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Sea-level rise and shoreline retreat: time to abandon the Bruun Rule

J. Andrew G. Cooper[a,*], Orrin H. Pilkey[b]

[a]School of Environmental Studies, University of Ulster, Coleraine BT52 1SA, Northern Ireland, UK
[b]Nicholas School of the Environment and Earth Sciences, Division of Earth and Ocean Sciences, Duke University, Durham, North Carolina 27708, USA

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Abstract

In the face of a global rise in sea level, understanding the response of the shoreline to changes in sea level is a critical scientific goal to inform policy makers and managers. A body of scientific information exists that illustrates both the complexity of the linkages between sea-level rise and shoreline response, and the comparative lack of understanding of these linkages. In spite of the lack of understanding, many appraisals have been undertaken that employ a concept known as the "Bruun Rule". This is a simple two-dimensional model of shoreline response to rising sea level. The model has seen near global application since its original formulation in 1954. The concept provided an advance in understanding of the coastal system at the time of its first publication. It has, however, been superseded by numerous subsequent findings and is now invalid.

Several assumptions behind the Bruun Rule are known to be false and nowhere has the Bruun Rule been adequately proven; on the contrary several studies disprove it in the field. No universally applicable model of shoreline retreat under sea-level rise has yet been developed. Despite this, the Bruun Rule is in widespread contemporary use at a global scale both as a management tool and as a scientific concept. The persistence of this concept beyond its original assumption base is attributed to the following factors:

1. Appeal of a simple, easy to use analytical model that is in widespread use.
2. Difficulty of determining the relative validity of 'proofs' and 'disproofs'.
3. Ease of application.
4. Positive advocacy by some scientists.
5. Application by other scientists without critical appraisal.
6. The simple numerical expression of the model.
7. Lack of easy alternatives.

The Bruun Rule has no power for predicting shoreline behaviour under rising sea level and should be abandoned. It is a concept whose time has passed. The belief by policy makers that it offers a prediction of future shoreline position may well have stifled much-needed research into the coastal response to sea-level rise.

Keywords: Sea-level rise; Transgression; Coastal erosion; Coastal management

* Corresponding author. Fax: +44 28 70324911.
E-mail address: jag.cooper@ulster.ac.uk (J.A.G. Cooper).

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1. Introduction

The global rise of sea level during the Holocene (Pirazzoli, 1991) and during the historical period have prompted studies of the short-term response of shorelines to changes in water level (Hands, 1979, 1980, 1983; Brambati et al., 1998; Ciavola and Corbau, 2002), geomorphological analysis of shoreline behaviour during transgression (Rosen, 1978; Carter and Orford, 1993; List et al., 1994, 1997) and investigations of transgressive coastal stratigraphic sequences (Kraft, 1978; Thom, 1983; Cowell et al., 1995; Cattaneo and Steel, 2003). Factors that cause changes in the morphology of coasts are numerous and include sediment supply, variations in wave energy, tidal currents, wind action, sediment type, tidal inlet dynamics, morphological feedback, etc. Isolating the influence of sea-level rise from these other factors is perhaps the biggest challenge in discerning its impact.

Prediction of future sea-level rise and the resulting shoreline retreat are, however, among the most important tasks facing coastal and global change scientists, particularly given the population concentration in coastal zones. Cohen et al. (1997) estimated that over 2 billion people (37% of the global population) live within 100 km of a coastline. Much of this concentration is in the tropics, but dramatic increases have been noted in the temperate regions of, particularly, the Mediterranean and the USA ocean coasts. In the Mediterranean, the coastal population was estimated at 146 million in 1990 and the urban coastal population alone is projected to rise to 176 million by 2025 with an additional 350 million tourists (Hinrichsen, 1998). In the United States, 55–60% of the population live in the 772 coastal counties of the Atlantic and Pacific coastlines. Coastal population density in the United States rose from 275 to 400 people per km^2 between 1960 and 1990 (Hinrichsen, 1998). Considerable effort has been expended on the prediction of sea-level rise (e.g. IPCC, 2001) although much uncertainty remains. The effort to predict shoreline behaviour related to such sea level changes has, however, received less attention.

Both identification and characterization of the critical parameters that control shoreline behaviour is difficult. While the prospect of future shoreline erosion related to sea-level rise is of global concern (Bird, 1985) it is increasingly apparent that the patterns of shoreline change during transgression are non-uniform and highly site-specific (Cattaneo and Steel, 2003). Thus, it might be expected that predictions of future shoreline erosion rates for given sea-level rise must be based, in significant part, on local geomorphological and sedimentological characteristics including the geological framework, sediment supply and dispersal rates, sediment type, existing geomorphology, vegetation, lithification rates, abrasion, contemporary dynamics, human influences, etc.

In spite of the scientific acknowledgement of significant local level control in shoreline response to sea-level rise, we show in this paper that the most widely used contemporary method of quantifying shoreline change is the 50-year-old Bruun Rule of erosion (Bruun, 1954, 1962, 1988). The "Bruun Rule", so named by Schwartz (1967), is a simple generic geometric model of nearshore profile evolution under rising sea level that is often assumed to work on all sandy shorelines.

In this paper we illustrate the extensive contemporary use of the Bruun Rule as a predictor of shoreline retreat and demonstrate that it is a significant contributor in shaping societal response to rising sea level. We critically review the Bruun Rule shortcomings, and discuss the reasons for the persistence of the approach in spite of its lack of scientific credibility. From this analysis, several generic conclusions are presented regarding the application of this and similar earth surface models for environmental management and policy formulation.

2. History of the Bruun Rule

Bruun (1954) concluded that, when considered in the shore-normal dimension, the nearshore zone existed in a profile of equilibrium on the basis of cross-shore profiles in Denmark and California. The profile could be described by Eq. (1):

$$h = Ay^{2/3} \tag{1}$$

where h is water depth, y is the distance offshore and A is a scaling parameter based on sediment characteristics.

In 1962 Bruun suggested that the equilibrium profile would remain unchanged as the shoreline moved back and up in response to a rising sea level. In this conceptual model (Fig. 1) he envisioned that sand was moved from the upper part of the beach profile to accumulate on the lower part of the profile. The upper profile volume of removed sand would be the same as the lower profile volume, which was held in place by a "sediment fence", called the closure depth. The closure depth concept is based on the assumption that sand transport on the shoreface occurs solely through the interaction of wave orbitals and sand on the sea floor. At the point of closure, the water is presumed to be sufficiently deep that sediment transport by waves is negligible. By definition, only small amounts of sand escape beyond the fence in a seaward direction. Other limiting conditions for this concept include no net longshore transport of sediment in or out of the shoreline reach under consideration as well as no significant loss to dunes or washover fans in a landward direction. Bruun (1962) envisioned the closure depth to occur off east Florida at a depth of 18 m but in recent years the assumed depth has become as shallow as 4 m for the purpose of nourished beach design (Pilkey and Dixon, 1999).

Dean (1977) modified the concept of the shoreface profile of equilibrium by examining a number of profiles along the US East and Gulf Coasts from Hayden et al. (1975). Dean concluded that the scaling parameter A was a function of grain size. Since A was the only free variable in the equation, the profile was assumed to be controlled by grain size alone; the coarser the grain size, the steeper the profile. Curray (1969) observed that the relative stillstand of sea level during the last 4000 years (compared to the rapid sea-level rise of the early Holocene) had allowed shorefaces to "mature", that is to steepen in response to onshore sand transport. Such shorefaces are at maximum steepness at the present time. The implication of Curray's suggestion is that present day shorefaces are not good indicators of future shoreface behaviour. Another implication is that on many shorelines, the point of sand starvation may have been reached as significant onshore transport has been cut off due to the depletion of relict shelf sources.

