A Review of Shoreline Response Models to Changes in Sea Level

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Abstract

Assessment of current and future coastal hazards is now a legislative requirement in New Zealand and most parts of Australia. Methods for assessment of erosion hazard are well established, and uncertainty in the present hazard can be reasonably well estimated. However, uncertainty in defining future climate-change associated erosion/recession hazard increases due to both the assumptions surrounding sea-level rise (SLR) as well as limitations of the models used to evaluate the associated shoreline response. The most widely used methods for defining the coastal erosion hazard extent utilise a modular approach whereby various independent components are quantified and summed to provide a final value (e.g. see [14]). The SLR response component is based on the well-accepted concept that an elevation in sea level will result in recession of the coastline. This component is often the largest contributor to erosion hazard zones, so understandably this term is often the subject of intense debate, media scrutiny and a focus in litigation. With the trends of increasing populations on the coast this controversy is only likely to escalate. A range of models for estimating coastal response to changes in sea level have been developed over the past 50 years. These methods range from the application of basic geometric principles to more complex process-based assessment. While some methods are used more widely than others, none have been proven to be categorically correct or adopted universally. While most attention has focussed on the response of open coast beaches to SLR, other shoreline types including gravel beaches and low energy coastlines such as lagoons and estuaries are also affected. This paper briefly reviews existing shoreline response models including the process assumptions, limitations, development and application history. While most models are based on similar underlying process assumptions, variation in the definition of model parameters (e.g. closure depth) can produce significant differences in predicted recession values. As such, robust and informed selection of model parameters are required to derive defensible conclusions.

Keywords: Coastal hazards, sea level rise, climate change, shoreline erosion, recession

1. Introduction

The intersection of land and ocean is inextricably linked to relative local sea level with basic geometric principles indicating inundation and landward adjustment of shoreline position as levels increase and seaward adjustment as levels lower. On shorter (century) timescales, waves, tides and sedimentary processes drive morphological evolution and complicate the basic passive inundation model, but recent analytical work by [26] show that in the long-term (millennia) timescales transgression will always follow the slope of the inland topography.

Similar to most areas, 85 per cent of the Australian population now lives in the coastal region and significant buildings, utilities, and transport networks are constructed in areas that experience periodic flooding and shoreline erosion [8], evaluating the shorter-term (decade to century scale) response of coastlines to future SLR is of critical concern to coastal managers, planners, engineers and the general public.

Sea levels have been rising over the 20th century with a global average rise of 1.8 ± 0.3 mm/year estimated between 1950 and 2000 [16]. Relative SLR in New Zealand and Australia appear largely consistent with these global averages [13]. Global sea levels are predicted to not only to continue to rise in the future but to accelerate as a warming climate causes thermal expansion of the oceans and increased glacial melt [16]. Future sea level predictions range from 0.18 to 0.59 m by 2100 [16] with inclusion of ice-sheet melt and other semi-empirical approaches suggesting that even higher rises may be possible. Existing guidance on SLR in New Zealand and Australia largely follows this with various State and National policies summarised in Table 1 (after [18]).

Several methods for estimating coastal response to changes in sea level have been developed over the past 50 years. These methods include approaches based on past recession rates, basic geometric principles and more complex process-based assessment. Within Australia and New Zealand, Government guidelines and policies generally include a requirement to account for shoreline recession associated with SRL (Table 1). While some methods are used more widely than others, not all are necessarily applicable to the variety of coastal types across Australasia and none have been proved categorically correct and adopted universally. This paper reviews the range of methods presented to date, evaluating the underlying process assumptions and limitations, and compares these with general policy and guideline recommendations available to practitioners, planners and managers.

