Shore-face profile response time-scale and its significance for shoreline evolution

D Patterson
BMT WBM Pty Ltd / University of Queensland, Brisbane

Introduction

Response time-scale concept

Beaches are part of the active system of unconsolidated sand that extends across the shoreline from the dunes to lower parts of the shore-face profile at water depths in excess of 20-25m (refer Figure 1). The beach system is continuously reworked by waves and currents, evolving its position, alignment and profile shape between controlling headlands. Shoreline change is commonly considered in terms of:

a) Cyclic behavior associated with storm erosion and gradual subsequent recovery, leading to balance (dynamic equilibrium) over the long term, provided sand supply and wave climate are statistically stationary; and
b) Longer term progressive recession or accretion associated with natural, anthropogenic or climate change factors including:
    - Loss or gain of sand volume, either direct (eg. nourishment or extraction) or indirect (eg. gradient in the alongshore sand transport) ; and/or
    - Sea level changes.

There is a depth dependence on the capacity of the waves to transport seabed sediment sufficiently to modify the profile shape, despite wave-induced mobility to considerable depth. Within and near the surfzone, high cross-shore sand transport rates and gradients may result in rapid adjustment of the profile shape and shoreline position. In deeper water outside the surfzone, both the rates and gradients in sand transport are reduced such that bed level changes are less significant and occur more gradually.

Continuous interaction between the shallow and deeper parts of the active shore-face profile occurs such that changes at one area affect other areas progressively at rates and extents commensurate with their respective response time-scales. For example:

- extraction of sand from lower (deeper) areas of the shore-face profile will affect the shoreline relatively slightly and over a long response time because its effects are distributed gradually across a wide profile extent from an area of relatively low net sediment transport; whereas
- extraction directly from the surfzone has direct and immediate effect on the shoreline, and will propagate over an increasing time-scale and with decreasing effect to the deeper shore-face areas.

In geological context, natural beaches have evolved to a condition approaching dynamic equilibrium with the prevailing wave climate at essentially constant sea level over the past 6,000 years, following the post-glacial sea level rise of more than 100m over the previous 12,000 years. There is a limit to the active contemporary beach shore-face depth beyond which it transitions to the relict morphology of the continental shelf. Future sea level rise will again shift the shoreline position landward and change how the beach profile responds across its active extent, in a manner that varies with depth.

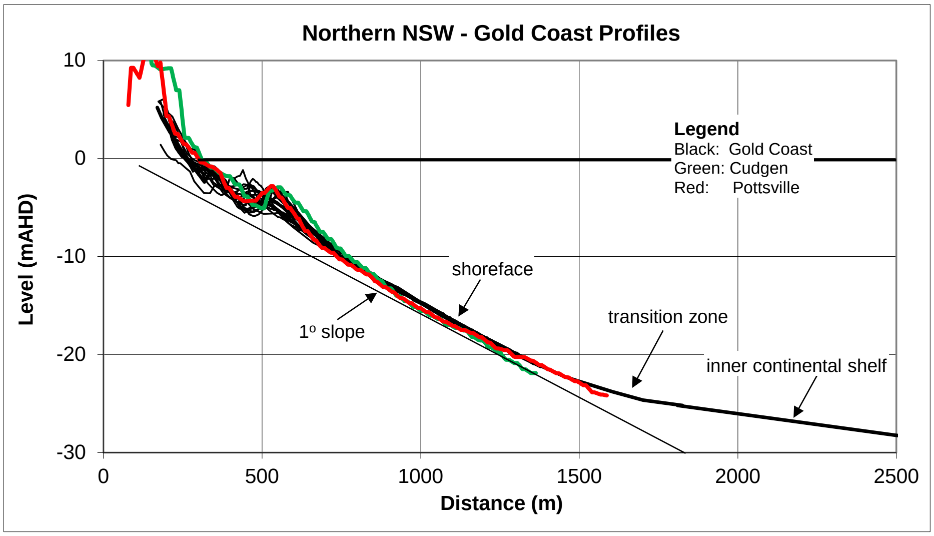


Figure 1: Typical Northern NSW & SE Queensland profiles: shore-face and transition to inner shelf

Key factors affecting shoreline change are thus the extent and time-scale of the depth-dependent beach system profile responses to perturbations that may result from losses or gains of sand volume or projected future sea level rise. This paper describes the range of considerations and implications relating to those factors.