The major contribution of Bruun (1962) was the recognition that shoreline response to sea-level rise was not a simple retreat of a line in the sand but rather was a response of the entire shoreface, which on the US east coast extends to a depth of 10–12 m. The next major step in our understanding of shoreface evolution was the conceptual model of Swift (1976). According to Swift the shoreface responded to sea-level rise in a variety of ways depending upon grain size, wave conditions, sediment supply and several other factors. The shoreface would not be expected to retain its shape as it evolved. The Bruun Rule could be considered to be a special case of the more general case outlined by Swift.

Recent research has added much additional understanding of shoreface evolution. Clearly it is much more complex than envisioned by the conceptual models of either Bruun or Swift. Through the use of instrumented tripods with current meters, sediment traps and cameras, Wright and co-workers, summarized in Wright (1995), have documented complex boundary layer processes including extensive offshore transport, especially under storm conditions. Clearly a number of processes are involved in shaping the shoreface besides wave interaction with the seafloor. These include wind- and wave-induced upwelling and downwelling, gravity flows such as turbidity currents,

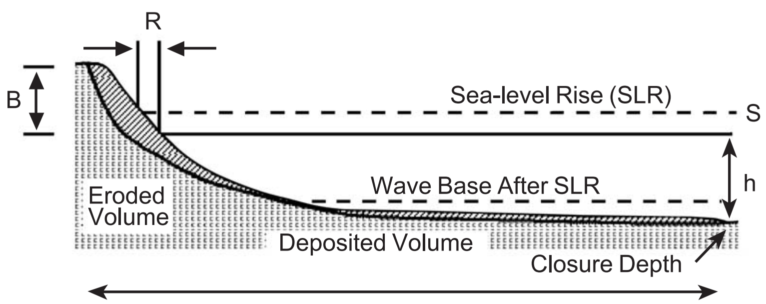

Fig. 1. The Bruun Rule of shoreline erosion.

tide- and wind-induced currents and interactions between waves and bottom currents of many origins.

The most recent step forward in understanding of shorefaces has been provided by side sonar mosaics of a number of US East Coast shorefaces (Thieler et al., 1995; Schwab et al., 2000). Combined with vibracoring, such records have provided evidence of complex sedimentary processes, frequent rock outcrops, rapidly changing surficial grain size of the sediment cover and unexpected bedforms, including shore-perpendicular, large-scale, linear, rippled depressions, apparently the product of large scale lateral currents during storms.

The original concept of shoreface retreat as postulated by Bruun, 50 years ago, was an advance in our understanding of large-scale coastal behaviour. It provided a conceptual basis for several advances that followed (e.g. Curray, 1964; Swift, 1976; Dean, 1990; Wright, 1995; Short, 1999). As this understanding of shoreface processes has evolved, the Bruun Rule and its accompanying shoreface profile of equilibrium concept have been utilised in applied coastal studies. They form the basis of a large proportion of the numerical mathematical models used to predict beach behaviour for engineering purposes, especially in the US (Thieler et al., 2000), and the Bruun Rule is the basis of theoretical models of coastal response to sea level rise (Cowell et al., 1995). Despite its initial breakthrough in identifying the entire shoreface as responsive to sea-level rise, the subsequent advances in scientific understanding outlined above have shown the Bruun formulation to be an inadequate descriptor of shoreface response to sea-level rise. Despite being in the dustbin of scientific history, however, the Bruun Rule remains central to many contemporary coastal management applications, and continues to occupy some scientists in seeking to find sites where it works.

3. The Bruun Rule and field evidence

The Bruun Rule states that beaches and nearshore profiles, when subjected to a sea-level rise, will translate upward and landward, maintaining their shore-normal geometry. If the amount of sea-level rise and the shape of the original offshore profile are known, the rule can be used to quantify the resulting shoreline retreat (Fig. 1). In a typical equilibrium nearshore profile, L is the length of the profile, Ø is the profile slope angle, B is the berm height and h is the depth at the base of the profile beyond which significant sediment exchange with the offshore does not occur (the closure depth). For a sea-level rise of the amount S, the profile will shift landward by the amount R according to the Bruun Rule equation (Bruun, 1988):

$$R = S(L/(B+h)) = (S)1/\tan Ø \qquad (2)$$

According to Storms et al. (2002), the Bruun Rule and its variants (Bruun, 1962; Edelman, 1972; Weggel, 1979; Dean and Maurmeyer, 1983; Dubois, 1975, 1976, 1977, 1992, 2001) is a geometric model which “quantifies and visualizes .... shoreface translation ... as long as the assumed geometric rules are valid.” A number of attempts to apply the Bruun Rule and compare its results with known erosion rates have been carried out, in for example Australia (Thom, 1983), Caspian Sea (Nikiforov and Rychagov, 1988), North Carolina (Pilkey and Davis, 1987), Louisiana (List et al., 1997), Chesapeake Bay (Rosen, 1978), Great Lakes (Hands, 1983). Unsurprisingly, given the simplified nature of the concept, none has demonstrated that it works.

The SCOR Working Group (1991) discussed studies that claimed to show that the Bruun Rule works. They point out serious flaws in many of the more widely cited proofs. For example, they criticize Schwartz’s (1967) verification of the Bruun Rule using the assumption that beach profile response to spring and neap tides would be comparable to profile response to sea level changes. The report does not mention the significant scaling problems with Schwartz’s (1965, 1967) wave basin studies. These wave basins were small (81×115 and 100×232 cm), increasing the chances of interference from edge effects. Schwartz used a mean grain size of 0.2 mm, maximum wave heights of 3 cm, and water level rises between 1 and 6 cm. According to Krumbein and Pettijohn (1988), sediment with a diameter of 0.2 mm is fine sand, which naturally occurs on many real beaches. If one mentally scales Schwartz’s sediment up to the size of a natural beach, these grains would be boulders. Additionally, global sea-level rise is on the order of about 1–2 mm per year, so Schwartz’s instantaneous water level rises are 100–600 times greater than the annual rate of change even at wave-basin scale. Although Schwartz (1965, 1967) used his results qualitatively, these results are extremely suspect due to these scaling problems.

The SCOR Working Group (1991) also reported that that the agreement between predicted and measured erosion rates for all of Chesapeake Bay found by Rosen (1978) is likely fortuitous. Dean's (1990) study compared state-wide average sea-level rise data from tide gauges to state-wide averaged erosion rates measured by Dolan et al. (1983). The widely scattered data points show no obvious trend, and three sites showed accretion even though relative sea level is rising. Therefore, Dean's (1990) regional approach fails more often than it works. The SCOR report also emphasized that the Rosen (1978) study shows how the Bruun Rule fails dramatically when applied to specific sites, with predicted vs. measured errors ranging from (+) 224% to (−) 68%. The SCOR report (1991) does not mention, however, that Rosen's (1978) use of statistics is egregiously in error. In this situation, using a weighted average of predicted erosion rates to compare to measured rates is misleading.

Lastly, the SCOR report (1991) discussed how Hands (1979, 1980, 1983) compared erosion rates predicted by the Bruun Rule to measured rates, and found that although the Bruun Rule over-predicted shoreline retreat while the lake level was rising, the retreat rates showed good agreement after lake levels began to fall. Hands concluded that this delay in agreement was due to the time lag of profile response. According to SCOR (1991), however, this agreement is probably due to the decrease in lake levels rather than the predictive ability of the Bruun Rule. If the lake level had continued rising, the initial disagreement almost certainly would have continued and might even have worsened.

