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Conceptual Model of the Effects of Sea Level Rise on Sandy Coasts

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ABSTRACT

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Over the past 40 years, consideration of the potential effect of sea level rise on sandy coasts has been dominated by the conceptual model proposed in the Bruun Rule, which is used to predict the horizontal translation of the shoreline associated with a given rise in sea level. A review of the hypotheses that form the basis for this two-dimensional model suggests that the assumption of net sand transfer to the nearshore profile and deposition of a thickness of sediment equal to the rise in sea level is probably incorrect. Moreover, the model omits consideration of a significant component of the coastal sediment budget, namely the dune sediment budget, and the processes associated with beach-dune interaction. An alternative conceptual model is developed on the basis of a two-dimensional equilibrium profile similar to that which forms the basis for the Bruun Model. The proposed model incorporates consideration of the dune sediment budget and foredune dynamics. In contrast to the Bruun Model, it predicts no net transfer of sediment to the nearshore profile and preservation of the foredune through landward migration. It is argued that the model proposed here offers a better starting point for developing more realistic models of shoreline response to sea level rise that incorporate consideration of alongshore sediment transfers and more complex coastal morphology and sediment characteristics. Testing of the validity of the model and its potential use for integrated coastal zone management will require consideration of the volume changes associated with sea level rise on a decadal scale.

ADDITIONAL INDEX WORDS: *Bruun rule, integrated coastal zone management.*

INTRODUCTION

It is well-recognised that changes in relative sea level can affect coastal processes and lead to changes in the shape of the coast and the location of the shoreline. The effects of changes in relative sea level can be considered at a variety of timescales, ranging from a few minutes to days (*e.g.,* infragravity waves, tides; storm surge), weeks to years (the spring-neap cycle; seasonal cycles), and geologic periods from thousands to hundreds of thousands of years. Perhaps the most obvious change on a geologic timescale is the postglacial rise in sea level as a result of melting of the midlatitude glaciers and ice sheets formed during the Wisconsinan glaciation, which gave rise to a transgression that has shaped the coastline of much of the world, particularly those in the mid- and low latitudes. Although the main Holocene eustatic sea level rise is generally thought to have ended more than 4000 years BP, eustatic sea level appears to be rising still in many areas at a rate of about 1–2 mm/y over the past century or so (GORNITZ, 1995).

During the past two decades, interest has heightened in the potential effect of sea level rise on shorelines as a result of concerns over a potential increase in the rate of sea level rise due to global warming. Actual predictions have tended to become more conservative over the past decade, but many estimates of total sea level rise over the next century are on the order of 3–6 mm/y. It seems prudent to take 100 years as the horizon for most planning exercises in the coastal zone and as a reasonable goal for the development of integrated coastal zone management. One task of coastal scientists, therefore, is to provide reasonable scenarios for the effects of a sea level rise of this magnitude on coastal processes, particularly processes controlling the coastal sediment budget and the position of the shoreline on a timescale of a century.

On this timescale, the approach or starting point of many of the studies of the potential effect of sea level rise globally, and at a local level, have been dominated by the simple conceptual model of shoreline response to sea level rise put forward by Per Bruun 50 years ago (BRUUN, 1954). Papers published by BRUUN (1962) and SCHWARTZ (1965, 1967) were responsible for increasing initial interest in the model, and they have been truly landmark papers in stimulating research on coastal change over a range of spatial and temporal scales. The Bruun Model has been modified to apply to other environments such as barrier islands (*e.g.,* DEAN and MAURMEYER, 1983) and cohesive coasts (BRAY and HOOKE, 1997). Since the appearance of the Bruun Model, several other models of shoreline response to sea level rise have been developed, but none have had the same impact conceptually, and it is still being used extensively to explain coastal response

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to sea level change (*e.g.,* BRAY, HOOKE, and CARTER, 1997; FRENCH, 2001). It was SCHWARTZ (1967) who proposed that the method for predicting shoreline displacement be termed "Bruun's Rule." In this paper, following the approach of the Scientific Committee on Ocean Research (SCOR; SCOR WORKING GROUP 89, 1991), the conceptual model will be termed the Bruun Model and will be distinguished from the numerical methodology, derived from consideration of the predicted profile change, that can be used to predict shoreline displacement—popularly known now as the "Bruun Rule."