Table 1 Policies and guidelines for evaluating shoreline recession due to sea level rise (after [18])

Area	Guideline	SLR Guidance	SLR retreat method
Aus Comm	DCC (2009b)	1.1 m	In the absence of full information the Bruun Rule may be used to provide a generalised indication.
Qld	DERM (2012)	0.8 m by 2100	Bruun Rule. Closure depth method not specific. Upper beach face slope suggested for moderate energy beaches
NSW	DECCW (2009)	0.9 m by 2100[1]	Bruun Rule. Closure depth by %outer+Hallermeier is suggested, but most practitioners use %inner:+Hallermeier or sediment characteristic boundaries
Vic	Victorian Coastal Strategy (2008)	Not less than 0.8 m by 2100	Recommended but method not specified
Tas	DPIW (2009)	Use IPCC AR4 scenarios	Recommended but method not specified
SA	SA (2012)	1.0 m by 2100	Recommended but method not specified
WA	WA (2006); WA (2012)	0.9 by 2110	Standard distance of 38 m to 2100 derived from SLR of 0.38 m and Bruun Factor of 100. To be updated to reflect higher 2110.
NT	NT (2009)	NA	NA
New Zealand	MfE (2008)	0.5 m to 0.8 m+	Variation of the Bruun Rule on open coasts provides general potential
	Royal Soc (2010)	0.5 m consider up to 1.9 m	

[1]Value repealed within NSW Stage 1 Coastal Reforms (NSW Planning & Infrastructure, 2012) but still commonly used

2. Open Coast Sandy Beaches

To maintain a state of dynamic equilibrium, unconsolidated sandy beaches continually adjust to environmental forcing. For example, prolonged changes in wave direction are known to induce rotation in bay planforms or asymmetrical adjustment in forelands, and changes in sea level result in onshore or offshore profile adjustment [1].

2.1 Geometric Equilibrium Models

The most widely known model for beach profile response is that of Bruun [1]. The Bruun equilibrium model assumes that as sea level is raised, the equilibrium profile is moved upward and landward conserving mass and original shape (Figure 1-d; Eqn. 1) according to the following assumptions [23]:

1. The upper beach is eroded due to the landward translation of the profile;
2. The volume of material eroded from the upper beach is balanced by equivalent deposition offshore and,
3. The rise in the nearshore bottom as a result of this deposition is equal to the rise in sea level.

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

(1)

Where R is the landward retreat, h_* defines the maximum depth of sediment exchange, L_* is the horizontal distance from the shoreline to the offshore position of h_*, B is the height of the berm/dune crest within the eroded backshore and S is the sea level rise This essentially reduces to a translation of the profile up a regional slope

This relationship was termed the Bruun Rule by [22] and has remained the principal method for establishing ±rule of thumbq shoreline response to sea-level rise [8]. As the rule is governed by simple, two-dimensional conservation of mass principles it is limited in its application in a number of aspects:

1. The rule assumes that there is an offshore limit of sediment exchange or a ±closure depthq beyond which the seabed does not raise with sea level.
2. The rule assumes no offshore or onshore losses or gains.
3. The rule assumes instantaneous profile response following sea-level change.
4. The rule assumes an equilibrium beach profile where the beach may fluctuate under seasonal and storm-influences but returns to a statistically average profile (i.e. the profile is not undergoing long-term steepening or flattening).
5. The rule does not accommodate variations in sediment properties across the profile or profile control by hard structures such as substrate geology or adjacent headlands.
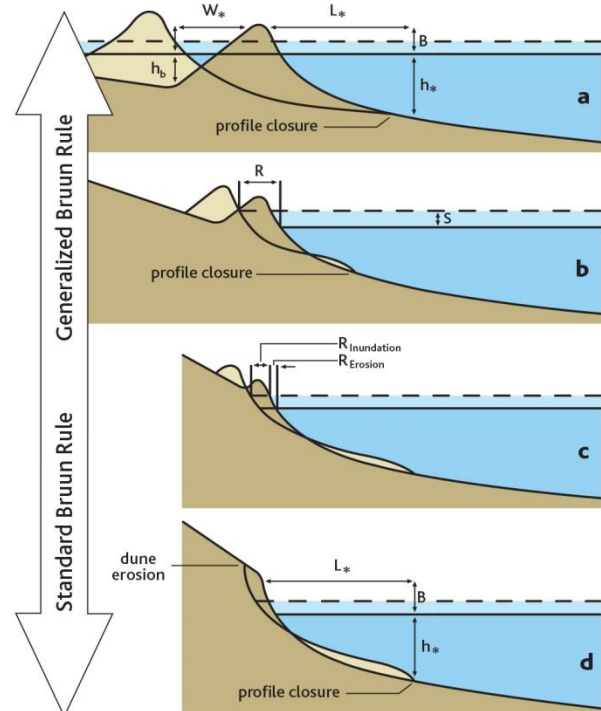

