1985). Combining the equal shear stress requirement with BAGNOLD's above mentioned expression for friction and using LOSADA and DESIRÉ's (1985) results, by which the amplitude is replaced by a linear function for grain diameter, D, DRUUN (1986–1987) found the relation:

$$d^{5/12} \cdot D^{3/4} = \text{constant} \; (d = y = \text{water depth}) \qquad (7b)$$

Equation (7b) has to some extent been confirmed by field results in Denmark, Iceland and Australia. D is taken as $D_{50}$. Variances are explained

An example of a detailed hydrodynamic approach is given by EAGLESON, GLENNE and DRACUP (1961). The result of their approach and computations is shown in Figure 2 and may be summarized as follows, referring to a single grain of well defined size, geometry, and specific gravity located on a straight slope on other grains as indicated in Figure 2 and subjected to a specific wave action:

(1) There is a point of "incipient motion" when the forces are just able to initiate movement.

(2) The motion may be either up- or downslope. Wave motion in the nearshore zone is always assymetrical with a tendency to shoreward predominance (as demonstrated by field as well as laboratory experiments.) At one point, theoretically speaking, an equilibrium condition between forces working upslope and forces working downslope exists. The direction of movement of any grain depends upon the relative location of the point of incipient motion and the point of equilibrium condition (the null point). If, as shown in Figure 2 the point of incipient motion is located at a greater depth in the profile than the point of oscillating equilibrium, material will migrate in an onshore direction from points inside the point of oscillating equilibrium but offshore outside the said point. This means that the profile, as a whole, flattens (winter profile). If the opposite is the case and the point of incipient motion is located at less depth in the profile than the point of oscillating equilibrium, all motion inside the point of incipient motion will be toward the shore, which means that the profile steepens (summer profile). See also BRUUN (1954b, 1954c), INMAN & RUSNAK (1956), and SWART (1974). This theory has practical aspects and confirms the "theory" by CORNAGLIA (1887) that there is a "null point" for each grain size on the nearshore bottom. As pointed out by MURRAY (1966) Eagleson's theory mainly refers to bed transport. From his field studies in Buzzard's Bay, Massachusetts, he concluded that "within the experimental range of the data it is concluded that under the same wave conditions, finer grain sizes have a greater tendency to move offshore than coarser grains. A change in wave state resulting in an increase in the maximum horizontal velocity near the bottom produces an increase in the tendency for all test grains to move seaward".

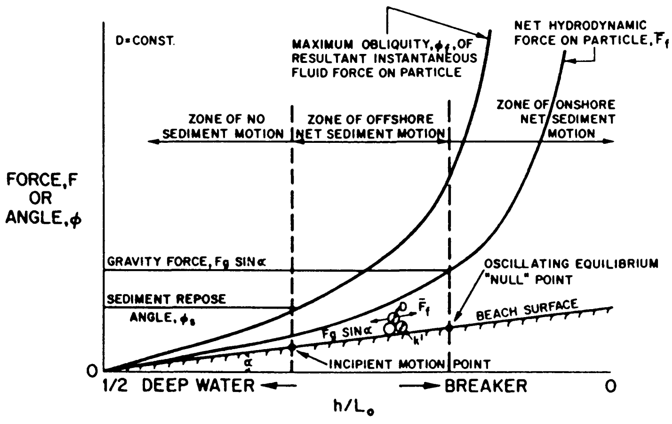

Figure 2. Stability situation for a single grain on a uniform slope (from Eagleson, Glenne and Dracup, 1961).

## Discussion of the Geometric Shape of the Bottom Profile

The relationship $y = px^m$, where $m = 2/3$ as proposed in BRUUN's theory, was investigated by DEAN (1977) who, based on a study of more than 500 beach profiles (BRUUN had about 30), found an equilibrium profile similar to BRUUN's with $m = 2/3$. DEAN showed that this profile, based on linear wave theory, was consistent with uniform wave energy dissipation per unit volume due to wave breaking. This, however, is a rather unrealistic assumption outside the surf zone.

Comparing a storm situation with a (low) swell condition: during the storm the point of incipient motion will be located far offshore while the point of equilibrium will be found closer to shore. Consequently, material will move offshore. Conversely, during a (low) swell situation the point of incipient motion will be fairly close to shore while the point of oscillating equilibrium will be located further offshore. Consequently material will move onshore from a certain depth.

## THE DEVELOPMENT OF THE BRUUN RULE

For some years, Bruun had been concerned with equilibrium beach profiles on the coasts of Denmark (BRUUN, 1954a), southern California (1954b), and Florida (BRUUN 1955). He offered the definition, "An equilibrium beach profile is a statistical average profile which maintains its form apart from small fluctuations including seasonal fluctuations". This concept was used in a later analysis of sea level rise as a cause of shore erosion (BRUUN, 1962), when Bruun hypothesized (Figure 1) that, given an equilibrium beach profile, a rise in sea level would be followed by: (a) a shoreward displacement of the beach profile as the upper beach is eroded; (b) movement of the material eroded from the upper beach would be equal in volume to the material deposited on the near offshore bottom; and (c) a rise of the near offshore bottom as a result of this deposition, equal to the rise in sea level, thus maintaining a constant water depth in that area. This proposition was essentially intuitive, although equilibrium forms were tested by field surveys (BRUUN 1954a), SCHWARTZ (1965) undertook laboratory wave-basin experiments to test the validity of the hypothesis. Utilizing different wave parameters and varying amounts of sea level change, measurements were made before and after each run to determine the water depth in the nearshore zone, and thus document profile translation and erosion-deposition relationships. These elementary experiments showed support for Bruun's hypothesis. A field study of the effects of sea level rise, based on investigations of the response to the effective rise in sea level occurring between high neap and high spring tides, was conducted on two Cape Cod beaches in the summer of 1964 (SCHWARTZ, 1979). The two beaches were the

Nauset Light Beach and the Herring Cove Beach, within the Cape Code National Seashore park, providing, respectively, an open ocean and a protected bay regime. Starting points for profile measurements were the protected-beach signs at each beach. The profiles were surveyed throughout the summer using a modified version of EMERY's two-stick-profile method (EMERY, 1961), in conjunction with SCUBA gear and enough weights to maintain negative buoyancy. Variations in profiles for a series of high neap to high spring events supported the hypothesis under investigation and it was proposed "that the concept henceforth be known as Bruun's Rule" (SCHWARTZ, 1967). The term *Bruun Rule*, first appeared in the coastal literature in an article by SWIFT (1968). This was followed closely in books by BIRD (1969), *Coasts*, and KING (1972) *Beaches and Coasts*. In 1972, FISHER included the Nauset Light and Herring Cove beach sites, together with a discussion of the early Bruun Rule research, in his guide to the geology of the Cape Cod National Seashore. The rule found its way into the Soviet literature in 1973 via KAPLIN's (1973) *Recent History of the Coasts of the World Oceans*. Further testing and refinement of the rule followed in DUBOIS (1975, 1976, 1977), HANDS (1976, 1977, 1979), and ROSEN (1978). The history of the hypothesis and research has been summarized by SCHWARTZ & MILICIC (1978, 1980a, 1980b).

In November of 1979 the International Geographical Union's Commission on the Coastal Environment held a Bruun-Rule Symposium in Newport, Rhode Island (SCHWARTZ & FISHSER, 1980). Susbsequent literature dealing with the Bruun Rule included ALLISON, CARBON & LICHTFIELD (1982), ALLISON & SCHWARTZ (1981a, 1981b), BRUUN (1983), HANDS (1983) and LEATHERMAN (1983). Furthermore, in connection with a recent Environmental Protection Agency study of the effects of sea level rise, the Bruun Rule and many of the aforementioned publications have been discussed by KANA, MICHEL, HAYES & JENSEN (1984), LEATHERMAN (1984), LEATHERMAN, KEARNY & CLOW (1983), and TITUS & BARTH (1984).

