

The response of soft rock shore profiles  
to increased sea-level rise □

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## **Summary**

A process-based numerical model has been used to explore the sensitivity of equilibrium recession rates ( $\varepsilon$ ) and equilibrium profiles of eroding soft rock shores to a range of sea-level rise rates. Shore erosion was simulated under ranges of wave height and period, tidal amplitude, rock strength, beach volume and rate of sea-level rise. Equilibrium recession rates were found to be insensitive to beach volumes less than approximately 20 m<sup>3</sup>/m. Equilibrium shore profiles were dependent on the rate of sea-level rise. A simple expression was found to describe the relationship between future and historic rates of sea-level rise and equilibrium recession for shores with a low beach volume.

## **1 Introduction**

Understanding and quantifying shore profile response to accelerated sea-level rise is one of the most important issues facing coastal geomorphology (Dubois, 2002). If the impacts of climatic change on the coast are to be understood then we need to know how sensitive shores are to accelerated sea-level rise and how this sensitivity varies with shore characteristics such as rock strength, tidal range, wave climate, beach cover, historic rate of sea-level rise, etc.

Numerical modelling has an important role to play in addressing this issue, through the quantification, exploration and application of conceptual models. In particular, numerical models are a powerful means of dealing with the complex interactions of multiple parameters and in testing their response to scenarios of future change. Unfortunately model development, both conceptual and numerical, is hampered by the short periods over which relevant observational data are available (typically decades to one century). This lack of data makes validation of models that describe the response of eroding shores to a *changing* rate of sea-level rise very difficult. This context notwithstanding, Nicholls and Stive (2004) pointed out that analysis of future erosion trends requires more than extrapolation of past rates combined with an “expert eye”. Moreover, it is apparent that such analyses generally cannot be deferred in the face of population growth and development on coasts affected by rising sea levels (Cowell *et al.*, 2006).

Some progress has been made in understanding how sandy shores respond to steady sea-level rise. Bruun (1962) proposed that under rising sea-levels a beach’s equilibrium profile i.e. its average annual form, would be maintained whilst rising with the average water level (see Figure 1). Such an increase in elevation requires the deposition of a volume of sediment ( $B$ ), which is mined from the upper profile ( $A$ ). Consequently the equilibrium profile translates landward ( $R$ ) as it rises. This simple conceptual model is not universally accepted, and does not account for longshore sediment transport which must play an important role in the response of sandy shores (see Dickson *et al.*, 2007) but it does describe plausible processes through which sea-level rise may drive beach erosion. Zhang *et al.*, 2004 have shown that, in the absence of gradients in alongshore sediment transport, the Bruun model can be used to account for historic observations of recession of sandy coasts along the eastern USA. However, Bruun’s conceptual model does not represent shore profiles that include a soft rock shore platform and cliff.

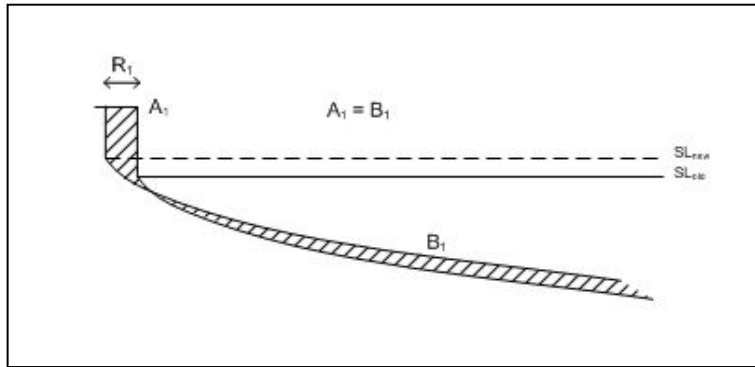


Figure 1. Bruun's conceptual model of sandy shore response to sea-level rise.

This paper explores the behaviour of a model of the erosion of soft rock shores to conjecture about generic response to increased sea-level rise. The model parameter space is examined and parameter sensitivity established. Despite the complexity of system interactions described within the model, results imply the existence of a simple relationship between future and historic rates of sea-level rise and rates of shore recession.