Subsequently, Leatherman et al. (2000), Leatherman (2001) and Zhang et al. (2004) claimed to demonstrate a relationship between sea-level rise and coastal erosion for beaches along the New Jersey, Delaware and Maryland Coast and "confirmed" as well that the Bruun Rule was valid. Sallenger et al., 2000 and Pilkey et al. (2000) strongly contested these conclusions arguing that the authors unreasonably subsetted their data in order to test the relationship between sea-level rise and shoreline retreat without interference from other causes of retreat. They eliminated shorelines with net longshore transport, and those affected by inlets or coastal engineering structures, shorelines that were accreting or were stable and erosion hot spots and finally shorelines that have experienced storm activity in recent years. Most of the subsetting factors were impossible to determine or document and even if they were correctly characterized, the net result would be that the Bruun Rule could be tested on very few shorelines. Furthermore, Leatherman et al. (2000) and Zhang et al. (2004) failed to address the concerns of previous studies (Thieler et al., 2000) concerning the poor fundamental assumptions behind the Bruun equation.

The SCOR study and several others (List et al., 1997; Thieler et al., 2000; Pilkey et al., 2000; Sallenger et al., 2000) have showed that the Bruun Rule has no validity as a generic predictor of shoreline retreat. However, it continues in widespread use. We argue in this paper that its use should be discontinued.

4. Why does the Bruun Rule not work?

There are a number of specific problems with the Bruun Rule, some of which have been touched upon in the historical description of the evolution of geological knowledge of the shoreface. The fundamental problem is that scientists who use the Bruun Rule have not revisited post-1960 shoreface theory. The Bruun Rule is a "one model fits all" approach, which is unsuitable for a highly complex sedimentary environment such as the nearshore zone with large spatial and temporal variations in sediment supply, wave conditions and coastal retreat rates, in variable geological frameworks. In addition, there has not been a single field verification that the Bruun Rule actually operates as Bruun (1962) envisioned it.

The three main groups of reasons that the Bruun Rule does not work are as follows:

1. The assumptions behind it are so restrictive that they probably do not exist in nature.
2. It omits many important variables.
3. It relies on outdated and erroneous relationships.

Each of these factors is discussed briefly below.

4.1. Restrictive assumptions

The Bruun Rule requires that a number of assumptions be met. These were outlined in Bruun (1962) in the initial publication and were expanded by Bruun (1983, 1988) specifically in the context of applications of the Rule for coastal management. The difficulties in finding coasts that apparently meet these criteria is illustrated by the work of Zhang et al. (2004) in their search for such sites on the eastern US coast. Nowhere were they able to identify conclusively sites where the conditions for the application of the Bruun Rule were met (Pilkey et al., 2000). The Bruun rule is a two-dimensional model that assumes a closed materials balance for the profile. There must be no net longshore transport. If there is a net or gain or loss of sand on the profile from any source, including aeolian, overwash or onshore transport then any observed change in the profile could be due to something other than sea-level rise. Such a situation is likely impossible to occur in nature, and if it did, would not be able to be proved.

The Bruun Rule assumes that rising relative sea level always causes shoreline retreat. It does not have an accretionary component. In nature many shorefaces have been known to accrete even under rapid sea-level rise. The work of Curray (1969) illustrated this implicitly, and subsequent work by Thom (1983) has shown numerous examples of this situation whereby coastline have accreted under sea-level rise due to abundance of sediment in the nearshore.

In short, the assumptions that must be satisfied for the Bruun Rule, are extremely (probably prohibitively) restrictive, meaning that in theory it is only likely to be applicable on a small number of coasts.

4.2. Omission of important variables

The problems with the oceanographic/geological assumptions behind the Bruun Rule have been extensively discussed by others (Thieler et al., 2000; Wright, 1995; Pilkey et al., 1993; List et al., 1994; Pilkey and Cooper, 2004). The major oceanographic problems with the Bruun Rule are that it assumes implicitly that all sand movement on the shoreface is related to waves and that there is a sediment fence (closure depth) at the base of the shoreface, that there are no rock or mud outcrops on the shoreface, that no sand is lost or gained in a lateral or perpendicular direction from the beach. It is now clear that there are a variety of bottom currents, many of them storm-related, that move sediment, often in conjunction with wave activity. These include rip currents, storm surge ebb currents, wind driven up and downwelling wave driven up and down welling, tidal currents and wind amplified longshore currents. Clearly no sediment fence is located at the base of the shoreface, and the shoreface is not a smooth surface as assumed. In addition, bedforms, which can determine the direction of transport on the shoreface, are not considered.

The Rule also implies that the slope of the upland over which the profile must translate does not affect shoreline retreat rate, yet we know that the surface slope of the coastal plain/continental shelf does play a role in retreat rates. Gently sloping coastal plains are likely to experience faster retreat than more steeply sloping ones (Cattaneo and Steel, 2003). Furthermore, as Cattaneo and Steel (2003) point out, transgression across a steep topography is associated with slow shoreline migration and wave action therefore has more time to rework and redistribute sediment than on low gradient continental shelves. On low gradient shelves, the shoreface may even be overstepped and drowned if the rate of sea-level rise is sufficiently high (Sanders and Kumar, 1975).

Shoreline response to sea-level rise is mediated by many factors that operate at regional to site-specific levels and which incorporate many potential feedback relationships. Many studies provide insights into the nature of shoreline response to sea level change. Carter and Orford (1993) for example illustrate the diversity of planform changes that occur on gravel barriers during sea-level rise. Similarly, the patterns of barrier island planform evolution under rising sea level are extremely complex, involving inlet formation, erosion, spit elongation, overwashing and accretion (Oertel, 1985; Woodroffe, 2002).

At millennial time scales, the patterns of coastal evolution are highly variable even at a regional or local level. Thom (1983), for example, showed that the sediment supply offshore determined whether barriers in eastern Australia accreted, aggraded or eroded during the past 2000 years under a consistent sea-level rise. In some cases, accretion of several hundred metres was recorded. At historical and millennial time scales, the patterns of shoreline change can also be mediated by processes of self-organisation (Ashton et al., 2001). Shoreline response to transgression is heterogonous and subject to a diversity of controls at the local level. This in itself is support enough for the abandonment of the Bruun Rule as a generic (one model fits all) tool.

4.3. Outdated and erroneous concepts

Several concepts now known to be erroneous provide the explicit and implicit foundation for the Bruun Rule. Firstly, the Bruun Rule relies on the shape of the shoreface being described by a profile of equilibrium that can be described by Eq. (1). While this equation may describe some shorefaces it is not universally applicable (Pilkey et al., 1993). The supposed relationship between the parameter A in the equation and grainsize has also been shown to be in error, particularly on sand beaches (Pilkey et al., 1993; Thieler et al., 2000). Furthermore, it is now known that many parameters (other than sediment grain size) determine shoreface shape including wave energy, storm frequency, and sand supply. Implicit in the shoreface profile of equilibrium concept is the assumption that underlying geology has no effect or control upon the translation of the profile. It is now known that the geology underlying the shoreface frequently plays a role in shoreline behaviour (e.g. Riggs et al., 1995; Cowell et al., 1995).

Related to the profile of equilibrium theory is the requirement that a closure depth exists, seaward of which no significant sediment transport of sediment from shallower water occurs. Modern oceanography shows there to be a temporally variable depth to which wave action disturbs the seabed (Berkemeier, 1985). During storms in particular, waves penetrate much deeper and may mobilise sediment far beyond the normally accepted closure depth. Furthermore, it is now known that many factors other than wave orbitals affect sediment transport on any shoreface (wind, tidal, wave-generated and gravity currents all potentially exist, as do secondary wave motions). The notion of a closure depth is therefore a gross simplification.