## Beach Erosion, Why and How

Beach erosion is the result of any one or more of the following adverse conditions (BIRD 1983; BRUUN 1973): (1) The effects of human impact, such as construction of artificial structures, mining of beach sand, offshore dredging, or building of dams on rivers; (2) losses of sediment offshore, onshore, alongshore and by attrition; (3) reduction in sediment supply due to decelerating cliff erosion; (4) reduction in sediment supply from the sea floor; (5) increased storminess in coastal areas or changes in angle of wave approach; (6) increase in beach saturation due to a higher water table or increased precipitation; and (7) sea level rise.

These conditions are subject to large variations as they are highly dependent on many external factors. The one aspect that will be dealt with here, as a cause of beach erosion, is "sea level rise".

## Material Budgets

To evaluate beach erosion quantitatively requires the establishment of a materials budget; which means a total account of all movement of material within an area limited up and down the profile by boundary lines where erosion or accretion is approximately zero, and on the sides by profiles defining the boundaries of the area in question.

In practice, that means that upwards the dune crest becomes the boundary (providing there is no significant transport of sediment across this line) while downwards various limiting standards will have to be considered. One of these is "the limiting depth for active movement" (HALLERMEIER, 1972, 1981a, 1981b; HANDS, 1979, 1980) which would come close to $2H_{bmax}$, where $H_{bmax}$ is the actual breaker height of the highest waves within a certain time period. The breaker height $H_b$ in relation to breaker depth Db is Hb equal to 0.7–0.9 $D_b$. Up to that point the profile movement would account for approximately 90% of the total profile movement, while the remainder may extend to a "limited depth" of approximately 3.5 $H_{bmax}$. Various two-dimensional theories have been proposed (EAGLESON, GLEEN & DRACUP 1961; HALLERMEIR 1972, 1981a, 1981b; SWART 1974; TRASK 1955), but all under idealized assumptions. The most practical way of determining the limiting depth of profile movement is by comparison between surveys, like Figures 3 and 4. It is, however, a fact that most profile-surveys have been seldom

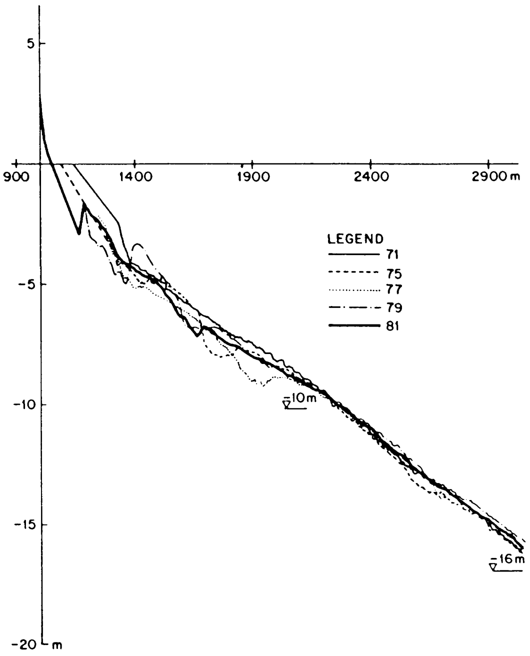

Figure 3. Comparison of profile fluctuations on the Danish North Sea Coast at Thyboroen. Data provided by the Danish Coastal Directorate, Lemvig.

Table 2a. *Profile characteristics.*

| | | |
|---|---|---|
| a) Cross section, A | 0–6m | 1,500m$^2$ |
| | 6–9m | 2,500m$^2$ |
| | 0–9m | 4,000m$^2$ |
| b) Width of the area, W | 0–6m | 350m |
| | 6–9m | 350m |
| | 0–9m | 700m |
| c) Mean depth, A/W | 0–6m | 4.0m |
| | 6–9m | 7.5m |
| | 0–9m | 5.5m |
| d) Steepness characteristic, A/W$^2$ | 0–6m | 10‰ |
| | 6–9m | 5‰ |
| | 0–9m | 8‰ |

extended offshore far enough to determine the limiting depth for profile movement (there are a few exceptions). The problem of three-dimensionality still exists, where the third dimension may be brought in by lateral, shore-parallel, movement and a steep bottom, with gravity influencing profile stability. The effect could be either erosion or accretion on the lower part of the profile. If it is erosion, the profile steepens whereas with accretion it becomes flatter. The difficulties involved in determining a practical limit for the material exchange zone may best be understood by considering some specific examples.

## MATERIAL BUDGET CALCULATIONS—PROPER USE OF THE BRUUN RULE

Possible causes of shore erosion were previously discussed and this section now deals with quantification of the sediment transfer accompanying a rise in sea level.

The Bruun Rule (BRUUN, 1962; SCHWARTZ, 1965, 1967) replaces more involved theoretical or semi-theoretical models by its simplicity. The basic assumption for the model is that the profile, whatever its form, maintains its shape during a period of sea level rise. The rule has been tested accordingly by various researchers (DUBOIS, 1976, 1980; FISHER, 1980a, 1980b; ROSEN, 1978, 1980; WEGGEL, 19790. If sea level rises "a" meters and the width of the bottom influenced by the sea level rise is "l" meters extending to depth "h" meters, the shoreline recession s is determined by (Figure 1)

$$s \cdot h = l \cdot a$$

or

$$s = \frac{l \cdot \alpha}{h} \qquad (8) = (3)$$

The validity of the Bruun Rule has been discussed by many authors (ALLISON, 1980; DUBOIS, 1976; FISHER, 1980b; ROSEN, 1978; 1980; SCHWARTZ, 1965, 1967; WEGGEL, 1979). BRUUN (1983, 1984) recommended adjustments related to the grain size of the shore material as well as to profile geometry including a steepening of the outer part of the profile as it is, for example, found off the southeast coast of Florida and at similar slopes, ditches or trenches in many other parts of the world.

To find the quantity of sediment eroded from the profile to maintain its prior form, following a rise in sea level, these steps are required:

(1) Survey of bottom profiles and comparison between profiles as far offshore as in possible considering variances (Table 2).

(2) Extreme wave analyses by which the ultimate or closure depth for exchange of material between land and sea (Bruun-rule) is determined by 3.5 $H_{b_{max}}$ (50–100) years (WES research by Hallermeier and Hands).