## **2 Future sea-level rise**

Tide gauge records indicate that global sea level has risen over the twentieth century at rates of 1.5 to 2 mm yr<sup>-1</sup> (Miller and Douglas, 2004). When driven by scenarios of greenhouse gas emissions, climate models predict that sea-level rise will accelerate due to global warming through thermal expansion of the oceans and the melting of land-based ice. For example the Intergovernmental Panel on Climate Change estimates a global increase in sea-level, from 1990 to 2100 of 90 to 880 mm, under SRES scenarios (Church *et al.*, 2001). It is also apparent that increased sea-level rise may continue for a long time. If CO<sub>2</sub> concentrations are stabilised within a few centuries, sea-level rise due to thermal expansion will take centuries to millennia to reach equilibrium, whilst sea-level rise due to ice melting will take several millennia (Church *et al.*, 2001).

## **3 Modelling soft rock shore erosion**

Until recently the complexity associated with the processes that erode soft-rock shores had prevented the development of process-based models. As a result, predictions of the response of shorelines to sea-level rise had relied on other methods such as analysis of historical trends (e.g. Leatherman, 1990), the Bruun rule and modifications of it (e.g. Dean, 1991).

Bray & Hooke (1997) assessed several such methods and concluded that the modified Bruun rule was particularly suitable for predicting the response of eroding cliffs.

The form of the Bruun model used by Bray & Hooke (1997) follows Dean (1991):

$$Q_2 = Q_1 + (S_2 - S_1) \frac{L_*}{P(B + h_*)} \quad \text{Equation 1}$$

where  $Q_1$  and  $Q_2$  are historical and future shore recession,  $S_1$  and  $S_2$  are historical and future sea-level rise,  $L_*$  is the length of the active (i.e. eroding) profile,  $B$  is the height of the retreating cliff,  $P$  is the proportion of sediment that is sufficiently coarse to remain in the equilibrium shore profile, and  $h_*$  is closure depth. The use of such models has been debated

at some length. Despite continued advocacy by some, other researchers contend that the Bruun rule is an overly simplistic representation of the response of shorelines to sea-level rise and should be abandoned (Cooper & Pilkey, 2004). In any case it is apparent that coastal response to sea-level rise is a complex morphodynamic issue, such that many feedbacks are to be expected beyond the simple profile translation envisaged by the Bruun rule (Stive, 2004).

Process-based mathematical modelling of rock-shore recession has been attempted by Trenhaile (2000) and Walkden & Hall (2005), but the scope and intention of the models differed. Trenhaile's (2000) model was targeted at investigating the sensitivity of shore platform morphology to variability in parameters such as tidal range, rock resistance, and wave climate. It was later adapted to simulate the effects on present platform morphology of higher sea levels during the penultimate and last interglacial as well as the late Holocene (Trenhaile, 2001). By contrast, the SCAPE models developed by Walkden & Hall (2005), and extended by Dickson *et al.*, (2007) and Walkden & Hall (under review), were developed explicitly to simulate the sensitivity of shore profile response (including rates of cliff recession) over a timescale of decades to centuries. A comparison of SCAPE predictions with those made using the modified Bruun rule (Equation 1) show that SCAPE predicts a more complex suite of responses and lower overall sensitivity of soft-rock shores to sea-level rise (Dickson *et al.*, 2007).

### 3.1 SCAPE

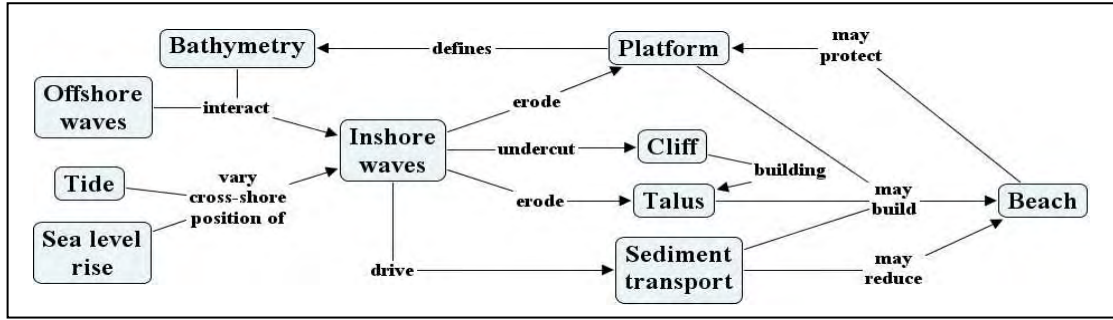


Figure 1. Processes represented in SCAPE

SCAPE simulates the emergence of soft rock shore profiles (Walkden & Hall, 2002, Walkden & Hall 2005, Dickson *et al*, 2006, Walkden & Hall, under review). Figure 1 illustrates the components of the system SCAPE describes. The profile is discretised into horizontally aligned elements, the seaward face of which is retreated every model timestep ( $\Delta t$ ), which is typically one tidal period. Equation 2 describes the landward retreat ( $\Delta y$ ) of each element:

$$\frac{\Delta y}{\Delta t} = \frac{F}{R} f_1(f_3(t) - z) \tan(f_2(z)) \quad \text{Equation 2}$$

where  $F$  represents the erosion force of the wave,  $R$  is a calibration term representing rock strength,  $f_1$ ,  $f_2$  and  $f_3$  are functions representing, respectively, the distribution of erosion under a breaking wave field, profile slope and variation of tidal elevation. The erosion of any element also depends on the presence of cliff debris (talus) or a beach. If sufficiently thick, relative to wave height, talus or beach sediments are assumed to protect the profile elements on which they rest.

This system, and therefore the emergent profile form, is regulated through feedback. For example, if a pattern of erosion results in an element becoming gently sloping, then its subsequent erosion will tend to be diminished. Such negative feedback allows dynamic equilibrium forms to emerge and brings model stability (see for example Walkden & Hall 2005). In addition, when the profile is excessively steep, positive feedback drives rapid change towards more gentle slopes (see Figures 6 to 8, Walkden & Hall 2005). Submergence due to sea-level rise is represented as a downward translation of the shore profile. Its effect becomes noticeable when extended periods are simulated.

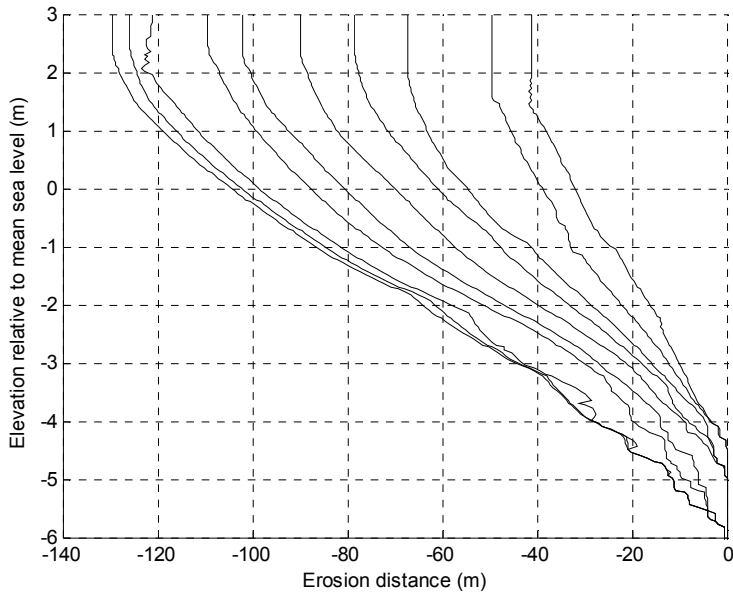


Figure 2. ‘Snapshots’ of the development of a model profile in 1 year stages.

Figure 2 shows example model output illustrating the early formation of a shore profile over ten years from an initial vertical cliff in deep water. The shore platform begins to form and the cliff toe becomes clearly demarked.

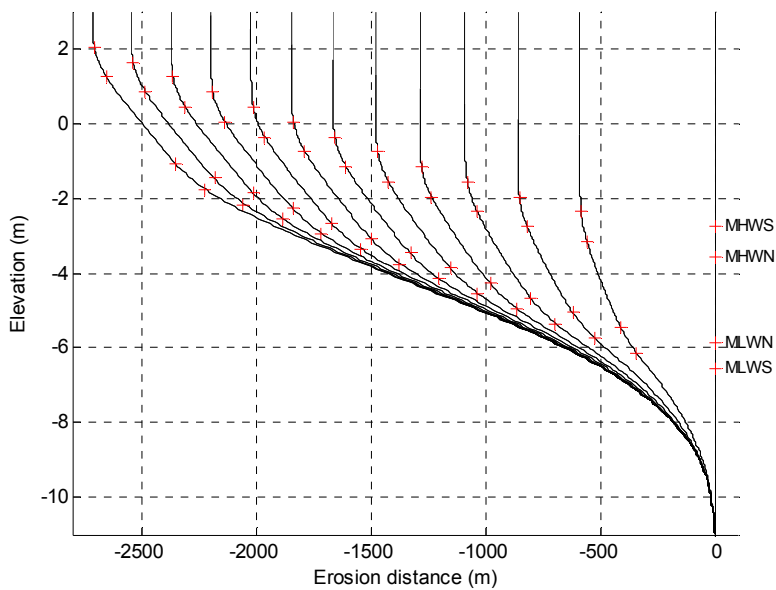


Figure 3. ‘Snapshots’ of model profiles representing 2400 years of development, in 200 year stages.