In its simplest form, as it is actually applied, the Bruun Rule states that shoreline erosion caused by sea-level rise is a function of the average slope of the shoreface, which is typically the steepest part of the nearshore profile (Eq. (1)). There is no evidence from field studies that shoreface steepness bears any relationship to shoreline retreat rates, and no reason to suspect that it does.

5. Current applications of the Bruun Rule

In reviewing the extensive literature of Bruun Rule applications in coastal management, it is apparent that the use of the rule is widespread. From a geographical perspective the Bruun Rule has found virtually global application in coastal management. Below we outline examples of its use in North America, The Caribbean, South America, Europe, New Zealand, Australia, SE Asia and the Middle East. Its applications fall into several categories listed below for each of which a few examples are cited:

- Application of the Bruun Rule for coastal management either (a) without question, or (b) after acknowledgement of some shortcomings;
- Non application because of recognition that a site does not meet the assumptions required by the Bruun Rule (still recognising it as a valid concept);
- Incorporation of the concept into other models such that it becomes hidden;
- Rejection of the concept that the Bruun rule relates sea-level rise and shoreline retreat;
- Application of the mechanism (with caveats and/or modification) for basic science.

5.1. Application of the Bruun Rule for coastal management either (a) without question, or (b) after acknowledgement of the shortcomings

The use of the Bruun Rule for practical prediction of the impacts of sea-level rise is widespread. Its use has been actively promoted by a number of authors. Leatherman et al. (1994), for example, present a four-step approach to the assessment of future sea-level rise and its impacts. This is aimed at national level assessments and follows IPCC (1991) in recommending that an assessment be undertaken for a 1-m rise in sea level. This approach involves the following steps:

1. Collection of all existing data (physical, socio-economic, etc.) on the coastline;

2. Assessment of the impacts of a 1-m rise in sea level. Specifically, the approach recommends 'for important beach areas, conduct a Bruun Rule analysis (Nicholls et al., 1994) and preferably a trend analysis (Leatherman, 1991) to assess likely shoreline recession given a one metre rise in sea level';
3. Assess the implications of future development; and
4. Assess potential responses (retreat, accommodate, protect).

Leatherman et al. (1994, p.23) suggest that 'sometimes tens or hundreds of kilometres of shoreline can be represented by one cross-shore profile, and hence erosion can be estimated with one application of the Bruun Rule', although no evidence of this was presented.

Details of how to apply the Bruun Rule for assessment of shoreline recession are given by Nicholls et al. (1994). They contend, (p.30) that 'the Bruun rule has been widely applied in studies of this type (e.g. Leatherman, 1991) although there is much debate about determining the best values for the input parameters'. Nowhere is the possibility that it is incorrect or inappropriate, contemplated. The application advocated by Nicholls et al. (1994) uses the form of the Bruun Rule adopted by Hands (1983) where:

$$R = SGL/(b + h_*) \quad (3)$$

where R is shoreline retreat, G is a factor that quantifies loss or gain of sediment from the profile, S is sea-level rise, L is width of the active profile, b is berm height and h is depth of closure.

For sandy coasts G is assumed to be 1 (i.e. no sediment is lost from the profile) due to a lack of data. The method advocates two calculations of the depth of closure, which "would likely encompass the actual depth of closure". These were $d_{L,1}$ (annual scale), determined from the annual exceeded wave height in a twelve hour period and $d_{L,100}$ (century scale) estimated as 1.75 $d_{L,100}$. These estimates of the depth of closure over a century and over a year were considered to provide high and low estimates, respectively of the likely erosional response of the shoreline to sea-level rise. The assumption that a 'profile of equilibrium' exists thus leads to the expectation that greater closure depths will lead to greater recession. Nicholls et al. (1994) and Nicholls (1998) also advocate the use of the Bruun formulation to sand and gravel coasts, erodible, cliffed coasts (Bray and Hooke, 1997) and, with some reservations, to muddy coasts.

It has been shown elsewhere that the closure depth concept has no validity (Thieler et al., 2000). The extent of wave-sediment interaction during storms in particular is poorly understood. Furthermore, significant sediment movement within the coastal zone can be accomplished by bottom currents (Wright et al., 1991; Jaffe et al., 1997), which are ignored in the Bruun Rule.

In a volume edited by Nicholls and Leatherman (1994), a number of studies are reported from the developing world in which the likely consequences of sea-level rise are assessed. Several of the studies reported did not use the Bruun Rule, however, seven of the ten national assessments utilised the Bruun Rule to assess shoreline recession. Studies in Malaysia (Midun and Lee, 1994), Egypt (El-Raey et al., 1994), Argentina (Dennis et al., 1994a), Nigeria (French et al., 1994), Senegal, (Dennis et al., 1994b), Uruguay (Volonte and Nicholls, 1994), and Venezuela (Volonte and Arismendi, 1994) applied the Bruun Rule in a variety of ways. The studies in Argentina (Dennis et al., 1994b) and Uruguay (Volonte and Nicholls (1994) not only applied the Bruun Rule to sandy coasts but also to mud coasts and erodible cliffs. French et al. (1994) only applied the approach to sandy coasts in Nigeria. In two case studies, Dennis et al. (1994a,b) (Senegal) and Volonte and Arismendi (1994) (Venezuela) the authors reported that contrary to expectations and experience elsewhere the dL_{100} large-wave-associated depth of closure predicts less recession than the smaller (annual) dL_1 wave condition. This was ascribed to the shape of the shoreface, and interpreted by Nicholls et al. (1994) as evidence that an equilibrium profile did not exist in those situations.

Cicin-Sain et al. (1997) question the Bruun Rule within the context of application of the IPCC common methodology in China and suggest that while it can be used it should be considered only as a 'general tool'. Chou (1994), considering sea-level rise in eastern Asia, similarly acknowledged that the Bruun model "omits potentially significant factors" but suggests that the method "remains the only practical way of yielding a rapid, semi-quantitative assessment of shore response to a rise in sea level" in the East

Asian seas region. In Christchurch, New Zealand, Tonkin and Taylor (1999) applied the Bruun concept to calculate shoreline recession for various sea-level rise scenarios, after acknowledgement that its verification has been hampered by time lags in beach response. To accommodate these uncertainties a range of beach regression scenarios were calculated. Cooper (1995) applied the Bruun Rule to mainland-attached shorelines in South Africa to estimate future sea level-related retreat while taking account of likely planform changes associated with local bedrock outcrop.

A number of instances occur where the Bruun Rule has been applied without apparent acknowledgement of its limitations, or results from its application are cited without appropriate caveats. For example, Peters (2000) applied the Bruun Rule to the beaches of Grenada and concluded that up to '60% of its beaches would disappear with a 50-cm rise of sea level' (Department of Economic Affairs, Grenada, 2001). Similarly Mimura (2001) concluded that erosion of beaches in Japan according to Bruun-Rule based calculations would lead to 56–90% of beaches disappearing for sea-level rises of 30 cm and 1 m, respectively. Mimura (2001) was also incorrect in assuming that shoreline retreat is synchronous with beach loss. The approach has also been applied to predict coastal recession in Gambia (Jallow et al., 1996), Estonia (Kont, 2000), Egypt (Frihy, 1992a,b) Lebanon (Republic of Lebanon, 1999) and Uruguay (Saizar, 1997).