Table 2b. *Calculation of various standard deviations in investigations of changes in the beach profile.*

Standard deviations (absolute and in %)

| Area | 0–6 m area | | | | 6–9 m area | | | | 0–9 m area | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of profiles | 500 m area | 2 prf | 4 prf | 16 prf | 500m area | 2 prf | 4 prf | 16 prf | 500 m area | 2 prf | 4 prf | 16 prf |
| Cross Section | | | | | | | | | | | | |
| $m^2$ | 190 | 130 | 100 | 50 | 250 | 180 | 130 | 60 | 130 | 90 | 70 | 35 |
| % | 13 | 9 | 7 | 3 | 10 | 7 | 5 | 2 | 3 | 2 | 2 | 1 |
| Width Bottom (area) | | | | | | | | | | | | |
| m | 25 | 20 | 15 | 5 | 40 | 30 | 20 | 10 | 35 | 25 | 20 | 10 |
| % | 7 | 6 | 4 | 1 | 11 | 9 | 6 | 3 | 5 | 4 | 3 | 1.5 |
| Mean Depth | | | | | | | | | | | | |
| m | 0.3 | 0.2 | 0.2 | 0.1 | 0.2 | 0.15 | 0.1 | <0.1 | 0.1 | 0.1 | <0.1 | <0.1 |
| % | 7 | 5 | 5 | 3 | 3 | 2 | 1 | <1 | 2 | 2 | 1 | <1 |
| Steepness | | | | | | | | | | | | |
| Characteristic-‰ | 0.6 | 0.4 | 0.3 | 0.15 | 0.9 | 0.6 | 0.5 | 0.2 | 0.4 | 0.3 | 0.2 | 0.1 |
| % | 6 | 4 | 3 | 2 | 15 | 12 | 10 | 4 | 5 | 4 | 3 | 1 |

(3) Analyses of bottom material revealing the bottom widths with grain sizes and granulometric characteristics similar to the finest fraction (10%) of the material found in the beach and dune material (heavy minearls excepted). While 1 and 2 will provide a more distinct depth, 3 may give a wide range. Having determined from the above a "closure depth", h located at distance 1 from the shore, the quantity eroded from the profile to maintain its equilibrium shape for a sea level rise of "a" and a shoreline recession "x" is then determined from eqs. (3) = (8).

## Thyboron Barriers, North Sea Coast, Denmark (Bruun, 1954, a,b).

Take as an example Thyboron in Denmark (Figure 3) where l up to 16 m depth is about 1500 meters. Erosion contributing to an apparent or expected sea level rise of 0.003 m/year will amount to about 5 $m^3$/m of shore. The remaining part of the erosion, which is approximately 50 $m^3$/m/year, is caused by a combination of waves and currents. The shoreline recession is computed as:

$$x = \frac{45}{(16 + 4)} = \text{about } 2\text{m/year.}$$

The actual figure is somewhat less (about 1.5 m/year) due to the steepening effect which groins built on the shore have on the nearshore profile.

As such the Thyboron Barriers were analyzed in great detail by BRUUN (1954, a,b) using an overall 2-dimensional approach in this 3-dimensional case as follows. On this approximately 20 km-long shore, surveys in profiles spaced about 600 m apart have been conducted for more than 100 years. At first, profiles were only taken to 6 m depth but later extended to 10 m and finally (since 1938) to 20 m depth (Figure 3). The movements in these profiles, including quantities eroded, are described in great detail by BRUUN (1954 a and b). Due to slight variations in survey accuracy and the fact that a particular survey line represents a bottom area of certain width, one has to accept some variability in depths, profile areas, steepness and, finally, in the calculated quantities based on the movement in the profiles. Because of the limited survey data available outside the 9 m depth, Bruun was only able to compute variations up to 9 m depth for profiles spaced about 600 meters apart and extending 600 to 900 m from the shore.

Table 2a gives average profile characteristics for the characteristic parameters: Cross Section up to a certain depth, corresponding width of profile, its mean depth and its steepness = depth/width. Table 2b shows standard deviations corresponding to Table 2a. Note that all standard deviations decrease with increasing profile dimensions and increasing number of profiles. In this particular case it was found that the limiting depth for onshore-offshore movement of any importance was at 16 m, corresponding to about $2H_{b_{max}}$ for very unusual storms of low frequency when waves of maximum height 8 m are not far from the breaking depth, $D^b$, at 16 m. From table 2b, one may conclude that standard deviations for depths up to 16 m would be $< 0.1$ m, or of the order of $\pm$ 0.05 m. The corresponding standard deviations for bottom width, profile sectional area, and steepness are also given in table 2b, based on 0–6 m, 0–9 m and 6–9 m bottom areas. It may be observed that all standard deviations are relatively small when there are 16 profiles.

The practical consequence of the above is that one should compare profiles surveyed over various periods up to the depth where the average difference in depths in the two profiles is less than $\sqrt{2x\ 0.05\ m}$, *i.e.* approximately 0.07 m, or at least less than 0.1 m. This, of course, assumes a firm (sand) bottom. This definition of "limiting depth" is practical but, as mentioned above, it requires knowledge concerning the development of depths out to a distance from the shore of at least $2H_{bmax}$ where $H_{bmax}$ designates extreme events of low frequency of occurrence, *e.g.* once every 50 years. Surveys, therefore must be undertaken when the sea is calm, or profile records must be "smoothed" properly by experienced surveyors and technique. Figure 3 compares profile fluctuations on the coast of Thyboroen for a 10 year period, 1971–1981. It may be noted that 10 m seems to be the limit for "active movement". Scaling up to 100 years, the figure may be 16–18 m while the "ultimate depth" could be as high as 25–28 m. If profile data like Figure 3 are not available, which unfortunately is the normal case, one may try to transfer experience from elsewhere, *e.g.* by analysis of extreme wave events using a WEIBULL distribution (BRUUN, 1981; HOUMB, 1981). This would require multiplying the 50 year maximum wave height, which is about 1.7–1.8 $H^s$, by two, arriving at $H^s$ 50 max times 3.5, and then using that depth as the outer or ultimate limit for exchange of material in the active profile. 3-D effects, however, occur in the deeper waters.

## The Lake Michigan Coast

Considering another practical case, Figure 4 by HANDS (1980) shows an envelope of profiles surveyed over a 9-year period (1967–1975) of rising lake level, followed by stable water levels, on Lake Michigan. It may be observed that profile changes were considerable up to about 11 m depth.

The Lake Michigan profile change occurred during a period of 9 years of rapid rise of lake level. There will be a phase difference in time between water-level rise and profile adjustment, depending upon wave conditions during storms occurring in Lake Michigan (HANDS, 1979, 1980). Considerably more information on profile behavior in Lake Michigan is available from the Waterways Experiment Station, CERC, Vicksburg, Mississippi.

Regarding transversal movement due to sea level rise, HANDS (1979, 1980) discusses the "closure depth" in the profile in relation to the Bruun Rule with special reference to the Great Lakes, which during the period 1967–1975 experienced a rapid rise in lake level. As expressed by Hands, the theoretical depth up to which bottom motion extends depends upon wave height, wave steepness (period) and grain size. Considering a certain number of years, the highest wave during that period would be the determining factor. This obviously means that the closure depth for $H_{max}$, 5 years is shallower than the closure depth for $H_{max}$, 50 years.

## Relation of Bottom Adjustments to Long-Term Rise in Sea Level

In principle there is no difference between short-term (Lake Michigan) and long-term rise (the eustatic sea level rise). The latter, however, is very slow and consequently difficult to trace directly. One may say that it is a natural, integrated consequence of short-term movements, extended over a very long period. The question is: "How long a period of time is required to enable us to measure the reaction of the profile to a long-term rise of sea level?" Assuming a world-wide sea level rise of 5 mm (0.005 m) a year, which is of the order of what we may expect during the next decades, in 10 years this would attain 5 cm (0.05 m) or a figure of the same magnitude as the standard deviaton associated with our surveys. Most likely the effect of such a rise on the profile development would be so small that it could not be detected, providing that none of the other aforementioned causes of erosion occurred during the period under consideration. After 40 years the effect could be seen clearly because a 0.2 m change in sea level would be detectable within the accuracy of the surveys.