Morphologic profile response zones

It has been identified (Roy & Stephens 1980a, 1980b; Chapman *et al* 1982; Roy 2001;) that many NSW coastal shore-face profiles exhibit a characteristic shape to a depth of about 15-20m, with an average slope of about 1^o, that has evolved in dynamic equilibrium between the wave climate and the coastal sediment. However, below that depth range is a wide diversity of profile shapes. Commonly a transition in the profile shape occurs at about 20-25m water depth from the relatively active and well defined shore-face to the inner continental shelf, where the profile has lower average gradient and its contemporary evolution is slow or imperceptible.

This transition is sometimes interpreted as the outer part of the equilibrium profile. However, its shape may not relate in any equilibrium sense to the prevailing wave climate but rather is strongly influenced by its evolutionary history. This leads conceptually to consideration of different morphological response zones, as illustrated in Figure 2, being:

i. The highly active upper zone of substantial profile change with response to varying wave conditions occurring over a short time-scale of weeks to several years;
ii. An active mid to lower shore-face zone where little change in the profile is evident even in storm events and any progressive evolution towards an equilibrium condition occurs at a long time-scale of decades to centuries; and
iii. A lower shore-face transition to the inner shelf where the profile response is slow to imperceptible and its geological history has a significant influence on the present seabed morphology.

For example, Figure 1 shows typical northern NSW and SE Queensland profiles that exhibit both an equilibrium shore-face shape and a transition at around 20-25m depth to the inner continental shelf. Figure 2 shows the deduced ‘equilibrium’ shore-face profile fitted empirically to surveyed data for northern Gold Coast and extrapolated past the transition depth, together with other measured lobe profiles that exhibit marked divergence from the equilibrium shape due to their formation by other site-specific processes, being:

- The Byron Lobe, which is thought to be currently actively supplied with littoral system sand by the East Australian Current; and
- The northern Gold Coast Spit lobe, which had formed previously as a river ebb delta and is now a residual feature evolving towards the equilibrium shape.

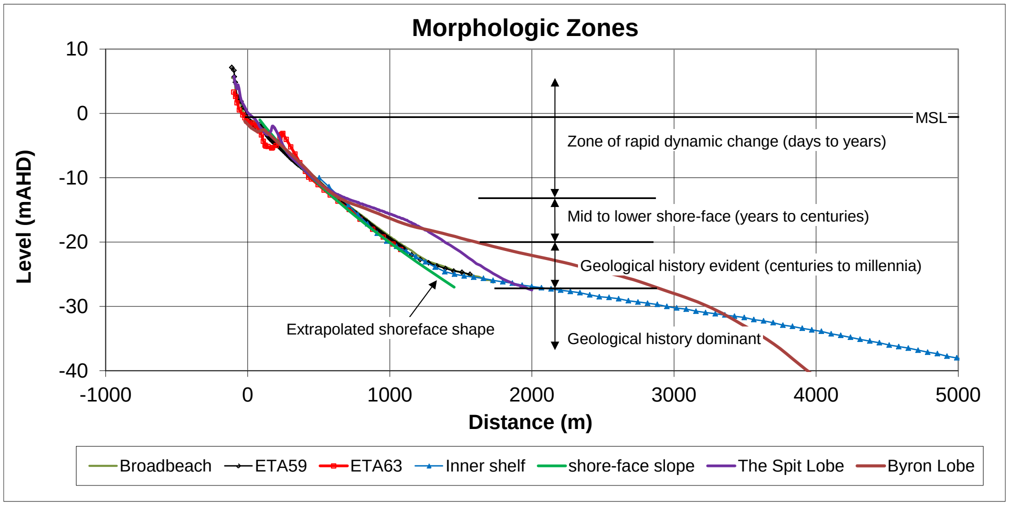


Figure 2: Profile morphologic zones

Variation with depth of the nature and time-scale of profile evolution thus affects how the shore-face profile evolves in response to changing conditions within the littoral zone and to sea level rise. This is consistent with the profile response zonation of Hallermeier (1977; 1981). He describes:

- the 'littoral' depth (h_L), defined generally as the depth to which vertical changes in the profile in major storm events are clearly evident in surveys and above which beach recovery after erosion occurs over a period of months to years;
- a depth (h_i) of potentially significant net cross-shore sand transport, corresponding to the depth from which some net movement of sand towards the coast is feasible, without there being significant vertical profile change; and
- A limiting depth of seabed sediment mobility, typically 80-100m along the NSW coast.