When the model is used to represent much longer periods, as in Figure 3, the profiles become smoother and more stable. Over such timescales the rate of sea-level rise becomes important in determining the profile shape. Eventually the model profile achieves dynamic equilibrium and no longer changes (on average) relative to the (rising) sea-level. In this state the starting conditions has no effect on the profile state and the average equilibrium retreat rate ( $\epsilon$ ) becomes constant.

Walkden & Hall (2005) used SCAPE to reproduce the profile form of a study site, the Naze peninsula, on the Essex coast in southern England. A quasi 3D (Q3D) model was assembled with a series of SCAPE profiles, which interacted through longshore exchange of beach material. The simulated recession rate was calibrated to match historic observations by varying the rock strength term  $R$ . The model was then validated through comparison of the emergent profile forms against survey and bathymetric data. Walkden & Hall (under review) and Dickson *et al*, (2006) later constructed regional scale SCAPE models of (respectively) 35km and 50km of the coast of North Norfolk (UK). The validation of these models was based on comparison of alongshore variations in recession rate, derived from historic maps recorded over 117 years.

#### **4 Model response to increased sea-level rise**

The work represented in this paper uses the model developed to describe the Naze shore. To reduce runtimes and simplify interpretation of the results, a single section was modelled. Parameters were selected to reproduce the conditions in the centre of the Naze model. Each simulation was run until the profile shape reached dynamic equilibrium to identify the equilibrium retreat rate ( $\epsilon$ ).

##### *4.1 Parameter space*

The model parameters include: (1) rock strength, (2) sea-level rise, (3) wave height, (4) wave period, (5) talus volume, (6) beach volume, (7) cliff height, (8) proportion of the rock comprising sediment suitable for building a beach and (9) tidal range. The purpose of this study, to use SCAPE to explore shore dynamic response to increased sea-level rise, implied the exploration of a very large parameter space. Efforts were therefore made to explore whether any of these parameters were redundant, i.e. did not influence equilibrium recession rates. During each test series all parameters, except that being explored, were held constant at the values used in the Naze model.

##### *4.2 Elimination of parameters*

The beach at each section of the original Q3D Naze model exchanged sediment with its neighbours. This could not be reproduced in the 2D model used in this study, so instead the beach volume was held constant for a range of values. The profile of the beach was described as a Bruun curve (see Bruun 1954, Dean 1991):

$$d = A_p x^{\frac{2}{3}} \quad \text{Equation 3}$$

Where  $d$  is the depth of water and  $x$  is the offshore distance from the still water line. The profile coefficient  $A_p$  is site specific, and for the Naze it was found to be 0.16. The Bruun curve is commonly used in coastal engineering to represent an annual average beach surface. The profiles in Figure 4 demonstrate how the platform responds to the introduction of the beach. Initially the beach slope is steeper than that of the platform so it forms a thick layer close to the cliff toe, protecting from erosion the part of the platform that it covers. The platform seaward of the beach continues to lower. As it does so the seaward edge of the beach migrates down the profile and so covers and begins to protect a wider portion of the upper platform. This process continues until the beach becomes so wide and thin that waves can erode the profile through it. At this point the average apparent erosion equalises at all levels and dynamic equilibrium is re-established.