In some instances the Bruun Rule has been applied to calculate set-back lines for coastal development in Nevis (Cambers, 1998), Eastern Caribbean (UNESCO, 1997), the Coromandel Peninsula, New Zealand (Environment Waikato, 2002) In Western Australia setback lines are based upon the Bruun Rule (a crude multiplier of 100× the sea-level rise is used) (Western Australian Planning Commission, 2001).

5.2. Non application but acceptance as a valid concept

In a volume (Barth and Titus, 1984) that the commissioning body explicitly points out was "written by EPA employees and EPA contractors" (http:www.EPA.gov/globalwarming/publications/impacts/sealevel/), Leatherman (1984) outlines the Bruun concept, and states that 'the difficulty of defining the offshore limit of sediment transport limited the application of this procedure' in a study of Galveston Bay, TX. While the Bruun approach was regarded as 'more sophisticated', the geomorphologically 'more realistic' use of historic erosion rate trend lines was adopted in that study. Similarly, Kirby (2000), developing an approach for assessment of sea-level rise impacts on tidal flats believed the Bruun rule to be conceptually viable for sandy shores and believed that it had been 'proved to be widely applicable seasonally and on the longer term'. A number of authors have accepted the Bruun concept and attempted to improve it by modifications that render hindcast results more similar to observed changes. For example Pranzini and Rossi (1995) modified the Bruun Rule by substitution of a polynomial equation (for Dean's profile of equilibrium) to describe the inshore profile in an attempt to improve the accuracy of predictions. Brambati et al. (1998) also modified the Bruun Rule to try to improve predictions, taking account of longshore transport.

5.3. Incorporation into other models

Societal response to sea-level rise of course requires many additional steps other than prediction of land losses due to coastal erosion. Thus a number of approaches have been developed that attempt to incorporate all areas of concern (physical, biological, socio-economic) together with potential response mechanisms. The IPCC (1991) 'Common Methodology' is probably the best known and involves a seven-step process of which step 4 is the quantification of physical impacts. The common methodology stops short of providing specific guidelines on how to assess physical impacts but several related papers make reference to the Bruun Rule.

Van Vuren et al. (2001) in developing a complex model that addresses social and physical aspects of shoreline change in response to rising sea level, include the use of the Bruun concept to calculate the shoreline retreat to sea-level rise without acknowledgement of its limitations. This information is then carried forward to other modules of the model. Nairn and Zuzek (2000) advocated the development of a module that "incorporates the Bruun Rule shift for predicting response of sandy shore profiles" into the Flood and Erosion Prediction System (FEPS) tool for the US Great Lakes. Silenzi et al. (2002) utilised the Bruun Rule as the basis of a risk assessment of coastal plains in Italy to rising sea level. Perhaps more importantly, the Bruun Rule is the basis of the concept of the profile of equilibrium (Dean, 1977). This concept pervades coastal engineering and mathematical modelling to predict shoreline behaviour. For example, it is the basis of the design of beach nourishment projects (Dean, 1983; Houston, 1996), and it appears in both GENESIS (Hanson and Kraus, 1989) and SBEACH (Larson and Kraus, 1989), two popular models of shoreline change. As Pilkey et al. (1993) and Thieler et al. (2000) demonstrate, the concept of the profile of equilibrium, as determined for these uses, is fundamentally flawed.

5.4. Rejection of the concept that the Bruun Rule relates sea-level rise and shoreline retreat

A number of authors have explicitly rejected the Bruun concept and/or its applicability. Kroonenberg et al. (2004), for example, in planning future coastal engineering research at Delft University concluded that "commonly applied engineering concepts of shoreface response to sea-level rise, viz. the "Bruun-rule" which ignores scale variability completely, are now known to be inadequate". Kaplin and Selivanov (1995) working in the Caspian Sea maintained that Bruun-type calculations gave only an order of magnitude estimate of shoreline retreat and in many cases could not be applied at all. List et al. (1997) noted that equilibrium profile conditions for application of the Bruun Rule were met on "only about half the studied profiles" along 150 km of the Louisiana coast. They concluded that "in terms of the Bruun approach, relative sea-level rise has no power for hindcasting (and presumably forecasting) rates of coastal erosion for the Louisiana barrier islands."

5.5. Application of the Bruun Rule (with caveats and/or modification) for basic science

Ciavola and Corbau (2002) in a study of the dynamics of an intertidal bar in Italy utilised the Bruun Rule to predict the response of an intertidal bar to sea-level rise over a ten year period. This was despite acknowledgement that the model did not take account of longshore drift and that this was an important process in the study area.

Ellison (1993) adopted the Rule and applied it to Caribbean mangrove swamps suggesting that the approach was appropriate for prediction of their response to sea-level rise. Kirby (2000) adopted the principles of what he regarded as the 'well established Bruun Rule' and applied them (maintenance of profile shape) to develop a generic model of mudflat response to sea-level rise. In both the latter cases there is no geomorphological basis for such an approach, other than the supposition that 'if it works for sandy beaches it ought to work in other locations'. The questions of sediment supply, compaction, geological control etc are equally important in muddy coast geomorphology as on sandy ones (Healy et al., 2002).

Each of the above examples demonstrate the widespread acceptance of the Bruun concept despite the lack of any proof of its validity.

6. Discussion

Because the Bruun Rule ignores various important geological and oceanographic principles, it does not and cannot predict shoreline retreat due to sea-level rise accurately. Therefore, coastal management strategies such as setback zones, coastal engineering models, coastal evolution studies, and beach nourishment design strategies based upon the Bruun Rule and the related concept of the profile of equilibrium must be re-evaluated.

Historically, long-accepted rules and principles of geology whose times have come and gone fade away slowly unless dramatic new discoveries such as plate tectonics or barrier island migration fundamentally and "instantly" disprove them. Principles tucked into equations and models may take even longer to disappear as the Bruun Rule illustrates. It has been made more durable by the facts that (1) the rule addresses a very important societal problem and (2) there is no simple, viable quantitative alternative.

Throughout these examples of coastal management application of the Bruun Rule is a thread of urgency. The problem of prediction of shoreline retreat is a critical one and only the Bruun Rule claims to have solved it. Inevitably managers, given the slightest encouragement, will apply it to their shoreline. Proponents of the use of the Bruun Rule have defended and promoted the Bruun Rule as a coastal management tool for many communities and countries (e.g. Leatherman, 1991, 2001; Leatherman et al., 1994, 2000; Nicholls and Leatherman, 1994; Nicholls et al., 1994).

It is clear that a number of users are concerned with possibly invalid assumptions behind the rule but they apply it nonetheless. In other cases the rule is applied to predict erosion on mudflats or gravel beaches for which even its strongest supporters, even Bruun (1988) never intended the model to be used.

It is unfortunate that in many instances, the discussion and caveats around the use of the Bruun Rule centre on choices of the depth of closure, the means of calculating the closure depth, the lack of available input data and choices of substitutes, or reasonable estimates of input factors. This type of superfluous discussion masks the essential discussion that relates to the applicability of the Bruun Rule. Given the wrong assumptions in its formulation, and the rare circumstances in which the necessary conditions are fulfilled for its theoretical application we contend that the Bruun concept, if it works anywhere, is not a 'rule' but rather an exception.