The next question is: "Is it possible to obtain advanced knowledge before the 40 years have elapsed (assuming that no reliable survey data

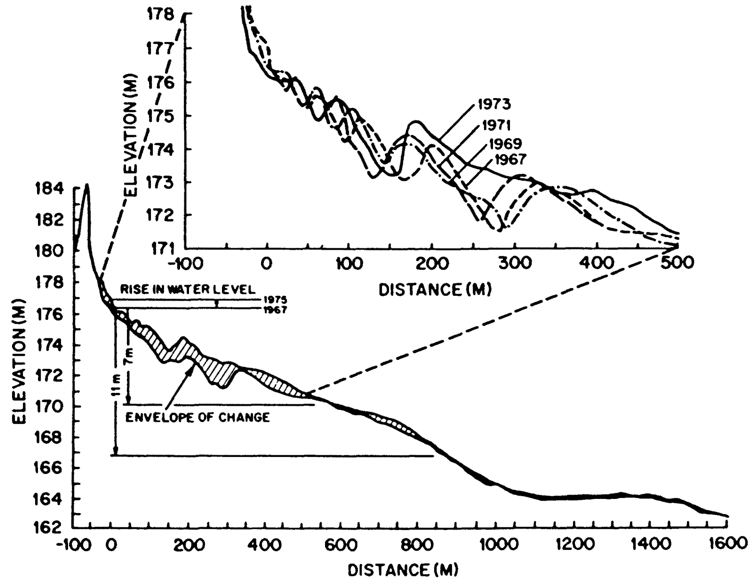

Figure 4. Profile adjustments in Lake Michigan over a 9-year period (Hands, 1979).

from earlier surveys are available), or will we be able to detect a slow offshore movement of material in the profile?" One way in which this could possibly be done would be by employing a long-term fluorescent tracer. In such a study tracers of various colors are placed at different depths, which should all be outside the depth of $2H_{bmax}$ 5 years. If $H_{bmax}$ 5 years is 5 meters, then fluorescent tracers should be placed at 10 m, 12 m, 14 m, 16 m and 20 meters depth and the movements of the tracers should be observed. Most likely such tests would demonstrate considerable diffusion, as was experienced at the EKOFISK tests in the North Sea at 72 m depth (BRATTLELAND & BRUUN, 1975), so the results may not be very reliable. A more direct method would be to establish a grid system by means of calibrated pegs placed in the bottom and have diver observation of sediment surface level over a large area. This would also indicate the existence of longshore current-generated bottom undulations, thereby material drift.

## THE EFFECT OF THREE-DIMENSIONS ON THE APPLICATION AND VALIDITY OF THE BRUUN RULE

The Bruun Rule was proposed as a two-dimensional model, but it is always used in three-dimensions. What does this actually mean? The fact is that true "academic two-dimensionality" does not exist in nature, because wave action is never exactly perpendicular to the shoreline. Even if it was, three-dimensional phenomena would arise due to wave breaking and the accompanying longshore currents parallel to shore. Two dimensions only exists (in its true sense) in a narrow wave tank like the one Schwartz used for his experiments in 1965. The fact that everywhere in nature we find bottom profiles following the equation $y^{3/2} = p \cdot x$ proves that the perpendicular to shore forces are by far the most important for profile development and geometries, including bars and troughs. They do, of course, not follow a simple equation.

With respect to the longshore drift, we use in littoral drift technology the terminology "nodal point" to describe the point or area of limited length longshore where the resultant drift "left minus right" is equal to zero. This is explored in great detail in BRUUN (1954b, c; 1973, BRUUN and SCHWARTZ, 1985). Computing and adding the drift quantities numerically in either direction one may wind up with a considerable quantity. In true three dimensionality there is a resultant drift in one direction. Considering two cross sections a-a and b-b located a distance a/b apart. The profiles within this length of shore are, due to a slight shore line curvature, subjected to wave action under a slightly deviating angle of approach in breaking causing a drift in one direction at the predominant storms. The question arises: "Does this influence the profile geometry?" It sounds logical that it will do so, but in practice it is not so. Profiles are, as mentioned above, always 3-dimensional. But the resultant or predominant longshore drift is always (much) smaller than the total numerical drift and even much smaller than the transversal drift in the profile (BRUUN, 1954, 1955, 1973, 1983 and 1985 with SCHWARTZ). From field observations we know how profiles develop along the shore depending upon which direction the shoreline turns compared to the wave action (BRUUN, 1954a, b, c). If the shoreline turns away from the wave direction it will usually develop an equilibrium configuration where profile steepness only changes very little.

If the shoreline remains straight and wave action does not change, profile steepness may increase (or decrease) slightly until a point where the shoreline turns up against the waves and steepness usually decreases due to deposits of materials (BRUUN, 1954 b, c). Comparing the profiles we find in all cases of uniform material that the geometrical shape follows the equation $y^{3/2} = p \cdot x$. A flattening of the profile in its deeper sections may occur, where the shoreline turns up against the waves. This puts a brake on the drift. Here the profile may approach the equation $y^2 = p. x$, as also developed by BRUUN (1954b). Changes come gradually in all cases. The question now arises: "How does this affect the Bruun Rule?" Obviously the only change is that a quantity of material must either be added to or subtracted from the quantity $1. a = s.h$ ($h$ = limiting depth as defined earlier as the end of a "fading-out" section). The total change of quantity in the profile is the Bruun Rule's $1 \cdot a$ (1 times a) plus or minus the change in littoral drift capacity between sections a-a and b-b. This quantity may increase or decrease, even to a negative value, but the basic principles of the rule remain the same as long as bottom materials are grains from fine sands and up. If not, adjustments, as mentioned later, will have to be made. We are still talking about shores uninterrupted by such three-dimension elements which may cause severe discontinuities in drift modes and patterns, as they *e.g.* occur by radical changes in bottom materials like outcropping of harder materials in reefs or in headlands, or where the shore is "punctured" by a river or tidal inlet, which disrupts the continuity of the drift, positively or negatively, and thereby disturbs the normal profile development, so that the Rule's basic principles of profile development are not valid any longer. But even then it should be remembered that as long as profile geometries remain the same the Rule can still be used, accepting the adjustment in quantities caused by the change in drift quantities.

There are yet other factors which may influence the profile development. Materials may be blown in by winds or gained or lost by diffusive processes as explained in the following. Such quantities may, however, be quantified and included in the balance equations. The main difficulty lies in an exact or even approximate definition of "the offshore limit" for the wave induced nearshore/offshore interaction process. No equilibrium balance situation needs to exist in the deeper offshore area, where currents are offshore-originated. Bottom sediments in movement are of clay and silt size, occasionally fine sand where currents are strong enough to carry the material. Current-generated ripple marks have been found at very great depths, *e.g.*, at 5000 ft (1500 m) on the Blake Plateau off the Carolinas and the US Southeast Coast, including indications of scour due to currents over shells. Depending upon the grain size, the "base" may extend to shallower or deeper water. This refers to open sea coasts, where sediments of silt and clay size may be carried long distances in suspension before deposition. In defining the area of exchange between nearshore and offshore drifts, one therefore has to consider the grain sizes and materials of certain characteristics available on the shore. The finest parts of this material, which may stay in suspension for long periods, therefore have to be included in the materials balance equations. This refers to a certain depth beyond which fines may still be transported to much deeper water for deposition (BRUUN, 1980; HANDS, 1980). Equation (3), $s = la/h$, then has to be adjusted. If the factor $r$ = ratio in percentage of eroded material smaller than 0.06 mm to the total amount of material eroded, the adjusted equation (3) = (8) becomes:

$$s = la\,(1 + r/100)/h \qquad (9)$$

A "dividing line" between inshore and offshore bottom areas therefore does not exist in a strict sense of limits. At the most one may be able to define a "dividing area" of a certain width, which could in turn be explored by comparing onshore and offshore sedimentary characteristics, by investigating the bottom fluctuations or by tracing the movements of the bottom sediments. Such tracing would then have to be continued over a sufficiently long period of time to establish the boundary area with a reasonable accuracy. For the establishment of a qualitative balance criterion it is, however, not absolutely necessary to go into the smallest details of the transverse exchange of materials. The offshore area of exchange may be set by long-term study of the variations in depth occurring. One may then still consider the losses of a certain very limited quantity of fines—if available—in the beach and the nearshore sediments. Another problem could be waves of material travelling on the offshore bottom due to current action (BRUUN, 1954 a, b). Figures 5 to 8 describe four different situations. Figure 5 shows a closed basin, *e.g.* a lake, where it is possible to account for all material depositions on the bottom, as erosion and river discharges are known. A rise of lake level causing erosion will therefore—with a certain phase delay—be balanced by a bottom deposit corresponding to the yield of sediment by erosion to the lake. This is a "Great Lakes phenomenon" in the United States, well described by several reports by the WES of the USACE in Vicksburg, Mississippi.