Over the four decades since the Bruun Model was first proposed, numerous attempts have been made to test the model and its predictive capability (BRUUN, 1988; LIST *et al.,* 1997; PILKEY and DAVIS, 1987; ROSEN, 1978; SCHWARTZ, 1967, 1987) with mixed results. Despite this, and the considerable increases in our understanding of processes controlling sediment movement in the nearshore, beach, and dune zones, relatively few attempts have been made to challenge directly the hypotheses on which the conceptual model is based. The overall purpose of this paper is to pose such a challenge by (1) critically examining the hypotheses on which the Bruun Model is based, (2) reviewing the principles for testing the model, and (3) proposing an alternative conceptual model that begins with the same initial simplifying assumptions as those of the Bruun Model.

THE BRUUN MODEL

The conceptual model put forward by BRUUN (1962) as it is generally portrayed (*e.g.,* SCHWARTZ, 1967; SCOR WORKING GROUP 89, 1991) has the following explicit assumptions.

- It applies to a two-dimensional profile normal to the shoreline so that all net sediment transfers are onshore-offshore and no consideration is given to inputs or outputs alongshore.
- The profile is assumed to be an equilibrium profile entirely developed in sand, with the mean profile form reflecting the wave climate and the size of the sediment.
- The material landward of the shoreline consists of easily erodible sand with characteristics similar to those in the nearshore.

A fourth implicit assumption is that the wave climate frequently produces waves of sufficient size to erode, transport, and redistribute sediment over the profile—clearly if there are no waves, sea level rise would simply result in inundation of the landward profile. Thus, the relaxation time for the system to adjust to major storms or other fluctuations in wave energy must be an order of magnitude less than the period over which sea level rise is modelled.

The Bruun Model is constructed from three hypotheses (BRUUN, 1962): (1) As a result of translation of the profile because of sea level rise, wave action erodes the upper beach; (2) the material eroded from the upper beach is deposited on the nearshore profile with the volume of sediment eroded equalling the volume of sediment deposited on the profile; and (3) the thickness of sediment deposition on the nearshore profile equals the increase in sea level, thus maintaining a constant water depth in the nearshore.

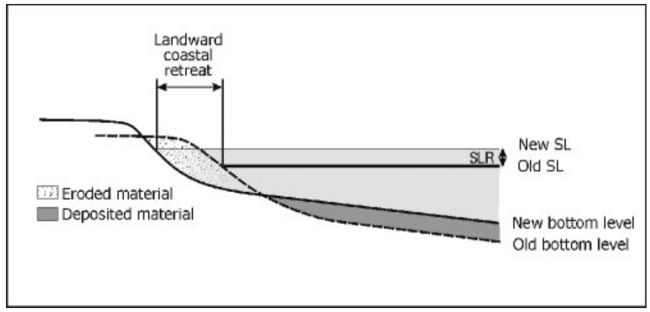

Figure 1. Schematic illustration of the Bruun Model of profile response to sea level rise showing erosion of the upper beach and offshore deposition.

The Bruun Model (Figure 1) is thus elegant in its simplicity. The matching of thickness of sediment deposited on the profile to the height of the sea level rise means that the landward displacement of the shoreline is essentially a function of the profile slope and the vertical sea level rise as long as there is an abundant supply of sediment landward of the shoreline.

Specification of the seaward endpoint of the profile and its behaviour has been the subject of some debate, but it is now generally assumed to be synonymous with the concept of depth of closure (HALLERMEIER, 1981). Thus, the term nearshore is defined here as the zone extending from the shoreline to the depth of closure. If one considers that sea level rise takes place gradually, then the position of the depth of closure should migrate landward and upward, producing a sloping profile without the discontinuity that might appear if only the initial and final profiles are considered (Figure 1).

The nature of the land surface over which the profile is translated is clearly critical to the operation of the model because it must provide the volume of sediment required to raise the height of the nearshore profile in step with rising sea level. Initially it is simplest to assume a volume of sand sufficient for the operation of the model and to address complexities such as a mixture of sediment sizes or presence of a landward lagoon (*e.g.,* DEAN and MAURMEYER, 1983) at a later stage.