Figure 1 Schematic diagrams of the Bruun model modes of shoreline response (after [6])

To address these limitations a number of variations to the basic Bruun rule were introduced [12] to account for losses of fines from the littoral zone using an 'overfill ratio' ($F_A > 1$) and net longshore movement of sediment (Q_S) into or out of a control shoreline length (Y) in the time period of of consideration (Eqn. 2).

$$R = \frac{L_* F_A}{B + h_*} S + \frac{\Sigma Q_S}{Y(B + h_*)} \qquad (2)$$

[9] produced a generalised version of the Bruun rule to account for the landward migration of sediments over a barrier system by overwash (Eqn. 3) where W_* and H_b are the width and height to the lagoon face (Figure 1-a). This appears to be the basic form also proposed conceptually by [7].

$$R = \frac{S(L_* + W_*)}{h_* - h_b} \qquad (3)$$

Numerous researchers have tested the Bruun Rule against a variety of field and laboratory data as summarised in [23], [27] and others. As Zhang et al. describes, using field data to assess long-term responses is complicated by overlying short-term fluctuations and underlying cross-shore and alongshore sediment budget imbalances. Laboratory data is also limited by scale errors and testing duration. Some of the better known comparisons include studies by [12] in Lake Michigan where twenty five beach profiles over 50 km were monitored over 8 years where lake levels rose and fell by up to 0.39 m. Results showed overall recession when lake levels rose, followed by progradation as lake levels fell and an overall mass balance between offshore deposition and erosion. Observations showed less profile response than predicted by the Bruun Rule (with closure depth defined according to the seaward extent of the envelope of profile change) which was attributed to a lag in profile response time. While the eventual drop in lake level brought the observed profile position back into agreement with the Bruun Rule prediction, [23] argue that with a continual increase in sea level, the disagreement between modelled and observed retreat would have persisted and increasingly diverged.

Region-wide field studies have found mixed agreement between the Bruun Rule predictions, although reasonable agreement was found when sediment budgets are accounted for [10, 27] or results over larger regions are averaged thus balancing positive and negative budgets. Overall, the inclusion or exclusion of a sediment flux becomes somewhat irrelevant when used in the context of hazard assessment when long-term shoreline movement, a proxy for sediment flux into or out of the profile, is calculated as a separate variable during an erosion hazard assessment.

The major uncertainties that remain in using the Bruun rule include the definition of a closure depth (h_*) or cross-shore slope (1/tan) and lack of any lag time between sea level change and profile response. While some have questioned the actual existence of a closure depth, i.e. [3], the rule is not necessarily reliant on its physical existence. While long-term sediment exchange may occur to very deep water depths, i.e. the 'pinch-out' point [12], this 'ultimate' profile adjustment extent is only valid if either the profile response is instantaneous or if sea-level changes and then stabilises with the profile 'catching up'. As sea-level rise is expected to be ongoing [16] and a lag in profile response is apparent [12], the outer limit of profile adjustment is likely to be 'left behind'. The closure depth can therefore be more realistically defined as the point at which the profile adjustment can 'keep up' with sea-level change and becomes a calibration parameter in lieu of an adequate depth-dependent lag parameter.