Hallermeier (1977) suggests a depth value for the seaward limit of the littoral zone (h_L), of $2.28H_s(1–4.78H_s/L_o)$, where L_o is the deep water wave length and H_s is the significant wave height exceeded for 12 hours per year (0.14% of the time), giving an approximate depth of 9-10m along northern NSW and SE Queensland. For more intense storm wave conditions over a longer decadal to century statistical time-frame, this depth corresponds to about 13-14m. These depths are consistent with the measured depths of profile change at the Gold Coast where considerable monitoring data exists. Hallermeier (1981) indicates the depth of h_i is given as $H_{sm}T_{sm}(g/5000d_{50})^{0.5}$, where subscript m denotes the long term median value and T_s is the significant wave period. The recorded northern Gold Coast nearshore wave data indicates H_{sm}=1.1m and T_{sm}=8.4s, yielding h_i = ~25m. This is reasonably close to the identified northern Gold Coast transition from the steeper shore-face to the flatter inner continental shelf in the absence of other determining factors (Delft Hydraulics Laboratory 1970; Figure 1). For more exposed open coast situations, H_{sm} is about 1.4m, yielding h_i = ~30-35m.

Correspondingly, Patterson (2102; 2013) developed a depth-dependent relationship for potential cross-shore sand transport to determine relative shore-face profile response time-scales (Figure 3). These correlate with the morphological response zones in Figure 2, notably the transition from lower shore-face at about 20m depth (centuries) to the inner continental shelf depths greater than 25m (millennia). They correlate reasonably with the Hallermeier h_i values, indicating that they may be regarded as approximately equivalent to the depth at which the evolved profile transitions from the shore-face, dominated by contemporary wave and sea level forcing, to the inner shelf dominated by its geological history.

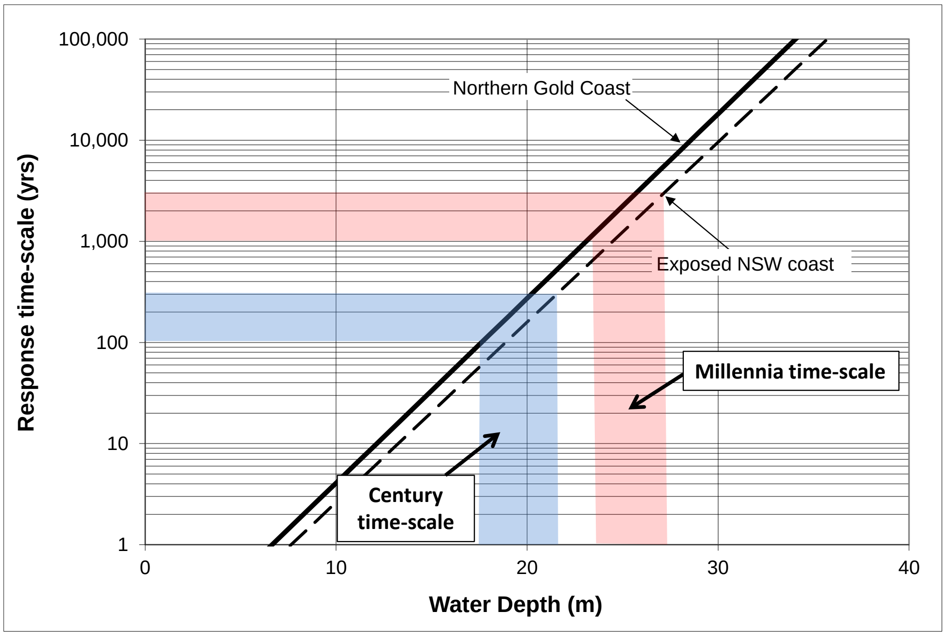


Figure 3: Profile response time-scale (Patterson 2013)

Equilibrium profiles

The formation of equilibrium profiles has been proposed and tested by many researchers and is the basis of the model of shoreline change in response to sea level rise proposed by Bruun (1962). In principle, a profile in equilibrium will retain its shape over time, requiring that there is no gradient in the long term wave-induced net cross-shore transport at any location (Figure 4). In the case of zero net input or loss (q_{s1}) at the deep water end of the profile, or no net gain or loss of sand (q_{s2}) at the beach by (for example) a longshore transport gradient or wind erosion, it is necessary that there is zero net cross-shore transport at all parts of the profile averaged over the long term.