On the basis of the assumptions of the Bruun Model, BRUUN (1962) derived the basic relationship for predicting the horizontal recession of shoreline R from an increase in sea level S:

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

L_* is the cross-shore distance to depth h_* (the depth of closure, which marks the transition from nearshore to offshore sediments), and B is the height of the berm or other sandy sediments forming the area on land that is eroded. As noted by SCOR WORKING GROUP 89 (1991), Equation (1) can also be expressed as Equation (2),

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

where $\tan \theta \approx (B + h_*)/L_*$ is the average slope of the nearshore along the cross-shore width L_*. Because the slopes of many sandy profiles are in the range 0.01–0.02, Equation (2) predicts a landward movement of the shoreline of from $50S$ to $100S$ (SCOR Working Group 89, 1991). The displacement of the shoreline is independent of the actual profile shape and, thus, whether bars are present or not (Allison and Schwartz, 1981). A small increase in sea level is predicted to cause a substantial retreat of the shoreline. This predicted displacement is roughly the same as that which would occur from simple inundation of a linear profile, but what is different is the postulated sediment volume required to produce the upward shift of the equilibrium profile, and thus the nature of the processes controlling this change. It should be noted that Equation (2) assumes that $B \ll h_*$. If B is large, for example a high dune, then this will greatly reduce the predicted value for R in Equation (1).

TESTING THE BRUUN MODEL

Over the past four decades, the Bruun Model and associated Bruun Rule have been the subject of considerable discussion and debate and numerous attempts have been made to test the model, beginning with the work of Schwartz (1965, 1967). The model also has been modified and applied to various scenarios that go beyond the initial assumptions—*e.g.,* to barrier island and lagoon systems (Dean and Maurmeyer, 1983; Eitner, 1996) and soft-cliffed coasts (Bray and Hooke, 1997), where the nature of the onshore profile is considerably different from that assumed by Bruun. It is not the purpose of this paper to review this literature, and much of the material is described and discussed in several recent studies (Kaplin and Selivanov, 1995; List *et al.,* 1997; SCOR Working Group 89, 1991).

Two general points can be made with reference to testing the model. The first is that validation of the Bruun Model requires demonstration that the three hypotheses related to erosion of land, offshore transport, and accretion of the nearshore profile hold (Everts, 1985; SCOR Working Group 89, 1991). It is not possible to validate the model by comparing measured values of shoreline recession to values predicted by the Bruun Rule. A number of studies have compared measured shoreline displacement with those predicted by the Bruun Rule, with widely differing results (Dean, 1990; List *et al.,* 1997; Pilkey and Davis, 1987; Rosen, 1978). However, it is clear that it is quite possible for measured shoreline displacement to equal predicted values even though the volume transfers required by the Bruun Model do not occur.

The second point is that testing the applicability of the Bruun Model to slow sea level rise over a timescale of a century requires very careful consideration of the processes that are responsible for controlling the equilibrium profile. We can assume that sediments on the beach and nearshore profile will be subject to a wide range of wave and water level conditions over 100 years. Water level fluctuations will occur on a variety of timescales from hours to days as a result of daily tides, the fortnightly neap-spring cycle, short-term changes reflecting the effects of storm surge, seasonal and annual changes associated with sea surface dynamics, and changes on the order of years to decades produced by oceanic and atmospheric phenomena such as El Niño. Likewise, wave conditions will reflect the full wave climate incorporating storm and nonstorm conditions and the effects of differing storm intensity and duration. It is to be expected therefore that the small annual increase in sea level will be smoothed out in the dynamics of these wave and water level processes. In particular, it is important to note that the gross volume of onshore-offshore sediment transport and the exchange between the nearshore and the beach and backshore over the period under consideration will be several orders of magnitude greater than the net volume change predicted by the Bruun Model.