Figure 6 shows a wide shelf, where all erosion material or other material discharges, *e.g.* by rivers, will be deposited on the shelf and for this reason is traceable by mineral composition and grain sizes.

Figure 7 presents a narrow shelf limited oceanward by a steep slope extending to deep water. In this case it will be necessary to introduce a "loss-function" at the outer edge, which may be determined by topographic surveys or by tracing. Loss of sediment to canyons is a known phenomenon, *e.g.* in California. If the percentage of loss can be evaluated, one has to add another loss percentage R to eq. 3 making it:

$$s = \frac{l \cdot a}{h}\left(1 + \frac{r}{100}\right)\left(1 + \frac{R}{100}\right) \qquad (9)$$

It may, of course, be difficult to determine R, unless material deposits on a slope.

Figure 8 is a common case on shores with an offshore platform generated during a period with a lower sea level. It shows a relatively steep slope some distance from shore which becomes an area of deposition for sediments "creeping or washed out from shore". This does not necessarily mean that some fines may not escape beyond that limit. On a sand shore this will usually be a matter of minor quantities only. The slope, in other words, indicates the limit of the exchange area, but deposits on the slope itself could be of considerable magnitude, eventually causing slides as experienced *e.g.* off Newfoundland.

Usually it will be possible to evaluate the outer limit of the exchange area by more than one method, *e.g.* using depth topography and results of sedimentological investigation, and thereby arrive at a reasonable result that is useful for a practical quantitative evaluation of erosion and deposition.

At the Hadera offshore terminal in Israel (BRUUN, 1989) profile analyses using the statistical methods described in BRUUN (1954 a, b), radioactive tracing and steel pegs placed in grid system, have been used to determine the offshore longshore drift versus the transverse drift. On relatively exposed shores there are

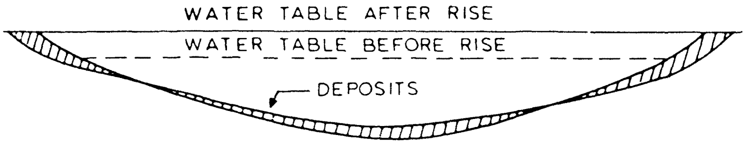

Figure 5. Closed basin reaction to rising sea level (Bruun, 1983).

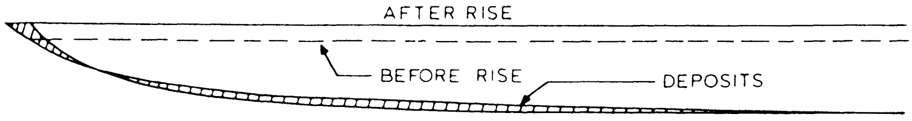

Figure 6. Wide shelf reaction to rising sea level (Bruun, 1983).

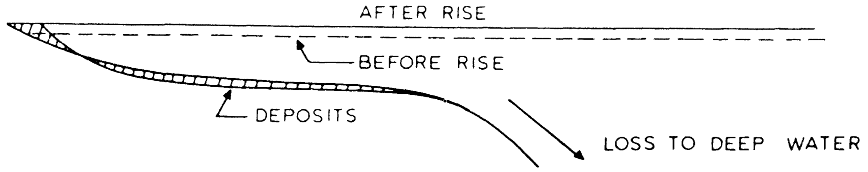

Figure 7. Narrow shelf reaction to rising sea level (Bruun, 1983).

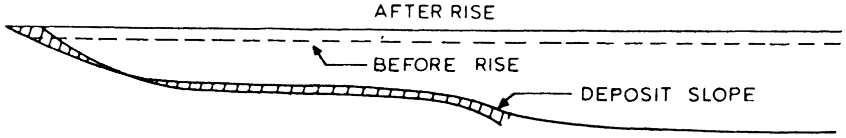

Figure 8. Profile with deposit slope under rising sea level (Bruun, 1983).

Table 3. *Means of vertical, short-term fluctuations (Bruun, 1973).*

| Place | 0–20 ft (0–6 m) | 20–30 ft (6–9 m) |
|---|---|---|
| Tokai, Japan | 0.0 ft<br>(0.0 m) | 0.5 ft<br>(0.15 m) |
| Mission Bay, California | 0.8 ft<br>(0.25 m) | 1.5 ft<br>(0.45 m) |
| Danish North Sea coast at Bovbjerg | 1.4 ft<br>(0.40 m) | 2.4 ft<br>(0.7 m) |

Table 4. *Test on bottom fluctuations at La Jolla, California (Inman, 1956).*

| Depth in ft (m) | Level change in ft (m) | | Sand level occurrence in % of obs. time |
|---|---|---|---|
| 70 (21) | 0.15 | (0.04) | 61 |
| 52 (17) | 0.16 | (0.05) | 88 |
| 30 (9) | 0.29 | (0.10) | 100 |
| 18 (5.5) | 0.62 | (0.20) | 100 |

many indications that the offshore limit may be in the 50 to 70 ft (15–21 m) deep area on a long-term basis (TRASK, 1955).

How deep the limit is largely depends upon the wave exposure. By splitting up bottom areas in depth intervals, one many arrive at figures for variations in depth as shown in Table 3 (BRUUN, 1973) for three different areas extending from relatively mild (Japan) through medium (California) to exposed (Denmark, North Sea) conditions. Recent Danish results as mentioned earlier demonstrate that shore-term fluctuations on the North Sea Coast at Thyboron vanish at a depth of 16 m. This is about $2H_{max}$ (BRUUN, 1973). Here 3-D effects also occur.

Table 3, however, only demonstrates that seasonal fluctuations go deeper than 9 m. Field examples from La Jolla Beach in southern California close to Mission Bay gave the results listed in Table 4 (BRUUN, 1956; INMAN and RUSNAK, 1956). It may be seen that fluctuations still take place at 21 m (70 ft) depth and probably further out. This, however, may be a result of offshore drift phenomena and could, of course, also be survey variances. TRASK

(1955), referring to the southern California coast, maintains that the 30 ft (9 m) depth is the boundary for the larger seasonal nearshore fluctuations and that the 60 ft (18 m) depth is the final boundary for the seasonal offshore fluctuations of the bottom. The long-term exchange zone referring to a "geological development" like sea level rises undoubtedly extends deeper, beyond 20 meters.