We attribute the longevity of the Bruun Rule to several factors:

1. There is a certain appeal in a simple, easy to use analytical model that is in widespread use. It is simple to apply for coastal managers who may have no understanding of the "Bruun Rule" weaknesses.
2. Several studies in the scientific literature that purport to prove the Bruun Rule taken by themselves provide support for the use of the approach. Equal validity accorded to proofs and disproofs places other scientists and managers in the position of not knowing which to accept without significant analytical effort that may be beyond their time, knowledge, or ability limits.
3. The approach can be applied easily. There is no need for detailed field study (profiles are sometimes determined from navigation charts). This obviously enables rapid assessment of large areas by policy makers and enables international obligations to be met.
4. Positive advocacy by some scientists adds impetus to the utilization of the approach. Strong advocacy can overcome doubts that may be entertained (see point 2, above) and encourage use of the technique.
5. The numerical form in which the Bruun Rule is stated acts to mask the real meaning of the relationship. For example, the rule essentially says that the average shoreface slope controls coastal retreat. There is no geological evidence for such a relationship and such a concept stated in word form would almost certainly promote instant rebuttal in the geological literature. The same factor may also be responsible for the Bruun Rule being viewed as a purely applied concept (in the engineering field) and this may serve to disconnect it from the realm of scientific scrutiny.
6. Application by other scientists without critical appraisal. Too often, such concepts are adopted and applied in the mistaken expectation that the scientific review process provides all necessary validity. We believe that this has bolstered the longevity of this concept. The application of the approach by high profile scientists also lends credence to the approach. Only, it appears, by determined, directed and conclusive critical review can such concepts be proven invalid and discarded.
7. The lack of an alternative is presented as a constraint in several of the studies reviewed. In many ways this simply serves to show (a) the lack of research into transgressive coasts (this has inhibited the search for relationships between sea-level rise and coastal retreat) and (b) the lack of data with which to test alternatives.

The Bruun Rule, which was a useful tool at the time of its conception, is an example of a principle that is fading very slowly and that, having moved into the applied sphere, maintains a momentum that has carried it far beyond its original assumption base. We conclude that it has outlived its usefulness and should be abandoned.

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References

Ashton, A., Murray, B., Arnauly, O., 2001. Formation of coastline features by large-scale instabilities induced by high angle waves. Nature 414, 296–299.

Barth, M.C., Titus, J.G. (Eds.), 1984. Greenhouse Effect and Sea-Level Rise: A Challenge for this Generation. Van Nostrand Reinhold, New York, 325 pp.

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

Bird, E.C.F., 1985. Coastline Changes: A Global Review. Wiley, Chichester, 219 pp.

Bray, M.J., Hooke, J.M., 1997. Prediction of soft-cliff retreat with accelerating sea-level rise. Journal of Coastal Research 13, 453–467.

Brambati, A., de Muro, S., Marocco, R., Selivanov, A., 1998. Barrier island evolution in relation to sea-level changes: the example of the Grado Lagoon, northern Adriatic Sea, Italy. Bolletino di Geofisica teorica ed appluicate 39, 145–161. http://www.ogs.trieste.it/bgta/volumi/v1998/vol39-2/testo5.html.

Bruun, P., 1954. Coast erosion and the development of beach profiles. Technical Memorandum, vol. 44. Beach Erosion Board, Corps of Engineers, 82 pp.

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

Bruun, P., 1983. Review of conditions for use of the Bruun Rule of erosion. Coastal Engineering 7, 77–89.

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.

Cambers, G., 1998. Planning for coastline change. Coastal development setback guidelines in Nevis. UNESCO/SeaGrant, University of Puerto Rico. 40 pp. http://www.unesco.org/csi/act/cosalc/cosalc2a.pdf.

Carter, R.W.G., Orford, J.D., 1993. The morphodynamics of coarse clastic beaches and barriers: a short- and long term perspective. Journal of Coastal Research 15, 158–179.

Cattaneo, A., Steel, R.J., 2003. Transgressive deposits: a review of their variability. Earth-Science Reviews 62, 187–228.

Ciavola, P., Corbau, C., 2002. Modeling the response of an intertidal bar to " medium energy" events. Solutions to Coastal disasters '02. Proceedings of the American Society of Civil Engineers, 526–542.

Chou, L.M. (Ed.), 1994. Implications of expected climate changes in the East Asian Seas region: an overview. Regional Coordinating Unit, East Asian Environmental Programme, UNEP, RCU/EAS Technical Reports Series No. 2., Bangkok. http://www.unep.org/unep/regoffs/roap/easrcu/publication/Clamate/Pref.rtf.

Cicin-Sain, B., Ehler, C.N., Knecht, R., South, R. and Weiher, R., 1997. Guidelines for integrating coastal management programs and national climate change action plans. Developed at the International Workshop: planning for climate change through integrated coastal zone management, Taipei, Feb 24–28, 1997. http://icm.noaa.gov/guidelines/PDF_Files/Taipei.pdf.

Cohen, J.E., Small, C., Mellinger, A., Gallup, J., Sachs, J., 1997. Estimates of coastal populations. Science 278, 1211–1212.

Cooper, J.A.G., 1995. Sea-level rise and its potential physical impacts on the shoreline of KwaZulu-Natal: Tugela River Mouth to Mtamvuna River mouth. Natal Town and Regional Planning Reports, vol. 81, 100 pp.

Cowell, P.J., Roy, P.S., Jones, R.A., 1995. Simulation of large-scale coastal change using a morphological behaviour model. Marine Geology 126, 45–61.

Curray, J.R., 1964. Transgressions and Regressions. In: Miller, R.L. (Ed.), Papers in Marine Geology. Macmillan, New York, pp. 175–203.

Curray, J.R., 1969. Shore Zone Bodies-Barriers, Chenier, Sand Beach Ridges. In: Stanley, D.J. (Ed.), The New Concepts of Continental Margin Sedimentation. American Geological Institute, pp. 1–18.

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

Dean, R.G., 1983. Principles of beach nourishment. In: Komar, P.D. (Ed.), Handbook of Coastal Processes and Erosion. CRC Press, Boca Raton, Florida, pp. 217–231.

Dean, R.G., 1990. Equilibrium beach profiles: characteristics and applications. Journal of Coastal Research 7, 53–84.

Dean, R.G., Maurmeyer, E.M., 1983. Models for beach profile responses. In: Komar, P.D. (Ed.), Handbook of Coastal Processes and Erosion. CRC Press, Boca Raton, Florida, pp. 151–166.

Dennis, K.C., Niang-Diop, I., Nicholls, R.J., 1994a. Sea-level rise and Argentina: potential impacts and consequences. Journal of Coastal Research 14, 205–223 (Special Issue).

Dennis, K.C., Schnack, E.J., Mouzo, F.H., Orana, C.R., 1994b. Sea-level rise and Senegal: potential impacts and consequences. Journal of Coastal Research 14, 243–261 (Special Issue).

Department of Economic Affairs, Grenada, 2001. National report. Integrating Management of watersheds and coastal areas. Ministry of Finance, St George's Grenada. http://www.cep.unep.org/programmes/amep/GEF-IWCAM/Grenada/Grenada%20cover%20page.doc.

Dolan, R., Hayden, B., May, S., 1983. Erosion of the United States shorelines. In: Komar, P.D. (Ed.), Handbook of Coastal Processes and Erosion. CRC Press, Boca Raton, Florida, pp. 285–299.