One consequence of the points noted above is that it invalidates approaches to testing the model by simple wave tank experiments that involve establishing an initial profile then raising the water level and noting the effects of wave action at the higher level. It also rules out short-term field experiments related to spring-neap cycles and seasonal fluctuations in water levels, *e.g.,* in the Great Lakes. Thus, the initial laboratory experiments of Schwartz (1967), even apart from all the limitations of his experimental equipment, were more suited to testing the effect of storm surge and are invalid as a test of the Bruun Model. Likewise, the field experiments carried out by Schwartz (1967), which involved comparison of profile changes between spring and neap tides, again excluding any consideration of the limitation of his experimental procedure, do not constitute a valid test of the Bruun Model. Thus, Schwartz (1967) was not justified in concluding that his studies validated the Bruun Model to a "first approximation," and this removes the premise on which he based his proposal that it be termed "Bruun's Rule." The need for the rate of water level rise to be very small so as to permit response to the full range of water level fluctuations and wave climate variations also invalidates tests such as those performed by Dubois (1975) and probably those of Hands (1983). The latter study, though it involved measurements of profile change over a number of years in Lake Michigan in response to long-term lake level rise, did not extend significantly into the period of subsequent lake level stability and decline.

The Bruun Model is based on the transfer of volumes of sediment between the beach and nearshore, and its validation, as noted above, thus requires a sediment budget approach in which these predicted transfers are determined. Given the advances that have been made in our understanding of the dynamics of sandy beach profiles, and especially of the factors that control the transfers of material in both directions between the beach and nearshore and the beach and the dune, is it still reasonable to accept the hypotheses that form the basis for Bruun's conceptual model? In particular, is it reasonable to expect that transgression will result in a net transfer of all sediment eroded from the land to the ocean?

The majority of sandy beaches are backed by a foredune complex, and in assessing the coastal sediment budget, it is usual to distinguish between the littoral sediment budget, associated with the beach and nearshore zone, and the dune sediment budget, associated with the foredune and embryo dune. Exchanges of sediment between these two zones are common such that wave scarping of the embryo dune and foredune produce a transfer of sediment from the dune to the beach, whereas aeolian transport from the foreshore and backshore constitute a loss from the littoral budget and a gain to the dune sediment budget. The processes of beach-dune interaction have been documented extensively, and a number of simple conceptual models explicitly link the relationship between the beach and dune sediment budgets (*e.g.,* NICKLING and DAVIDSON-ARNOTT, 1990; PSUTY, 1988; SHERMAN and BAUER, 1993). Omission of consideration of the dune sediment budget is a major conceptual weakness of the Bruun Model, and it can be argued that it also throws into doubt the key hypothesis, namely that all sediment eroded as a result of sea level rise is deposited on the nearshore profile.

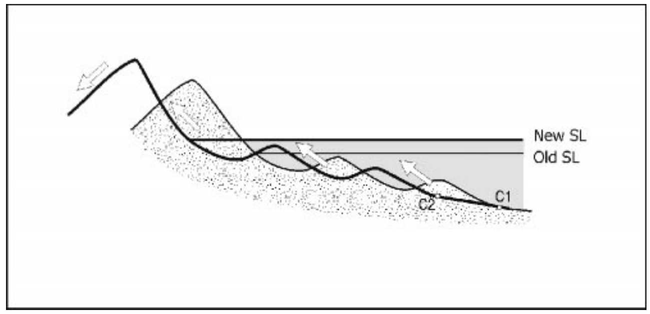

Figure 2. Schematic illustration of the model proposed here of profile response to sea level rise showing erosion and landward migration of the nearshore profile and transgression of the beach and foredune.

PROPOSED CONCEPTUAL MODEL OF COASTAL RESPONSE TO SEA LEVEL RISE

One approach to highlighting the perceived weaknesses of the Bruun Model noted above is to put forward an alternative conceptual model starting with the same initial assumptions. Thus, the model proposed here assumes a two-dimensional equilibrium profile developed entirely in sand with no net alongshore transfers. It also assumes a full spectrum of water level and wave conditions and that sea level rise takes place slowly with respect to high-frequency water level and wave fluctuations. Finally, it is assumed that the profile landward of the initial sea level is developed in easily erodible sand, and in this case, it is explicitly assumed that the beach is backed by a foredune complex.

The hypotheses that form the basis for the proposed conceptual model are as follows.