It may be noted that fluctuations are small from 17 m oceanward and that sand levels were not always present at depths of 70 ft (20 m) and 52 ft (17 m). Even if the exchange area may extend further out, the importance of the depositions beyond 21 m may be relatively small and not disturb the "rule" to any practical extent. If in certain areas material is carried toward land from deeper waters by current-wave interactions this material must, of course, be included in balance equations. But this is a rare case. Normally bottom material decreases in size oceanward. If the offshore bottom was a source for natural nourishment of the nearshore area grain size would increase oceanward from a certain point. It should then be possible to trace the drift shoreward by grain-size distributions. This could happen in front of shores which have been glaciated, such as Denmark. The author, however, does not, at this moment, know of even one case, where this happens (or has happened), but he has experienced "negative cases" where it could possibly take place but did not. An example is the west coast of Jutland, Denmark, where sea level for a very long period, has stayed relatively stable compared to land due to a glacial rebound which is now being overpowered by sea level rise. Here coarse glacial sand is available in the near-offshore. A similar result may be arrived at by a different logic. If such a source existed it would eventually run dry. Furthermore, an equilibrium slope would develop resulting in an equilibrium profile *and this is one of the Bruun-Rule's main assumptions.* Adjustments of grain sizes are from land and out. Finally, and most logical for every representative of the physical sciences, a rising sea level does not "generate sand". It rather makes it worse for the waves to pick up sand offshore even during the "rare events". To consider the offshore bottom a source of material for the nearshore, therefore, is illogical, unless conditions like special current-wave interactions might make it possible. If sea level drops, or it stays stable for a longer time period, the offshore bottom may, until a certain limit, offer material for the construction of beach ridges, as pointed out by TANNER (1988) in an article published in the *Journal of Coastal Research* (4(1), 83–91). Ridges, however, may be built up any time—also during a rising sea level on shores, where the littoral transport slows down. This is very apparent, where the beach drift material is coarse.

In his article on "Additional Sediment Input to the Nearshore Region" published by *Shore and Beach* (Oct. 1987), R. Dean points at the nearshore bottom as a source of "considerable likeliness" for beach nourishment even under a rising sea level. Particular reference is made to Florida. In doing so he makes several errors in his references to the Bruun-Rule. Dean does not seem to be acquainted with the rule's adamant assumptions of "equilibrium profile" and "ultimate depth for exchange of material between shore and offshore" (BRUUN, 1962, 1983). His assumption of a slowly rising sea level during the last 6,000 years is in opposition to facts. Sea level has fluctuated. See *e.g.* the earlier cited article by TANNER (1988). Dean refers to ridges built during a rising sea level, not a lowering. They were, however, mainly built during a lowering or a stable sea level interrupted by rising levels. BRUUN (1962) explains that it may be a considerable phase-lag between sea level rises and profile reactions. As mentioned earlier ridges may also be built any time as a result of decreases of littoral drift capacities, as we see it in spits, recurved spits, angular forelands, tombolos *et cet.* (BRUUN, 1954). It is also very possible that material inside "the ultimate depth" which is always located quit a distance from shore, *e.g.* more than 20 m depth on the Florida east coast and more than that on the heavily exposed Danish North Sea Coast (BRUUN, 1954, 1962; BRUUN and SCHWARTZ, 1985) may be moved towards shore if it happens to be surplus material, *e.g.* deposited by currents on "the top of the equilibrium profile". Net-movements towards the shore, however, stop when an equilibrium slope or condition has developed. As mentioned by BRUUN (1962) there might be a phase lag in time between water table movements and the reaction of the profile, particularly for gentle slopes.

Dean's postulate on movement of material towards shore in a laminar sublayer refers to a horizontal bottom. If the bottom has a slope or if it (as is usually the case for deeper waters offshore) is composed of fine particles which easily become "fluidized" by high pressure gradients caused by wave action, the movement may be in an offshore direction in a kind of "density current". The experimental results by MURRAY (1966) mentioned in connection with Figure 2 clearly demonstrated the tendency for finer grains to move seaward, undoubtedly a result of turbulent diffusion. ZENKOVITCH (1962) in his field experiments in the Black Sea describes how "the distribution of colored sand particles showed the presence of a powerful bottom outflow seawards". A wind blowing with the waves which is the normal case produces a current with the wind at the surface and a return current at the bottom, further increasing the tendency for smaller grain sizes to move seaward. BRATTELAND and BRUUN (1975) undertook tracer experiments at 72 meters depth on the bottom of the North Sea. They found that material mainly moved up against the wave action. Depth was about 3.5 times wave heights during severe storms confirming Hands and Hallermeier's earlier results. Inside the ultimate depth for any movement, as assumed by the Bruun-Rule, material may move shoreward by bottom creep (LONGUET-HIGGINS, 1953; CARTER, LIU and MEI, 1973), but only until the bottom has developed an equilibrium slope, considering the effects of nearshore circulation systems. Dean's statements on grain sizes are also peculiar considering the pre-condition of equilibrium profile until the ultimate depth in the Bruun-Rule. Material does not start moving shoreward outside the ultimate depth just because sea level rose. It will probably rest even better!! Finally it is a fact that most shores of the world (80%) erode. In Florida, inlets are mainly responsible. Not so in most other parts of the world where sea level rise (in most cases) is the only plausible cause of erosion (see *e.g.* EVERTS, 1985).

A most recent contribution is probably the paper by P. NIELSEN (*Coastal Engineering*, vol. 12, no. 1, 1988, pp. 43-62) titled "Models of Wave Transport." Nielsen shows how wave-induced transport by non-breaking waves over a horizontal, rippled bed can be presented by three different models which are evaluated through comparison with wave flume data. The conclusion from this testing is "the simpler the better." It is shown that the process in question can be modelled without quantitative consideration of suspended sediment distribution. Only a reference average concentration at the bed is needed. On the other hand, classical diffusion models severely under-predict the transport of coarse sand in suspension because the process is much more organized than diffusion. In the conclusion of his paper Nielsen states that the influence of wave shape, or the shape of the oscillating water velocity movement, on the direction of material transport is determined by the relative maximum and minimum velocities and by entrainment coefficients. This refers to fine sands but for coarser sands acceleration effects need to be included.

Nielsen's figures demonstrate how sands $<$ 0.2 mm had a predominant transport up against the direction of wave propagation that means opposite to the largest absolute velocities. This is a confirmation of the field results by MURRAY (1966). "Fine sand" is interpreted relatively as $d/A < 0.004$, $d$ = grain diameter. $A$ = semi excursion fundamental mode. The finest non-cohesive particles move until they come to an "ultimate rest." Before then the relatively coarser grains have stopped movements. In this respect it is interesting to note the classical results by SHIELDS (1936), BROWN-KALINSKE (1950) and BROWN-EINSTEIN (1950). According to Shields bed load transport is proportional to $1/D$ where $D$ is grain diameter, BROWN-KALINSKE got the same and BROWN-EINSTEIN $1/D^{2/3}$. Nielsen's results may be influenced by a shallow water condition of rather steep ripple marks. For more rounded ripples, which may be found in deeper waters, the predominance of offshore transport decreases and may turn to onshore for a horizontal bottom. When the bottom starts sloping updrift is again reversed, particularly if wind generated return flows of bottom waters enter the picture. In deeper waters like "the ultimate depth" three-dimensional phenomena like current-generated moving sand waves or undulations may have arrived on the scene. They were already noted by divers on the Danish North Sea Coast off Thyboron in the 1940's and were reported to move parallel to shore. Recent research seems to prove that they may also move under an angle probably with a meandering current. If they move in at one place due to such current they must move out again somehow at a different place simply due to the equation of continuity for flow. The magnitude of transport however is small.