There are two fundamentally different concepts of the equilibrium profile, namely:

Equilibrium Concept 1: The profile that would develop under any particular steady wave and water level condition; or

Equilibrium Concept 2: The profile shape towards which the bed evolves in response to the prevailing wave climate, as a varying but, on average, dynamic equilibrium state.

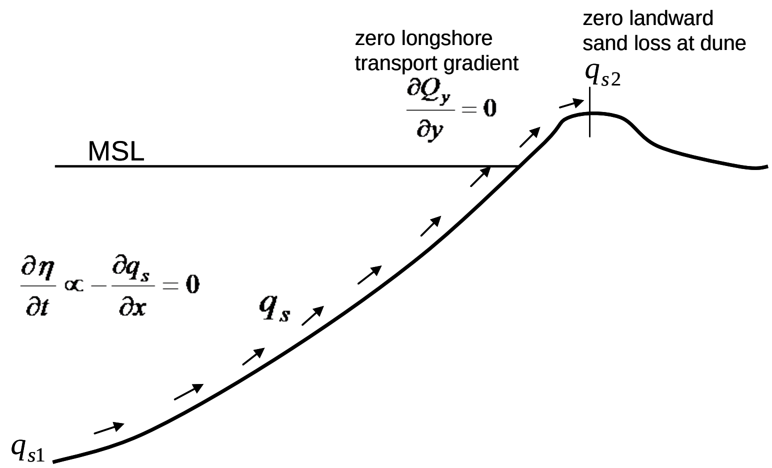


Figure 4: Equilibrium profile concept

Wave conditions are continually changing and the first of these conceptual equilibrium profile forms will never occur in nature. While Concept 1 profiles have been the subject of considerable investigation in laboratory wave flume testing, mainly involving surfzone processes related to beach/dune erosion, prolonged flume tests of profile evolution outside the surfzone are limited and subject to uncertain scale effects.

Attempts have been made to define the equilibrium profile shape of prototype beaches. Bruun (1954), Dean (1977) and Dean and Dalrymple (2002) found that the average of profiles for a range of locations fits the relationship $h = Ax^{2/3}$, where h is water depth, x is distance offshore and A is a scaling constant ($m^{1/3}$). The value of the scaling constant A has been related to grain size through the fall velocity of the bed sediment (Moore 1982; Dean 1987; Dean *et al* 2002). Huxley (2009) and Patterson (2013) found the surfzone profile of Dean and Dalrymple (2002) compared well with the surveyed Gold Coast profiles, with A=0.1 to 0.125 (Figure 5 green).