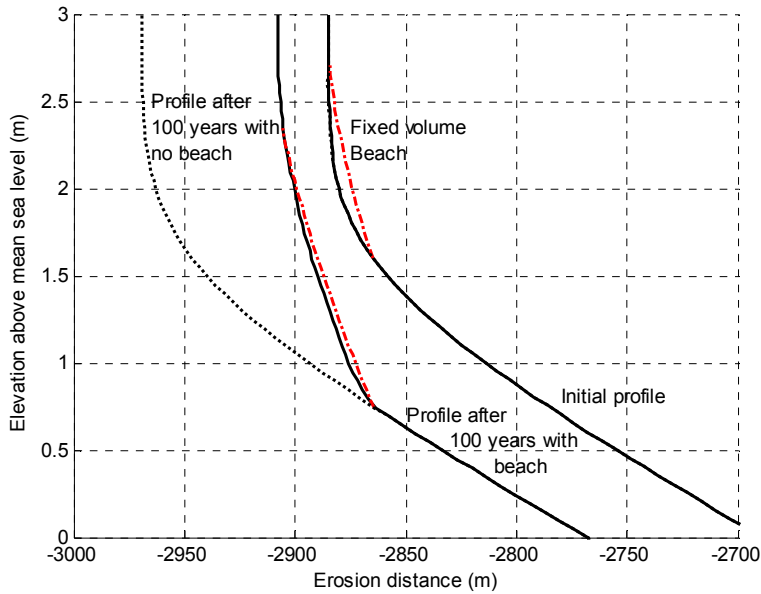


Figure 4. Shore profile adaptation to the introduction of a beach.

Walkden & Hall (2005) provide an example in which equilibrium recession rates are shown to be insensitive to the presence of a beach. In the present study a series of profiles with different beach volumes were simulated and their recession rates were observed. In the decades following the introduction of the beaches the recession rates fell. However, once each profile had adapted to the beach (as in Figure 4) and dynamic equilibrium conditions had emerged, the recession rate became almost independent of beach volume below approximately  $20 \text{ m}^3/\text{m}_{\text{run}}$ , as shown in Figure 5.

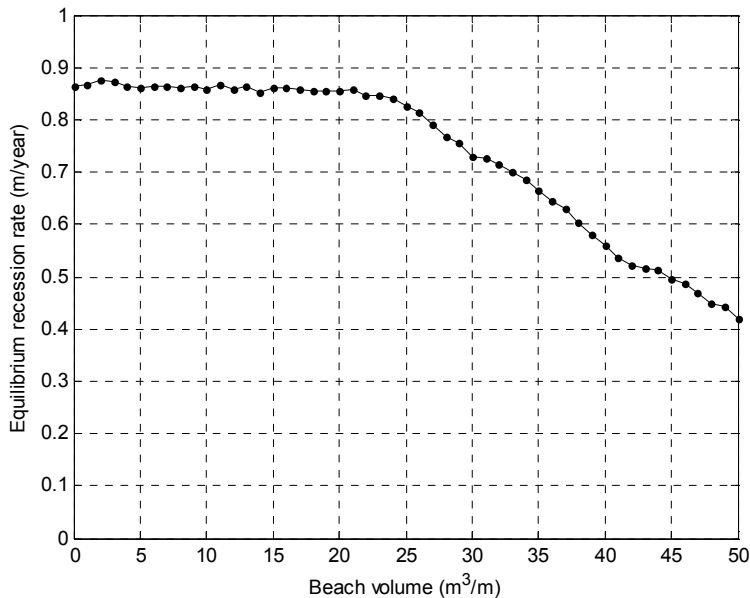


Figure 5. Sensitivity of equilibrium shore recession rates to the presence of a beach.

These results indicate that a beach volume may vary below  $20 \text{ m}^3/\text{m}_{\text{run}}$  without influencing the equilibrium recession rate. This insensitivity initially appears counter-intuitive since, clearly, beaches dissipate wave energy that would otherwise erode the substrata, and larger beaches dissipate more energy. Indeed, in the model the beach is represented as a protective layer.

However, as can be seen in nature (Kamphuis 1987) and in Figure 4, the shore platform adapts to mimic the slope of the beach overlying it, so that the beach steepens the section of the profile closest to the cliff. It follows that any waves that penetrate the beach impinge on a steepened profile. The model results show that once dynamic equilibrium is established the amplification of erosion caused by this platform steepening cancels the protective effect of the beach. This behaviour emerged from the model rather than being designed into it, and may well be realistic. The value of the threshold beach volume (approximately  $20\text{m}^3$ ) will be dependent, to some degree, on the model assembly, particularly the representation of the protective capability of the beach, and was not explored further in this study. Instead these results were interpreted as showing that equilibrium recession rate is independent of low beach volumes. The scope of the remainder of this paper is restricted to this type of shore system, such that the beach can be neglected and eliminated from subsequent models. Consequently the cliff height and sand content are also eliminated since they only influence the shore profile dynamics through their effect on beach volume. The talus wedge may also be neglected since its influence on the profile shape is similar in principle to that of the beach, and much smaller in practice.