- The beach and foredune are eroded as a result of the translation of the profile because of sea level rise, and the junction between the beach and the dune migrates landward and upward to keep pace with rising sea level.
- A net onshore migration of sediment in the nearshore profile keeps pace with rising sea level. The outer part of the nearshore is eroded, and the point of closure moves landward and upward to keep pace with sea level rise and with the landward movement of the shoreline.
- All the sediment eroded from the dune will be transferred landward, and as a consequence, the foredune will migrate inland. Because the volume transferred landward is equal to the volume eroded, the dune will maintain its overall volume.

The conceptual model proposed here (hereafter termed the RD-A Model) is illustrated in Figure 2. Note that, for personal preference and to emphasise the difference between the two models, the profile shown is characterised by the presence of bars in the nearshore; as with the Bruun Model, the shape of the nearshore has no effect on the outcome of the model.

DISCUSSION

Two major differences arise between the model presented here and the Bruun Model because of the underlying hypotheses. In the first place, in the area under sea level rise, the outer nearshore profile becomes a zone of erosion with net sediment transfer landward to maintain the equilibrium profile. This is in contrast to the Bruun Model, which proposes that sediment eroded from the land accumulates on the nearshore profile. The second major difference is that transgression and erosion of the backshore and dune leads to a landward transfer of sediment and inland migration of the dune. There is no net transfer of sediment to the nearshore as postulated by the Bruun Model. Moreover, the actual volume of sediment transferred on the landward portion of the profile is determined primarily by the height and width of the existing dune rather than by the magnitude of sea level rise.

Landward migration of the profile under sea level rise is controlled by the average nearshore slope and is predicted by Equation (2). Thus, the predicted transgression is similar to that of the Bruun Model, except without the dependence on height B. Over the time frame of 100 years, the model can be applied equally to sandy mainland beaches and to sandy barriers, in the latter case acknowledging the potential for some part of the landward movement of sediment to take place through overwash or inlet breaching.

No attempt is made here to provide a rigourous test of these two hypotheses of the RD-A model, but we can examine the basis for postulating them.

It is generally recognised that storms lead to erosion of the beach and backshore, with sediment being deposited in the inner nearshore. Where bars are present, they tend to migrate offshore during intense storms or move into shallow water during an extended period of fair weather waves. The most intense storms with large rips or strong undertows will move sediment offshore as far as a depth approximating the point of closure. Sediment is moved onshore from the outer nearshore by periods of swell wave activity on exposed coasts or, on fetch-limited coasts, by less intense storms (*e.g.,* AAGAARD, NIELSEN, and GREENWOOD, 1998; GREENWOOD and DAVIDSON-ARNOTT, 1975; LEE, NICHOLLS, and BIRKEMEIER, 1998; SHEPARD, 1950; SHORT, 1978; WIJNBERG and KROON, 2002; WRIGHT and SHORT, 1984). The outer bar on a barred profile thus tends to oscillate around an equilibrium position that is controlled by the depth of water and wave breaking during storms. If there is no net transfer of sediment to the

Figure 3. Photograph taken November 30, 2002, of the foredune at Greenwich dunes, Prince Edward Island National Park, showing a scarped stoss slope and deposition on the crest and lee slope. The dune is about 12 m high. Sea level is rising here at 3–5 mm/y. For color version of this figure, see page 1193.

nearshore profile, then as water depth increases as a result of sea level rise, these oscillations should result in a gradual landward migration of the bar to keep pace with the location of the equilibrium depth and distance offshore. Similar arguments can be made for all bars present on a profile and indeed for all sediment in the nearshore profile.

This dynamic behaviour applies primarily to the upper shoreface and ignores the effects of processes in the lower shoreface. However, over periods of hundreds to thousands of years, profile evolution will also be controlled by the form of the lower shoreface and by processes occurring there (COWELL, ROY, and JONES, 1995; STIVE and DE VRIEND, 1995). Also, over long time periods and large coastal systems, the available accommodation space and availability of sediments become critical in determining shoreline response to sea level rise (*e.g.,* HOSEMANN and STREIF, 2004). In the model presented here, these considerations are ignored because of the relatively short timeframe considered.