Various definitions of closure depth have been presented in the literature including an ultimate definition of closure of 3.5 x H_{sb} [2] where H_{sb} is related to an extreme significant wave height (50 or 100 year ARI) or twice H_{sb} [25] However, as discussed above these 'ultimate limit' closure depths are likely to over-predict recession during on-going SLR. The method of [11] is one of the most widely accepted for defining closure depths, as it is based on site specific physical characteristics and processes. [11] defined three profile zones, namely the *littoral zone*, *buffer zone* and *offshore zone,* and surmised that the actual closure depth falls somewhere between the seaward limit of the *littoral* zone (d_l) and the offshore zone (d_i). Hallermeier suggests that the inner closure depth, d_l , is a function of sediment characteristics and local wave climate but, for a sandy beach, can be approximated [19] as:

$$d_l = 2.28 H_{s,t} - 68.5(H_{s,t}^2 / gT_s^2) \cong 2 \times H_{s,t} \qquad (4)$$

where d_l is the closure depth below *mean low water spring,* $H_{s,t}$ is non-breaking significant wave height exceeded for 12 hours in a defined time period, nominally one year, and T_s is the associated period. The outer closure depth can then be approximated as $d_i \, ^1 \, 1.5 \times d_l$. Hallermeier noted that uncertainties remain in this definition of closure, especially when d_i exceeds 20 m, which is usually cited as an ultimate limit to significant wave-induced sand transport.

Other definitions of closure depth include changes in seabed geometry or seaward limit of *significant* profile change. [19] suggested a seaward limit of *significant* change occurs based on a 6 cm of vertical change criterion. Using field data from a range of sites in the United States and Europe, he found the inner closure criterion of [11] to provide a robust outer limit for this profile change criterion. [17] used a variation of the geometric translation model and the beach face slope to predict storm erosion during periods of elevated water level on the United States West Coast. This could be

considered an inner limit as the beach face is near certain to adjust to a rise in sea level over longer time-frames. Some practitioners refer to this closure option as the *Komar Approach*.

[4] implemented the geometric transformation described by the Bruun and generalised Bruun models within a numerical framework but by relaxing the closed sediment budget restrictions allowed for evolution of the profile, longshore and cross-shore losses and gains to the system and variable resistance in substrate material. The framework, termed the *Shoreface Translation Model* (STM), allowed for a continuum of response models (Figure 1b . 1c) between the two extremes of encroachment and transgression and the time-dependent solution allows parameters such as closure depth to be adjusted.

2.2 Probabilistic assessment

The parameters used within the geometric equilibrium models are subject to considerable uncertainty, particularly closure (or more practically the speed at which sediment is moved from the beach face) and assumed future SLR. [5] point out that predictive precision in deterministic models conveys a false sense of confidence if not provided with appropriate estimates of uncertainty. They undertook a rigorous stochastic simulation to test the effect of uncertainty in input parameters (i.e. barrier and back barrier geometry, assumed closure depth, relative SLR, etc.) on predicted response. While many of the parameter bounds are selected by heuristic reasoning, the approach provides a more rigorous way of managing uncertainty resulting in a probability distribution for recession - although the practitioner or manager must still select an appropriate value, which in itself is likely to remain controversial.

2.3 Non-equilibrium process-based models

While geometric translation models are concerned only with ultimate morphological response (even if applied in a time-stepping framework), process-based models include time-dependent forcing and profile response. Such processed-based modelling has been used extensively to simulate shoreline change during storm events, such as the Convolution Method developed by Kriebel and Dean, SBEACH, and more recently XBeach.

Non-equilibrium, process-based models are beginning to be used to simulate the long-term effects of sea-level rise. Crude approximations of this include simulating a single storm event with sea level elevated to represent some future condition. However, as profile response is known to significantly lag sea level changes [12], such short-term modelling will likely under-predict the ultimate profile response. Other methods include simulating multiple storm events while raising the sea level incrementally between each. However, since these methods don't incorporate any accretionary component of beach recovery between storms, the profile remains in a permanently eroded state. If the time period simulated is extremely long, this method will consequently over-predict future recession, however, with only a few storms simulated, the profile may not fully adjust to the future long term average. These models are useful in this context as an alternative means to estimate profile closure depth, however, their use in estimating recession due to sea level rise is a misapplication of the model.