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

Dubois, R.N., 1976. Nearshore evidence in support of the Bruun Rule on shore erosion. Journal of Geology 84, 485–491.
Dubois, R.N., 1977. Predicting beach erosion as a function of rising water level. Journal of Geology 85, 470–476.
Dubois, R.N., 1992. A re-evaluation of Bruun's Rule and supporting evidence. Journal of Coastal Research 8, 618–628.
Dubois, R.N., 2001. Using a quadratic model to theoretically describe the nature of equilibrium shore rise profiles. Journal of Coastal Research 17, 599–610.
Edelman, T., 1972. Dune erosion during storm conditions. Proc. 13th Intl. Conf. Coast., pp. 1305–1312.
Ellison, J.C., 1993. Mangrove retreat with rising sea level, Bermuda. Estuarine, Coastal and Shelf Science 37, 75–87.
El-Raey, M., Nasr, S., Frihy, O., Desouki, S., Dewidar, K., 1994. Potential impacts of accelerated sea-level rise on Alexandria Governate, Egypt. Journal of Coastal Research 14, 190–204 (Special Issue).
Environment Waikato, 2002. Development setback lines for the Coromandel Peninsula. Environment Waikato: Coastal Hazards and development setback Recommendations. Summary Report, May 2002. http://www.ew.govt.nz/enviroinfo/hazards/naturalhazards/coastal/summary.htm.
French, G.T., Awosika, L.F., Ibe, C.E., 1994. Sea-level rise and Nigeria: potential impacts and consequences. Journal of Coastal Research 14, 224–242 (Special Issue).
Frihy, O.E., 1992a. Beach response to sea-level rise along the Nile Delta coast of Egypt. Sea Level Changes; Determination and Effects, Geophysical Monograph, vol. 69, pp. 81–85.
Frihy, O.E., 1992b. Sea-level rise and shoreline retreat of the Nile Delta promontories, Egypt. Natural Hazards 5, 65–81.
Hands, E.B., 1979. Changes in rates of shore retreat, Lake Michigan, 1967–76. U.S. Army Corps of Engineers Coastal Engineering Research Center Technical Paper No. 79-4. December 1979, Vicksburg, Mississippi, 71 pp.
Hands, E.B., 1980. Prediction of shore retreat and nearshore profile adjustments to rising water levels on the Great Lakes. Coastal Engineering Research Center, Vicksburg, Mississippi, Technical Memorandum No. 80-7, 119 pp.
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. CRC Press, Boca Raton, Florida, pp. 176–189.
Hanson, H., Kraus, N.C., 1989. GENESIS: Generalized Model for Simulating Shoreline Change. Vicksburg, Mississippi: U.S. Army Corps of Engineers, CERC, Technical Report CERC-89-19, 185 pp.
Healy, T., Wang, Y., Healy, J.-A., 2002. Muddy coasts of the world: processes, deposits and function. Proceedings in Marine Science vol. 4. Elsevier Science, Amsterdam, 556 pp.
Hinrichsen, D., 1998. Coastal Waters of the World: Trends, Threats, and Strategies. Island Press, Washington, DC, 275 pp.
Houston, J.R., 1996. Engineering practice for beach-fill design. Shore and Beach, 27–35.
IPCC, 1991. The Seven Steps to the Vulnerability Assessment of Coastal Areas to Sea-Level Rise—A Common Methodology, Intergovernmental Panel on Climate Change, Response Strategies Working Group, 20 September 1991, Revision No. 1, 27p+3 appendices.
IPCC, 2001. Changes in sea level. In: Church, J.A., Gregory, J.M. (Eds.), Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, pp. 641–693.
Jaffe, B.E., List, J.H., Sallenger Jr., A.H., 1997. Massive sediment bypassing on the lower shoreface offshore of a wide tidal inlet: Cat Island Pass, Louisiana. Marine Geology 136, 131–150.
Jallow, B.P., Barrow, M.K.A., Leatherman, S.P., 1996. Vulnerability of the coastal zone of The Gambia to sea-level rise and development of response strategies and adaptation options. Climate Research 6, 165–177.
Kaplin, P.A., Selivanov, A.O., 1995. Recent coastal evolution of the Caspian Sea as a natural model for coastal responses to the possible acceleration of global sea-level rise. Marine Geology 124, 161–175.
Kirby, R., 2000. Practical implications of tidal flat shape. Continental Shelf Research 20, 1061–1077.
Kont, A., 2000. Implications of accelerated sea-level rise (ASLR) for Estonia. Proceedings of SURVAS expert workshop on European vulnerability and adaptation to impacts of accelerated sea-level rise (ASLR). Hamburg, Germany, June 19–21. http://www.survas.mdx.ac.uk/content.htm.
Kraft, J.C., 1978. Coastal stratigraphic sequences. In: Davis, R.A. (Ed.), Coastal Sedimentary Environments. Springer-Verlag, New York, pp. 361–383.
Kroonenberg, S.B., Heemink, A.W., Cooke, R.M., Stive, M.J.F., 2004. Transient processes in hydraulic engineering and geohydrology. Delft Interdisciplinary research programme on hydraulic engineering and geohydrology. http://www.waterbouw.tudelft.nl/dioc/.
Krumbein, W.C., Pettijohn, F.J., 1988. Manual of Sedimentary Petrography, vol. 13. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Reprint Series Number, 549 pp.
Larson, M., Kraus, N.C., 1989. SBEACH: Numerical Model for Simulating Storm-Induced Beach Change. Vicksburg, Mississippi: U.S. Army Corps of Engineers, CERC, Technical Report CERC-89-9, 256 pp.
Leatherman, S.P., 1984. Coastal geomorphic responses to sea-level Rise, Galveston Bay, Texas. In: Barth, M.C., Titus, J.G. (Eds.), Greenhouse Effect and Sea-Level Rise: A Challenge for this Generation. Van Nostrand Reinhold, New York, pp. 151–178.
Leatherman, S.P., 1991. Modeling shore response to sea-level rise on sedimentary coasts. Progress in Physical Geography 14, 447–467.
Leatherman, S.P., 2001. Social and economic costs of sea-level rise. In: Douglas, B.C., Kearney, M.S., Leatherman, S.P. (Eds.), Sea-Level Rise, History and Consequences: International Geophysics Series, vol. 75. Academic Press, NY, pp. 181–223.
Leatherman, S.P., Nicholls, R.J., Dennis, K.C., 1994. Aerial videotape-assisted vulnerability analysis: a cost-effective approach to assess sea-level rise impacts. Journal of Coastal Research 14, 15–25 (Special Issue).
Leatherman, S.P., Zhang, K., Douglas, B.C., 2000. Sea-level rise shown to drive coastal erosion. EOS 81, 55–57.

List, J.H., Jaffe, B.E., Sallenger Jr., A.H., Williams, S.J., McBride, R.A., Penland, S., 1994. Louisiana Barrier Island Erosion Study: atlas of sea-floor changes from 1878 to 1989. U.S. Geological Survey Miscellaneous Invest. Series 1-2150-B. 82 pp.

List, J.H., Sallenger, A.H., Hansen, M.E., Jaffe, B.E., 1997. Accelerated relative sea-level rise and rapid coastal erosion: testing a causal relationship for the Louisiana barrier islands. Marine Geology 140, 347–365.

Midun, Z., Lee, S.C., 1994. Implications of a greenhouse-induced sea-level rise: a national assessment for Malaysia. Journal of Coastal Research 14, 96–115 (Special Issue).

Mimura, N., 2001. Impact of climate change on the coastal zone. Scientific committee on problems of the environment (SCOPE). XIth General Assembly and Scientific Symposia. Sept 24–28, Bremen, Germany. http://www.scope-germany.uni-bremen.de/scope_ga/ga_mimura.html.

Nairn, R., Zuzek, P., 2000. Introduction to the flood erosion and protection system. Lower Great Lakes Erosion Study, Workshop Sept 20–21, Niagara Falls, New York.

Nicholls, R.J. 1998. Coastal vulnerability assessment for sea-level rise: evaluation and selection of methodologies for implementation. Technical report TR 98002. Caribbean Planning for Adaptation to Global Climate Change (CPACC) project. http://www.cpacc.org/download/c6_methodology.pdf.