#### 4.3 Parameter tests

The remaining model parameters were tested by applying amplification factors to the Naze-based model. For each amplification factor the equilibrium recession rate was found for a range of rates of sea-level rise. Table 1 contains the parameter amplification factors and rates of sea-level that were tested. In addition, more extensive sea-level rise rates were tested on the basic Naze model without parameter modification.

| Parameter         | Amplification Factors | Rates of Sea-level rise, mm/annum (min:step:max) | Number of combinations |
|-------------------|-----------------------|--|------------------------|
| Rock strength (R) | 0.25, 0.5, 1, 2, 4    | 2, 4, 6, 8, 10, 12, 14, 16                       | 40                     |
| Tide range (TR)   | 0.5, 1, 1.5           | 2, 4, 6, 8, 10, 12, 14, 16                       | 24                     |
| Wave height (H)   | 0.5, 1, 1.5           | 2, 4, 6, 8, 10, 12, 14, 16                       | 24                     |
| Wave period (T)   | 0.75, 1, 1.25, 1.5    | 2, 4, 6, 8, 10, 12, 14, 16                       | 32                     |

Table 1. Parameter combinations tested.

## **5 Results and discussion**

### *5.1 Equilibrium profile shapes*

The results show a strong relationship between sea-level rise and recession rate. This can be seen in Figure 6, which shows equilibrium profile shapes resulting from different rates of sea-level rise that emerged from the baseline test series (i.e. in which all the amplification factors were set to 1).

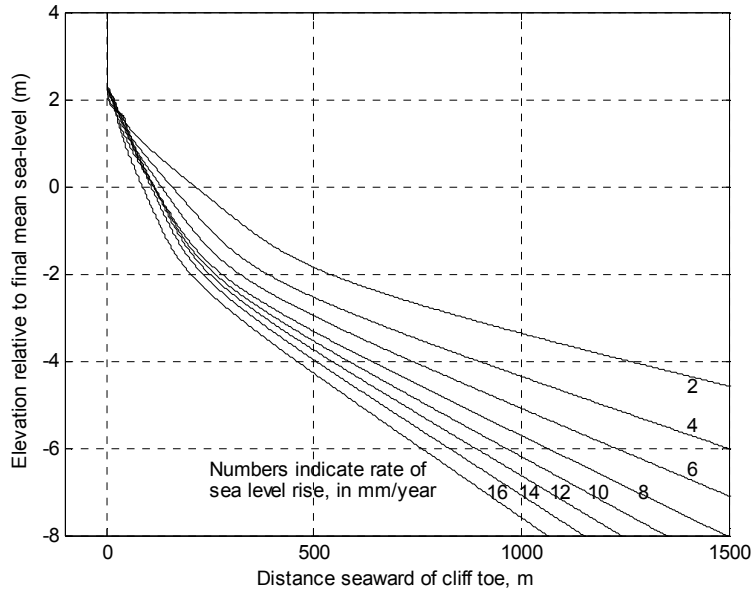


Figure 6. Equilibrium profile sensitivity to rate of sea-level rise.

The output of SCAPE differs fundamentally from Bruun's conceptual model in that the equilibrium profile form varies with the rate of sea-level rise. The Bruun model proposes an equilibrium profile that is migrated upward and landward maintaining its shape relative to still water level. By contrast, changed rates of sea-level rise result in new SCAPE equilibrium profiles. For instance, Figure 6 shows emergent modelled equilibrium shapes at rates of sea-level rise of between 2 mm/year and 16 mm/year. It is apparent that the equilibrium profiles become increasingly steep for higher rates of sea-level rise.

This behaviour can be understood by considering the period that each elevation in the profile experiences wave attack. Wave action causes flattening of the shore profile, whilst sea-level rise translates the zone of wave attack to higher elevations. Each elevation in the profile is flattened less under higher rates of sea-level rise because the period it is exposed to wave attack is shorter.

These results do not contradict the Bruun model, which was conceived for deep beach shores, but does show that the assumption of an unchanging equilibrium form under accelerated sea-level rise is unrealistic for the shore type considered here.

### 5.2 Equilibrium recession rate

The historic (equilibrium) recession rate ( $\epsilon_1$ ) is normally used when estimating future recession of a site because it represents the geological characteristics and sediment transport pathways in response to the imposed hydrodynamic loads. The future recession rate ( $\epsilon_2$ ) of a system *in dynamic equilibrium* may be assumed to be equal to  $\epsilon_1$ , but this is not the case under increased sea-level rise.  $\epsilon_1$  may still be used as a normalising factor, however, to account for geology and stationary hydrodynamic loads. Figure 7 shows the equilibrium recession rates from all of the parameter tests, whereas in Figure 8 the same data has been normalised to assumed historic rates.