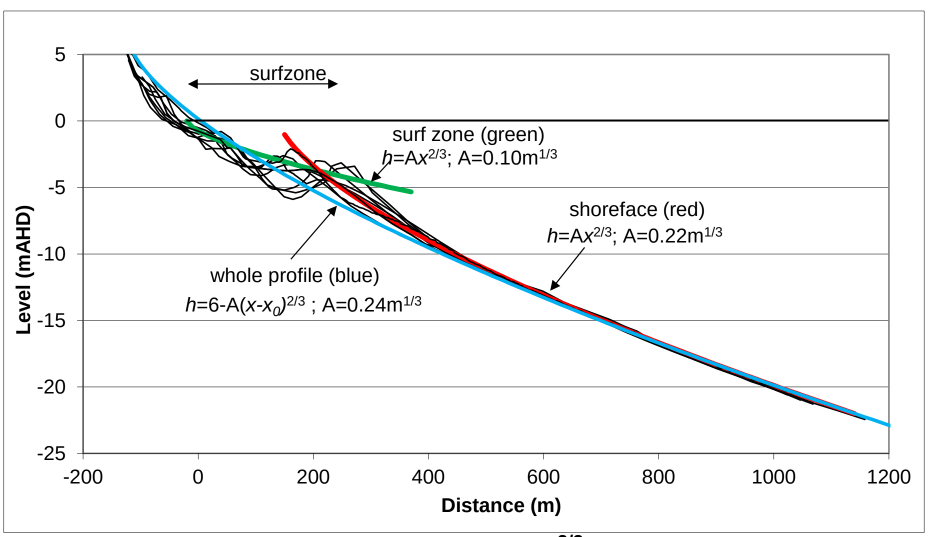


Figure 5: Best fit equilibrium profiles of A$x^{2/3}$ form: Northern Gold Coast

The wave and sand transport processes are different in character within and seaward of the surfzone and it is not expected that the entire profile shape could be described by one simple shape relationship. There is an interface between the surfzone and the deeper profile seaward of the surfzone marked by a step or shore-parallel bar, the seaward face of which is a transition to the lower shore-face. An approximate curve-fit for the lower shore-face yields a value of A=0.22 that fits well at depths of 5m to 22m, notwithstanding the erosion profile bar (Figure 5 red). However, this does not match the upper bar area and surfzone parts of the profile. Despite that, a fit to the whole profile can be achieved using the form h = B-A(x-x_0)$^{2/3}$ as shown (blue) in which A=0.24 and B=6m. In all cases, the extrapolated best fit equilibrium shapes extend below the surveyed profiles in the transition to the inner shelf.

A profile that is in dynamic (Concept 2) equilibrium may change from time to time with changing wave conditions, but maintains a steady mean shape within a range of dynamic variability. Alternatively, the bed levels (z) of a profile that is not in equilibrium for some reason, such as net gain or loss of sand in one part of the profile or changing sea level, will evolve by means of cross-shore sand transport (q_x) towards its equilibrium shape relative to the prevailing sea level, as discussed below (refer Equation 2).

A condition of dynamic equilibrium of natural beaches is that, over the long term, sand transported offshore during storm erosion events is returned to the beach/dune by the smaller swell waves. This implies that, for dynamic equilibrium, the depth to which sand is transported during storms must not exceed that to which shoreward transport under swell conditions can balance the higher short term seaward transport by storms. Otherwise, there would be a net gain or loss of sediment somewhere across the profile and its shape would change over time towards equilibrium.

Implications for one-line shoreline evolution models

One-line models such as GENESIS (Hanson 1987) describe the variation over time of shoreline position resulting from changes in sand quantity at each location caused by gradients in the alongshore sand transport and/or losses or gains of sand due to other factors such as the effects of coastal structures, beach nourishment or bypassing within the littoral zone. The fundamental basis of the one-line model is that erosion or accretion of the beach occurs as simple horizontal translation of the active beach and nearshore profile, which moves parallel to itself without changing shape above a designated depth, referred to as the 'depth of closure' (D_C), to the dune or berm level (D_B) as illustrated in Figure 6 and described mathematically in equation (1). This determines that the shoreline movement is given as the volume change divided by the active profile height and is linearly dependent on the adopted depth of closure.