Nicholls, R.J., Leatherman, S.P. (Eds.), Potential Impacts of Accelerated Sea-Level Rise on Developing Countries, Journal of Coastal Research, Special Issue, vol. 14, 324 pp.

Nicholls, R.J., Leatherman, S.P., Dennis, K.C., Volonte, C.R., 1994. Impacts and responses to sea-level rise: qualitative and quantitative assessments. Journal of Coastal Research 14, 26–43. (Special Issue).

Nikiforov, L.G., Rychagov, G.I., 1988. Development of the Caspian shoreline under the present increase in its level. Vestnik Moskovskogo Universiteta, geografiya, no. 2, pp. 47–51. Translated by Jay K. Mitchell, PlanEcon, Washington, DC 20005.

Oertel, G.F., 1985. The barrier island system. Marine Geology 63, 1–18.

Peters, E.J., 2000. Beach Erosion in Grenada. Ministry of Agriculture, Lands, Forestry and Fisheries. Government of Grenada.

Pilkey, O.H., Davis, T.W., 1987. An analysis of coastal recession models: North Carolina coast. In: Nummedal, D., Pilkey, O.H., Howard, J.D. (Eds.), Sea-Level Fluctuation and Coastal Evolution. Society of Economic Paleontologists and Mineralogists, pp. 59–68.

Pilkey, O.H., Young, R.S., Riggs, S.R., Smith, A.W.S., Wu, Huiyan, Pilkey, W.D., 1993. The concept of shoreface profile of equilibrium: a critical review. Journal of Coastal Research 9 (1), 255–278.

Pilkey, O.H., Young, R.S., Bush, D.M., 2000. Comment on Sea-level rise by Leatherman et al. EOS 81, 436.

Pirazolli, P.A., 1991. World atlas of Holocene sea-level change. Elsevier Oceanography Series 58, 300 pp.

Pranzini, E., Rossi, L., 1995. A new Bruun Rule based model: an application to the Tuscany coast, Italy. Proceedings of the Second International Conference on the Mediterranean Coastal Environment Medcoast '95. October 24–27 1995. , pp. 1145–1159.

Republic of Lebanon, 1999. Climate Change. Technical Annex to Lebanons first National communication. Ministry of Environment, Lebanon. http://www.moe.gov.lb/MOE%20Site/Publications/PublicationMain.aspx.

Riggs, S.R., Cleary, W.J., Snyder, S.W., 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. Marine Geology 126, 213–234.

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

Saizar, A., 1997. Assessment of impacts of a potential sea-level rise on the coast of Montevideo, Uruguay. Climate Research 9, 73–79.

Sanders, J.E., Kumar, N., 1975. Evidence of shoreface retreat and in-place "drowning" during Holocene submergence of barriers, shelf off Fire Island, New York. Geological Society of America Bulletin 86, 65–76.

Sallenger, A.H., Morton, R., Fletcher, C., Thieler, R., Howd, P., 2000. Comment on Sea-level rise by Leatherman et al. EOS 81, 436.

SCOR, Working Group 89, 1991. The response of beaches to sea-level changes: a review of predictive models. Journal of Coastal Research 7, 895–921.

Schwab, W.C., Thieler, E.R., Allen, J.R., Foster, D.S., Swift, B.A., Denny, J.F., 2000. Influence of inner-continental shelf geologic framework on the evolution and behaviour of the barrier-island system between Fire Island Inlet and Shinnecock Inlet, Long Island, New York. Journal of Coastal Research 16, 408–422.

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

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

Silenzi, S., Devoti, S., Nisi, M.F., De Donatis, M., Gallerini, G., Aminti, P., Pranzini, E., Rossi, L., Gabellini, M., 2002. Integrated Hazard of Italian Coastal Plains with Respect to Relative Sea Level Rise: A Case Study in Versilia Plain. Littoral 2002, The Changing Coast. EUROCOAST/EUCC, Porto–Portugal. Ed. EUROCOAST–Portugal, pp. 115–124. http://www.io-warnemuende.de/homepages/schernewski/Littoral2000/docs/vol2/Littoral2002_14.pdf.

Short, A.D., 1999. Handbook of Beach and Shoreface Morphodynamics. John Wiley and Sons, Chichester, 379 pp.

Storms, J.E.A., Weltje, G.J., van Dyke, J.J., Geel, C.R., Kroonenberg, S.B., 2002. Process-response modeling of wave-dominated coastal systems: simulating evolution and stratigraphy on geological timescales. Journal of Sedimentary Research 72, 226–239.

Swift, D.J.P., 1976. Continental shelf sedimentation. In: Stanley, D., Swift, D.J.P. (Eds.), Marine Sediment Transport and Environmental Management. John Wiley & Sons, New York, pp. 311–350.

Thieler, E.R., Brill, A.L., Hobbs, C.H., Gammisch, R., 1995. Geology of the Wrightsville Beach, North Carolina shoreface: Implications for the concept of shoreface profile of equilibrium. Marine Geology 126, 271–287.

Thieler, E.R., Pilkey, O.H., Young, R.S., Bush, D.M., Chai, Fei, 2000. The use of mathematical models to predict beach behavior for US Coastal Engineering: a critical review. Journal of Coastal Research 16 (1), 48–70.

Thom, B.G., 1983. Transgressive and regressive stratigraphies of coastal sand barriers in southeast Australia. Marine Geology 56, 137–158.

Tonkin and Taylor, 1994. Study of the effects of sea-level rise for Christchurch. Report to Christchurch City Council. Tonkin & Taylor Ltd., Christchurch, New Zealand. http://archived.ccc.govt.nz/Reports/1999/SeaLevel/sealevel2.pdf.

UNESCO, 1997. Planning for coastline change. Guidelines for construction setbacks in the Eastern Caribbean islands. CSI info 4, UNESCO, Paris. vii+14pp.

Van Vuren, B.G., Jorissen, R., Kok, E., 2001. Stochastic economic optimization model for the coastal zone. In: Goudas, C.L., Katsiaris, G.A., May, V. (Eds.), Soft Shore Protection. An Environmental Innovation in Coastal Engineering Science, Proceedings of the First International Conference. University of Patras, Greece, pp. 75–90.

Volonte, C.R., Arismendi, J., 1994. Sea-level rise and Venezuela: potential impacts and consequences. Journal of Coastal Research 14, 285–302 (Special Issue).

Volonte, C.R., Nicholls, R.J., 1994. Sea-level rise and Uruguay: potential impacts and responses. Journal of Coastal Research 14, 262–284 (Special Issue).

Weggel, J.R., 1979. A method for estimating long-term erosion rates from a long-term rise in water level. U.S. Army Corps of Engineers Coastal Engineering Research Center CETA 79-2, May 1979. 16 pp.

Western Australian Planning Commission, 2001. Draft statement of planning policy: State Coastal Planning Policy, Perth. http://www.wapc.wa.gov.au/publications/policies/SPP/SPP_2_6.pdf.

Woodroffe, C.D., 2002. Coasts: Form, Process and Evolution. Cambridge University Press, NY, 623 pp.

Wright, L.D., 1995. Morphodynamics of Inner Continental Shelves. CRC Press, Boca Raton, FL, 241 pp.

Wright, L.D., Boon, J.D., Kim, S.C., List, J.H., 1991. Modes of cross-shore sediment transport on the shoreface of the Middle Atlantic Bight. Marine Geology 96, 19–51.

Zhang, K., Douglas, B.C., Leatherman, S.P., 2004. Global Warming and Coastal Erosion. Climatic Change 64, 41–58.