For each test series (i.e. sequence of tests in which the amplification factors were held constant whilst the rate of sea-level rise was varied) it was assumed that the lowest rate of sea-level rise (2 mm/a) represented historic conditions (i.e.  $S_I = 2$  mm/a). This value was chosen simply because it is typical for southern Britain, and many other regions during the

20<sup>th</sup> Century. Each value of  $\varepsilon$  was then divided by the value of  $\varepsilon$  resulting from this  $S_1$ . Likewise, the rates of future sea-level rise were normalised to  $S_1$ . This effectively removed the scatter in the data, as can be seen in Figure 8.

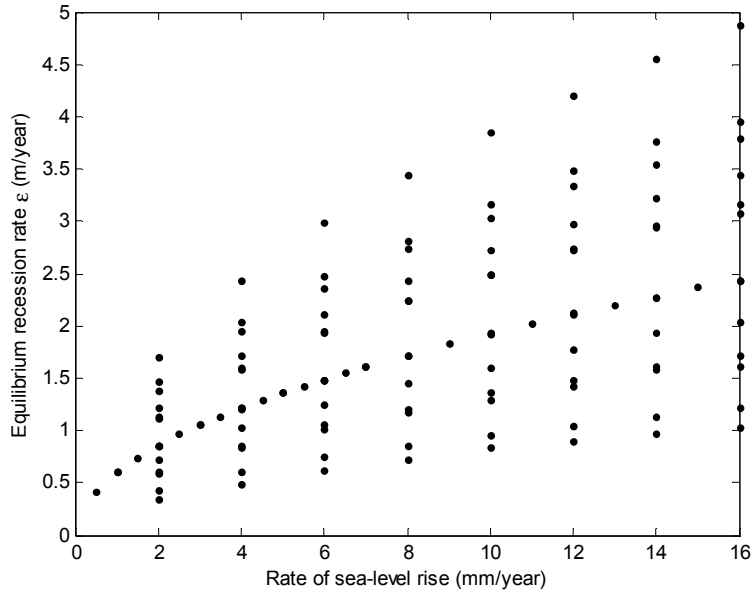


Figure 7. Equilibrium recession rates of the parameter tests.

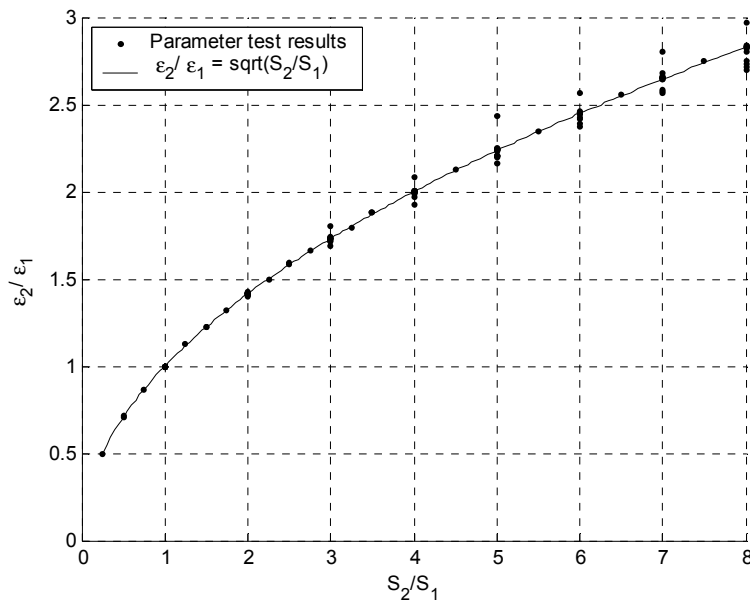


Figure 8. Normalised rates of sea-level rise and equilibrium recession.

The following expression fits the data in Figure 8 with a correlation coefficient of 0.98:

$$\frac{\varepsilon_2}{\varepsilon_1} = \left( \frac{S_2}{S_1} \right)^{0.5} \quad \text{Equation 4}$$

Hence, the model's response to increased sea-level rise, within the parameter space tested, for the case of an absent/small beach can be expressed as:

$$\varepsilon_2 = \varepsilon_1 \sqrt{\frac{S_2}{S_1}} \quad \text{Equation 5}$$

Equation 5 describes the relationship between future and historic equilibrium retreat rates. Equilibrium conditions take some time to emerge following a change in the rate of sea-level rise. The simulation passes through a transient stage, as illustrated in Figure 9 which shows results for one model, in which a step increase in sea-level rise from  $S_1 = 2$  mm/a to  $S_2 = 6$  mm/a was introduced at 6000 years. The results have been averaged within 100-year windows. It can be seen that the recession rates take around 1000 years to stabilise at approximately 1.47 m/a from the prior rate of approximately 0.85 m/a. However, approximately half of the total increase in retreat rate is achieved by the middle of the first century following the step change.