## CONSOLIDATION

Various geological settling or tilting theories have been proposed. Tiltings are usually associated with fall areas, like the Californian Pacific which seems to tilt up causing less relative sea level rise, 1–2 mm/year compared to the Atlantic (2–4 mm/year). The same is true for most of the Pacific coast where the San Andreas fault line is close to shore. Tectonic movements may also be of volcanic nature, such as part of the Icelandic, Italian, and Japanese shores. Most Scandinavian shores are still rising relative to sea level as a result of glacial rebound. This includes the northernmost part of Jutland, but not Skagen, the northernmost point where, as explained by Hauerbach in a 1988 article published in the *Journal of Coastal Research* (4(4)), subsidence due to compaction of deep water silts in a finger of the Norwegian Trench apparently takes place causing a negative balance of 3–5 mm/year. This assumes no glacial rebound at Skagen. Most of Sweden, apart from the southernmost province of Skaane, is rising. This is very evident in the west coast province of Bohuslän south of the town of Gothenborg where Svante Arhenius' famous experiments on the relative movement of land and sea were begun in 1890 with the drilling of holes in rocks facing the sea, and in parts of the Oslo Fiord in Norway. In other sections of the Scandinavian peninsula, such as the Norwegian Atlantic coast, movements have largely stopped, but it is undoubtedly continuing in the northernmost part of the Fenno-Scandinavian peninsula. The character of the bed rock may be responsible for the differences in recorded movements.

In the Mediterranean area the relative movements may have been influenced by subsidence, *e.g.*, at Venice, where the withdrawal of water and gas from underground has undoubtedly been responsible for the recorded sinking. Table 5 (BRUUN, 1983) shows that movements at Venice have not been solely eustatic. On the other hand, Table 6 indicates that the Venician subsidence now has stopped and a small recovery may take place following reduced withdrawal of groundwater. This tendency has continued.

Table 5. *Rises of sea levels during the period about 1930 to 1971.*

| | Venice | Trieste | Florida East Coast |
|---|---|---|---|
| Total | 0.8 ft (25 cm) | 0.3 ft (10 cm) | 0.4 ft (12 cm) |
| Eustatic | 0.3 ft (10 cm) | 0.3 ft (10 cm) | 0.4 ft (12 cm) |
| mm/year | 6 mm | 2.5 mm | 3.0 mm |

Other areas of subsidence include parts of Holland, where filling on top of silt and clay layers has been undertaken, the Hokkaido Island in Japan where sinking is mainly due to recovery of gas from the subsurface, and part of the Los Angeles area in California where extraction of oil has taken place. Gas extraction from the sea bottom is expected to cause considerable subsidence of the Dutch North Sea coast in local areas (Wiersma, pers. communication, 1988).

## DO LOSSES OR GAINS OF MATERIALS NOT RELATED TO SEA LEVEL RISE, TECTONIC MOVEMENTS, AND SUBSIDENCE INFLUENCE COASTAL GEOMORPHOLOGY AND THE APPLICATION OF THE BRUUN RULE TO EXPLAIN SHORE EROSION?

The answers to the above questions may be summarized briefly as follows.

(1) In the case of tectonic movements its known value is added to or subtracted from the sea level movement known from adjoining shores not subjected to tectonic movements.

(2) Subsidence, if known, is added to the known sea level rise. Some extraordinary surface sinkings, *e.g.* Hokkaido (Japan), Long Beach (California), local areas in Holland, and

Table 6. *Comparative annual movements at Venice, Trieste and Florida in mm/year. Period 1930 to 1971.*

| Period | Venice | Trieste | Florida East Coast |
|---|---|---|---|
| 1930–1950 | 7.5 | 2.5 | 5.0 |
| 1942–1962 | 3 | 2.5 | 4.0 |
| 1961–1971 | 4.5 | (2.5) | 3.0 |
| 1971–1980 | –1.6* | | |

* Pumping of ground water prohibited, causing a temporary uplift.

Venice (Italy) are in part caused by man's activities. In either case, (1) or (2), the shoreline movement will adjust itself to the actual relative movements land/sea. Consequently, uplifts will cause a relatively protruding shoreline in the local area of uplift and an indented shoreline where settling or downwarping occurs. These phenomena are well known, *e.g.* from California, the Danish North Sea Coast, Italian shores on the Adriatic and from Scandinavian shores where relative but uneven uplifts take place. Protruding areas will have a groin-effect on adjacent shorelines. Settling or sinking areas will give a trap effect, in either case necessitating adjustments in the use of Bruun Rule based on known movements.

## GENERAL CONCLUSION ON THREE-DIMENSIONAL EFFECTS

The Bruun Rule (1962) was proposed as a two-dimensional model for profiles which are subjected to wave action of perpendicular incidence or for the "so-called nodal areas" of littoral drift. In practice this a statistical not physical quantity. Moving away from these nodal areas bottom profiles retain their geometrical shape and steepness, if the shoreline, as at the Danish Thyboroen Barriers (BRUUN, 1954 b,c), turns slightly with the waves so that total drift increases with the gradual increase of the angle of incidence of waves or the breaker angle. If the shoreline is straight or turns slightly up against the wave action, profile steepness tends to decrease gradually as seen from the Danish North Sea Coast and from Lake Michigan. This, however, only changes the p-value in the e.q.: $y^{3/2} = p \cdot x$. As proven by numerous field surveys (United States, Denmark, Holland) the bottom profiles react to wave action causing nearshore/offshore exchange of materials up to depths of 3–4 $H^b$, where $H^b$ refers to waves occurring at intervals once every 20–50 or up to 100–200 years. Tectonic movements will of course interfere with the rate of profile movements relative to sea level change, but only if the shore is built up of alluvial materials, not with the profile geometry. The Bruun Rule still is applicable when used in relation with the relative land/sea level movements. Littoral drift barriers such as headlands and tidal inlets may cause major deviations in the development of bottom profiles. The Rule is only applicable if overall stability of profile geometries are maintained. Settling or consolidation of shores on softer materials, as well as erosion of softer bottom materials of silts and clays which when eroded diffuse away to deeper bottom areas will influence the rate of development, but not profile geometry if the bulk part of the material is sand. Such areas will act as material traps influencing the rate of erosion of not only the area itself (like many barrier coasts in Denmark and Florida) but the adjoining shore as well. The Rule is still applicable when adjusted to the actual relative movements land/sea level. Profile geometries do not change. The perpendicular-forces are the overwhelming ones!

## IS THE RULE APPLICABLE UNDER CONDITIONS OF A FALLING SEA LEVEL?

Falling of sea level has taken place in various geological periods, when interglacial ice melts were replaced by glacial periods. Tectonic uplifts have also occurred and this, of course, caused adjustments of beach and bottom profiles to the new situation. At a certain depth with a slope $\alpha$, adjustment to a steeper slope > $\alpha$ may then result. With reference to Figure 9, a preliminary inspection seems to support the view that the profile development now is going to be the opposite of the development shown in Figure 1 for a sea-level rise. But second thoughts cause some revision. Firstly, the eroding and accreting forces are very different. In the nearshore area a falling sea level will generally cause erosion of the bottom and accretion on the shore. This is the universal geological and geomorphological experience. On the beach, ridges may then build up (one after the other) as sea level continues to fall. Beach ridges are parallel to the shore and well known from the huge beach-ridge systems found on shores all over the world, particularly in coarse materials. This, however, mainly refers to steep shores. In the case of more gently sloping profiles, offshore bars may not only move seaward, but new bars or shoals may appear. The material in all cases comes from the surrounding shores and bottoms. It may come from the longshore drift building up marine forelands (BRUUN, 1954b; ZENKOVICH, 1967) or from offshore bottoms (TANNER, 1988). This requires adjustments of the general Bruun-

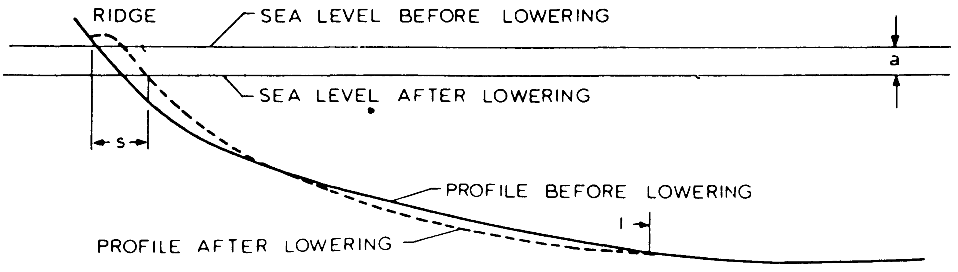

Figure 9. Profile development following a lowering of the sea level (Bruun, 1983).