Sediment eroded from the foreshore, backshore, and dune during major storms is deposited primarily in the inner nearshore, and in the intervening fair weather conditions, the beach, foreshore, and berm are built up either gradually through the transfer of individual grains or collectively through the onshore migration and welding of swash bars (DAVIS *et al.,* 1972). Wind action then transports sand from the dry foreshore to the backshore and into the embryo dune and the seaward slope of the foredune (*e.g.,* HESP, 1988). On an equilibrium profile, the embryo dune and lower foredune slope will be eroded during major storms, thus transferring the sediment back to the littoral budget.

Under rising sea levels, major storms likely will produce severe scarping of the foredune, leading to partial or complete loss of vegetation on the seaward slope. Whenever this occurs, onshore winds will tend to erode sand from the front face of the dune and transport it to the crest and over onto the lee slope, and some sediment will also be transported directly from the beach. Erosion of the base of the dune and deposition on the lee slope thus produce a landward migration of the dune form. This process is depicted conceptually in several beach-dune models (*e.g.,* NICKLING and DAVIDSON-ARNOTT, 1990; PSUTY, 1988) and might be hastened through the development of blowouts (HESP, 2002). Empirical support for this comes *e.g.,* from measurements of deposition in foredune at several locations that show this process in detail on Long Point, Lake Erie, following high lake levels of 1985–1987 (DAVIDSON-ARNOTT and LAW, 1996; LAW and DAVIDSON-ARNOTT, 1990). Similar landward transfers have been measured at Skallingen, Denmark, where the foredune is migrating landward at rates of >2 m/a (AAGAARD *et al.,* 1998, 2004).

Under rising sea level, therefore, it would be expected that the foredune will be scarped more frequently than under stable sea levels, thus reducing the mean vegetation cover and increasing sediment transport landward of the crest. The resulting dune will have steep stoss and lee slopes similar to those shown in Figure 3 of the east coast of Prince Edward Island where sea level is rising at 3–5 mm/y (OLLERHEAD *et al.,* 2003). The sediment that reaches the lee slope of the dune is effectively removed from the process of beach-dune interaction unless the dune itself migrates landward and they are exposed at the front of the dune or the dune itself is completely overwashed.

The landward migration of the upper shoreface is similar to predictions for low-gradient shorefaces in the Shoreface Translation Model (COWELL, ROY, and JONES, 1995) and to the model of DEAN and MAURMEYER (1983). Again, there is considerable empirical evidence to support the onshore migration of the nearshore profile. Measurements at Skallingen in Denmark show landward movement of sediment in the nearshore accompanying barrier transgression (AAGAARD *et al.,* 2004) and multibeam sonar measurements off the east coast of Prince Edward Island show that sediments associated with the transgression there are not being stored on the shoreface, but rather in the beach and dune systems and in ebb tidal deltas (DON FORBES, personal communication, 2003).

The conceptual model put forward here should only be used as a starting point for input to modelling the effects of sea level rise locally and regionally. Clearly, the numerical value of landward shoreline displacement predicted by the RD-A model is similar to that predicted by the Bruun Model. However, the effects of longshore sediment transport and other inputs and outputs associated with the littoral and dune sediment budgets will need to be accounted for in most realistic settings, as will the nature of the sediment characteristics and topography landward of the shoreline. What is important here is, if the proposed model is conceptually valid, that sandy shorelines where sea level is rising should be associated with erosion and landward transgression of the nearshore profile, as well as the maintenance and landward displacement of the beach-dune system. This is a distinct contrast to the predictions of the Bruun Model, and it should provide the basis for testing the applicability of each model.

CONCLUSIONS

From an examination of the hypotheses underlying the Bruun Model (BRUUN, 1962), it is questionable whether the basic premise that sediment is eroded from the land and deposited on the nearshore profile as a response to sea level rise is realistic given our understanding of dune, beach, and nearshore dynamics for a time period on the order of 100 years. As a means of stimulating a fresh approach to modelling the effect of sea level rise for coastal zone management, a new conceptual model is proposed here that is based on the same initial assumptions as those put forward for the Bruun Model. The RD-A model differs from the Bruun Model in that it explicitly includes beach-dune interaction and landward sediment transfers by aeolian processes, and it predicts that sea level rise will lead to nearshore erosion and landward migration and preservation of the foredune system.

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