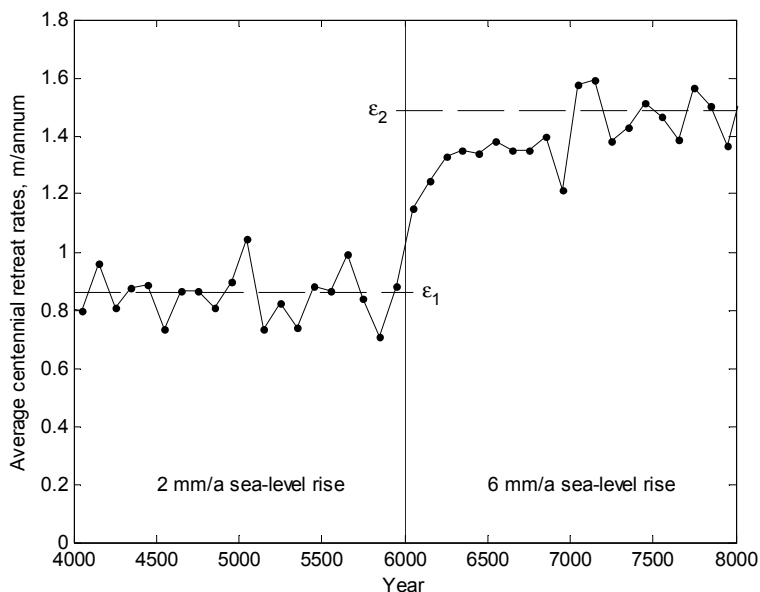


Figure 9. Example model recession rates before and after a step change in sea-level rise from 2mm/a to 6mm/a at 6000 years (averages of 100 year segments).

As stated above, these results describe the behaviour of shores with a low beach volume. It is difficult to estimate the proportion of shores at which this condition applies because coastal studies rarely observe beach volume or thickness. However, it is notable that shore platforms tend to mimic the slope of the beach overlying them (Kamphuis, 1987), such that beaches of relatively low volumes obscure a large platform area, perhaps the entire intertidal zone. Hence it is likely that many shores which meet this criteria, and therefore in behavioural terms are controlled by the dynamics of their shore platform, are probably currently being classified as 'beaches'.

Equation 5 does not describe future recession at sites with no historic sea-level rise. Results of SCAPE modelling not described here indicate that although such locations may recede they may not achieve a state of equilibrium, and so the concepts used to develop equation 5 do not apply. Exploration of this condition will require further work, however the limitation that this constraint imposes on the applicability of Equation 4 is not severe since the average global sea-level is rising.

## **6 Conclusions**

The response of shore profiles to increased sea-level rise is an important problem that lends itself to exploration through numerical model studies. At present few data are available to validate such models owing to the relatively long timescales over which rates of sea-level rise have changed. Nonetheless, by assuming scenarios of sea-level change and testing sensitivity to various model parameters, the range of possible responses of shore profiles can be usefully examined.

In this study an abstract process-based numerical model has been used to explore profile dynamics, particularly equilibrium profiles and recession rates, under different rates of sea-level rise and a range of input conditions. Equilibrium profile form was found to depend upon the rate of sea level rise, with higher rates leading to steeper foreshores. The results for equilibrium recession rate were found to be well represented with a simple relationship across all parameter values tested. This relationship is proposed as a means of rapidly estimating future equilibrium recession rates for soft rock shores overlain by a low volume (or absent) beach in which the profile is subjected to an increase in the rate of sea-level rise. In these numerical experiments the equilibrium recession rate proved to be insensitive to beach volumes below 20 m<sup>3</sup>/m. This value is proposed as a tentative first estimate of the beach volume below which the relationship applies. Subject to this condition the relationship should also be independent of cliff height and sand content of the rock as well as to alongshore exchange of sediment. The relationship is not appropriate in the case of non-equilibrium conditions, including accelerating sea-level rise and zero sea-level rise.

Within these constraints this work indicates the existence of a remarkably simple and broadly applicable relationship governing the response of soft rock coastal profiles to accelerated sea-level rise.

## **Acknowledgments**

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