Rule and its two-dimensional assumptions, as explained above. Maintaining profile equilibrium geometry the Rule is still valid even for an accreting shore under a rising sea level, with proper "amendments".

## LATEST DEVELOPMENTS IN RESEARCH

An extremely informative bibliography of sea-level changes along the Atlantic and Gulf coasts of North America has recently been published by LISLE (1982). The comprehensive material reported (200 references!) leaves no doubt that sea level has fluctuated dramatically in known geological history and that it has had an equally dramatic influence on the distribution of land and water masses and surfaces. There is little reason to assume that these events are not a continuing process caused by differences in energy emissions by the sun and the accompanying reactions on temperatures on the earth, possibly including some changes in the air chemistry. One may get an impression of the comprehensive work by LISLE (sponsored by the Office of Naval Research) by the following lines in direct quotation:

> "Sea level changes are also accompanied by morphologic reactions on the bordering coastlines. The evolution and migration of barrier islands, capes, and other coastal features appear to be directly related to sea level changes; thus they have been included in this bibliography. The Bruun Rule, proposed by Bruun, 1962, demonstrates how a shoreline is in equilibrium with its nearshore bottom. A rising sea level can cause that equilibrium to change, forcing immediate readjustments. Hoyt, Otvos, and Kraft *et al.*, among others, have examined the origin and migration of barrier islands. Estuaries and salt marshes have been considered against the light of sea level rises by Keene, Redfield, Kraft and Caulk, Swift, Kayan and Kraft, Froomer, Rampino and Sanders, and others."

The "main lines" of relatively slow geological development, therefore, leave no doubt. With respect to the short-term development, a great number of variables exist, as is explained earlier in this paper. If the shore is composed of uniform material of sand size from the dunes to depths of say 20 to 30 m and it is located in a neutral area with respect to littoral drift, conditions are optimum for fulfillment of the rule. If not, complications may arise. DUBOIS (1982) considers "Relation among Wave Conditions, Sediment Texture, and rising Sea Level". His remarks concentrate on the influence of sediment characteristics. If an eroding profile runs into very coarse material or if, conversely, it proceeds into very fine (silt and clay) materials, the profile has to adjust itself to a new situation and it may be difficult to check on the validity of the rule unless all the new characteristics are considered. Some authors (*e.g.* HALLERMEIER, 1981b) have already tried to do this in simple cases. Short-term evidence must of necessity rely upon conditions of an ideal nature like those reported from the Great Lakes (HANDS, 1980). We are, in other words, forced to develop an "envelope of possibilities" with factors carrying various weights, but comprehensive research on profile developments giving physical reasons (examples: BRUUN, 1954 a, b; WEGGEL, 1979; HANDS, 1980; HALLERMEIER, 1981b) and mathematical "commonsense reasonings" (ALLISON, 1980, 1981) all point in the same direction which is: Nature tries to establish a new equilibrium condition by erosion of the beach and nearshore bottom and deposition offshore of the material eroded. Some, perhaps all of it, will stay on the nearshore, predominantly wave-generated bottom. Other materials may move farther away. With the experience already gained in past geological history, combined with recent experience on sea-level rises which are evident and considering the unavoidable fact that this will cause a long-term, long-lasting erosion, American geologists have expressed concern in their statement of March 1981 entitled "Saving the American Beach: a Position Paper by concerned coastal Geologists", now widely distributed in the United States. Their concern is a product of much thought about the consequences of a continued losing battle against beach erosion. We shall, of course, accept this, but we do not necessarily need to defend ourselves or to win the battle everywhere, if we can win it where it is most needed. Coastal protection technology is still advancing ("God created the Earth, but the Dutch created Holland"). At some strategic points we will win or at least maintain a condition of equilibrium. In other, much larger, areas we must organize the retreat in an orderly manner and with determination. So we must zone the shore and just wait until sea level retreats again, as it has done before innumerable times (BRUUN, 1983).

The 1986 Environmental Protection Agency (EPA) conference in Washington, D.C., on "Effects of Changes in Stratospheric Ozone and Global Climate" contributed to the understanding of the large scale changes in the atmosphere and their climatic effects including warming trends and the resulting influence on the sea level, thereby on coastal erosion. Recent reports including the EPA report on the development of erosion at Ocean City, Maryland, work by EVERTS (1985), and report of the Louisiana Wetland Protection Panel (April, 1987) all present objective quantified views on the development which is progressing of great concern to all coastal scientists and engineers and to a number of coastal communities.

## SUMMARY AND CONCLUDING REMARKS

The Bruun Rule proposed in 1962 seems to have an overall general validity. But it is two-dimensional and therefore care should be taken in expanding it three-dimensionally. The two-dimensional boundary conditions in relation to the composition of beach and bottom materials and to the bottom geometry extending to the ultimate depth of exchange should be evaluated and accounted for in the material balance budget and equations. For this bottom fluctuation, statistics and tracing may be used. The theory is firstly one of erosion, not accretion. It is evident in a laboratory tank and under similar simple field conditions but in all other cases it must be subjected to realistic adjustments of its material balance assumptions and equations.

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## □ RESUMEN □

La regla de Bruun de erosion, denominada asi por geomofologos americanos (Schwartz, 1967) fue publicada por primera vez en 1962 (Bruun, 1962) y, en breve, se refiere al balance de sedimentos transversal de un perfil de playa a largo plazo. La regla se basa en la hipotesis de la existencia de un balance de sedimentos entre: (1) playa y (2) perfil del fondo del mar (exterior a la playa). La figura 1 es una representacion esquematica del efecto, una traslacion del perfil una distancia s despues de una elevacion de a del nivel del mar, produce una erosion de la linea de costa y un deposito de sedimentos. Este tema ha sido tratado teoricamente (Hallermeier, 1972; Allison, 1980; Bruun, 1980, 1983) y experimentalmente en la naturaleza (Bruun, 1954a,b, 1962, 1980, 1983,; Dubois, 1976; Rosen, 1978, 1980; Weggel, 1979; Fisher, 1980; Hands, 1980; Schwartz, 1965, 1967, 1979). Con posterioridad la Regla ha sido utilizada en diferentes informes sobre erosion de playas en Ocean City, Maryland, "Impacto potencial de la elevacion del nivel del mar en la playa de Ocean City, MD" publicado por la EPA, Octubre 1985 y en un articulo de Everts (1985).

La regla ha sido usada a veces indescriminadamente sin tener en cuenta sus limitaciones. En primer lugar debe tenerse en cuenta que la regla es basicamente bidmensional, pero se aplica casi siempre con caracter tridimensional. Esto ha causado un gran numero de malas interpretaciones. Usada objetivamente la Regla ofrece una linea de referencia sobre todos los desarrollos que ocurren en el perfil basico en relacion con el nivel del mar observado.

En este articulo se discuten condiciones de contorno, desviaciones y ajustes que hacen la Regla util para interpretar los fenomenos observados de una manera cuantitativa.—*Department of Water Sciences, University of Cantrabria, Santander, Spain*