[15] and [21] couple simplified erosion models with an accretion mechanism in a temporal framework. Once erosion models are calibrated to previous storm observations and the accretion mechanism (generally a constant) calibrated to replicate long-term changes (or to maintain equilibrium in a statistically static environment), long-term changes can be simulated by modifying the wave and water level input time series. This may include increasing the frequency or magnitude of storm events or increasing the mean water level. [21] use empirically generated timeseries of waves and water level in their *Probabilistic Coastline Recession* (PCR) *model* and by resampling and rerunning simulations (i.e. bootstrapping) produce probabilistic results of recession estimates.

Non-equilibrium, process based models solve some of the problems associated with Bruun-type equilibrium models such as requiring a set closure depth or the issues of lag in profile response. However, to be computationally feasible, parameterisations and simplifications of processes are required which introduce additional uncertainty. The calibration process also requires high-quality, long-term, site-specific field data. While increasing computational power and parallel computing are likely to enable the use of more physically representative long-term modelling in the future with less reliance on parameterisation, demands for high quality field data with which to calibrate will likely remain.

2.4 Comparison of model results

Probabilistic result of the non-equilibrium PCR model computed for Narrabeen Beach [21], a reflective to intermediate type beach system characterised by a steep offshore profile and single bar system, are compared to values predicted using the Bruun Rule and five depths of closure (Figure 2). These include an outer closure limit of twice the design significant wave height ($d_i = 2 \times H_{s\text{-}100} = -18\text{m}$) as proposed by [25], the Hallermeier inner limit ($d_l = -10.5$ m) [19], a closure depth defined by observed pre- and post-August 1986 storm profiles ($d_{storm} = -16$ m; [18]), depth defined by numerical modelling of a large storm event in July 2011 using the SBeach and Xbeach models ($d_{numerical} = -12$ m; [18]) and profile slope as defined by the spring tidal beach face [17].
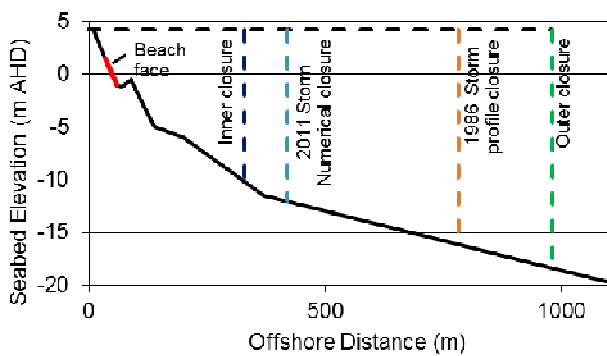
Figure 2 Narrabeen Beach profile (1986) with various closure definitions to define slope

Figure 3 shows the various definitions of closure to predict Recession/SLR (Bruun factor) values of 10 to 44, effectively straddling the entire probabilistic (2 . 99%) range predicted by the PCR model. Given that the actual probabilistic exceedance level selected by planners and managers in determining hazard lines is likely to be relatively low, i.e. of the order of 5% to 10%, in this case the Bruun rule estimates using the outer closure depth definition (d_i) appears to provide a reasonable upper bound predictions while the estimate using the inner closure definition (d_l) provides a mid-range result.
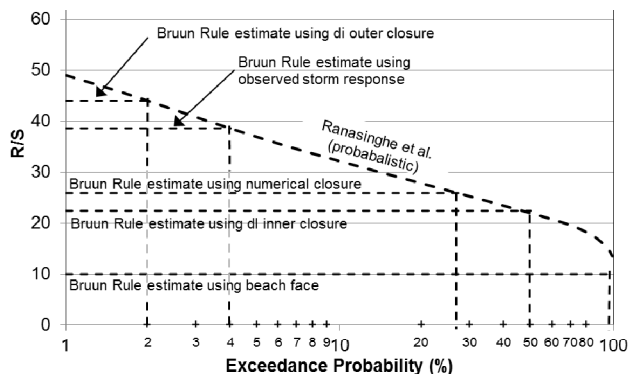

Figure 3 Probabilistic estimate of relative coastal recession at Narrabeen Beach (from [21]) with Bruun Rule estimates using a variety of closure estimators.

3.   Perched Beaches
Perched beaches occur where the underlying material differs from the beach material and there is minimal sediment exchange between the systems. This may occur on a rock shore platform, behind a reef-fronted lagoon and within an estuary where fine materials form flat, generally intertidal, slopes. In these locations the direct application of the Bruun Rule using a traditional closure depth is questionable given the differing sediment properties and processes affecting the steeper upper beach and flatter offshore profile. For a very flat and wide nearshore profile with low backshore elevation typical of many perched beach environments, the Bruun Rule, with a wave height-based definition of closure would predict very large recession values. The model eShorance [24] was developed as an alternative model to assess landward recession in estuarine environments.

This model is based on the assumption that sediment lost from the upper beach in an estuarine environment does not settle on the basin nearshore or bathymetric profile, but rather is lost from the system. While the model proposes separate components to account for shoreline movement from inundation and from recession, once rearranged the profile is translated by a Bruun principle using the foreshore or beach face slope. This is likely a reasonable assumption given the minimal sediment exchange further offshore.

Similarly, coral reef-top perched beaches violate a number of Bruun rule assumptions including the non-erodable reef flat surfaces truncating the active beach profile and the low backshore allowing overwash processes to occur [6]. Cowell and Kench suggest that the Bruun principle (applied within the *Shoreface Translation Model* framework) is likely suitable when the intersection of the perched beach and non-erodable reef surface is used to define closure depth.

4.   Gravel Beaches
Gravel beach processes differ from sandy beaches in that runup from storm waves push material higher on the profile, building the crest level, rather than moving sediment offshore and, if runup overtops the berm, material can be overwashed causing a loss of material from the front face and building of barrier back-berm. As sea level rises, increased material is overwashed resulting in recession. This process can essentially be modelled using the generalised Bruun rule as the profile transgresses up the combined shoreface and backface slope ($W_* + L_*$). [20] note, however, that the berm width may not remain constant, narrowing with slower rates of sea-level rise (as crest building dominates) and widening with increased rates as overwash dominates. A quantitative method for predicting these dynamic changes in morphology is not presently available.

5.   Conclusions
Sea levels have been rising through to the 20th century and are projected to accelerate during the 21st century and beyond. A range of models have been proposed over the last 50 years to predict shoreline movement in response to sea level changes. While some methods are used more widely than others, not all are necessarily applicable to the variety of coastal types across Australasia and none have been proved categorically correct and adopted universally. For unconsolidated beaches, geometric equilibrium models such as the Bruun model (and variations) have been widely used and, while subject to limitations, appear to provide reasonable results if used sensibly, i.e. sediment flux known and allowed for, closure depth acknowledged as an inexact parameter. The Shoreface Translation Model provides an improved mechanism for assessing equilibrium response within a numerical

framework but, at the time of writing, was unavailable for use on modern computing systems. Probabilistic analysis of input terms (profile geometry, closure depth, relative SLR, etc) provides a method for managing uncertainty - although for now many of the parameter bounds are still selected by heuristic reasoning. Process-based modelling offers a potentially powerful alternative but is, at present, constrained computationally and the necessary parameterisations remain highly dependent on the availability of long-term, quality data and/or practitioner judgement. Some suggested methods and model parameters for differing levels of analysis are provided in Table 2. Recession due to SLR is an important component for land use planning and defining coastal setbacks, but needs to be considered in conjunction with other setback components, some of which are unrelated to climate change [14].

Table 2 Suggested methods for assessing shoreline response to sea level change

Shoreline Type	Preliminary Assessment - Large area - Minimal or low quality data	Detailed Assessment - Site specific - Quality data
Unconsolidated Beach	Generalised Bruun rule[1] using inner and outer Hallermeier limit envelope	1. Probabilistic assessment using either an equilibrium model[2], or 2. With long-term, high quality data, process-based modelling could be considered
Perched Beach	Generalised Bruun rule[1] using beach face slope	
Gravel Beach	Generalised Bruun rule[1] using combined shoreface and backface slopes	

[1] Sediment flux must be assessed and incorporated in any prediction
[2]The Shoreface Translation Model is preferable but unavailable for use on modern computing systems at time of writing

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