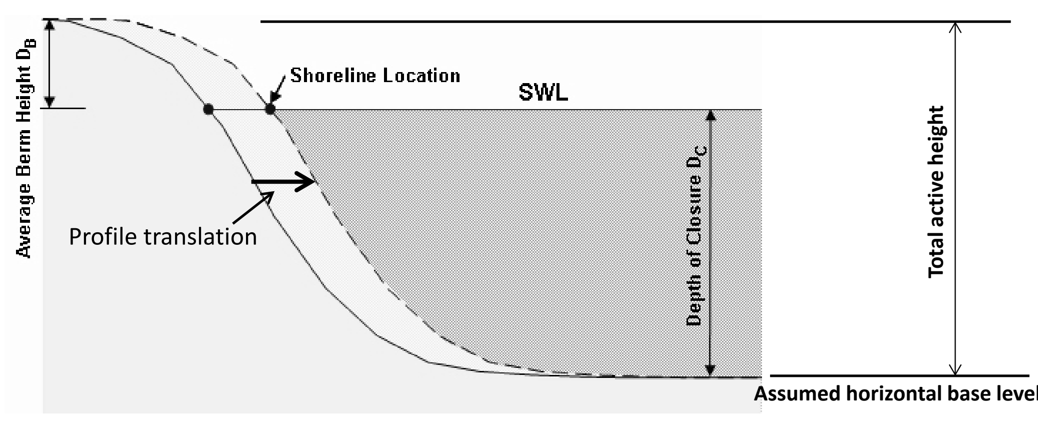
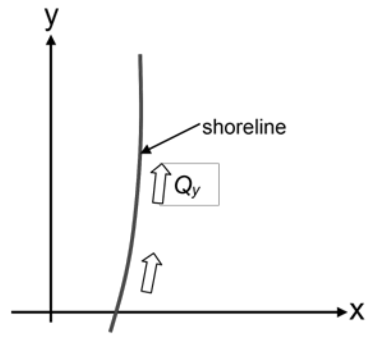


Figure 6: One-line shoreline change above depth of closure (GENESIS model; Jackson 2007)

$$\frac{\partial x_s}{\partial t} = -\frac{1}{(D_B + D_C)}\left[\frac{\partial Q_y}{\partial y} - q_y\right] \qquad (1)$$



Where, for the coordinate system illustrated:
x_s = shoreline position
y = longshore distance
Q_y = bulk volume longshore transport rate [m^3/s]
q_y = bulk volume sand source or sink per unit shoreline length [m^3/m/s]

Thus, the 1-line model is a form of profile translation model in which the translating profile maintains its geometric equilibrium shape at all times. The shape of the profile has significance only with respect to defining the width of the surfzone and the proportion of the alongshore sand transport intercepted by coastal structures such as groynes and seawalls located within the breaker zone.

Significance of closure depth

Commonly for this type of model, the closure depth is adopted as the depth to which changes in sand volume occur due to gradients in the alongshore littoral transport. This may be related reasonably to the Hallermeier littoral depth h_L. However, this ignores the secondary interaction of upper profile movements with lower parts of the shore-face, to which littoral zone changes propagate over time, as illustrated in Figure 7. In that example, recession due to littoral zone volume loss is distributed progressively down the profile, inducing profile slopes that are flatter than equilibrium and an associated shoreward sand transport that disperses the recession over a progressively increasing depth and reduces its extent within the littoral zone.

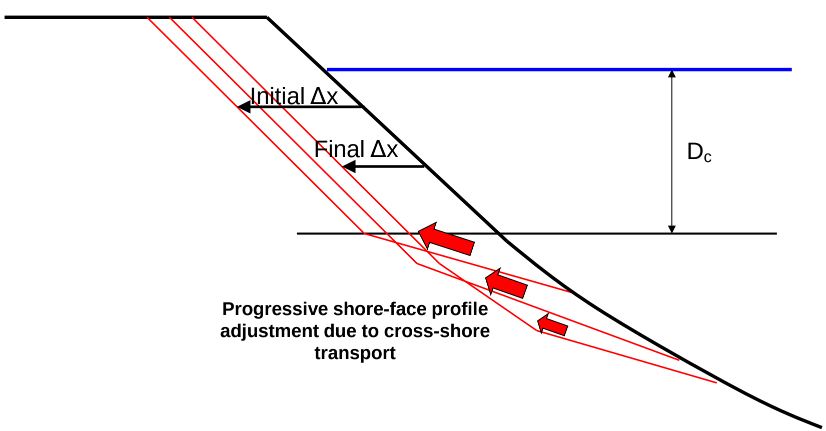


Figure 7: Conceptual profile adjustment below Dc following erosion

Adopting a value of D_C deeper than the littoral zone will lead to short term shoreline changes that are too small. Conversely, selection of a shallow depth of closure that relates directly to the limit of the alongshore transport will underestimate the height of the profile response over the longer term and predict excessive long term shoreline change. Because of this limitation, there is a need for a simulation process in which the lower shore-face profile may adjust towards equilibrium at time-scales that are appropriate at the water depths there, rather than an assumption of geometric equilibrium there at all times. This requires provision for cross-shore sand transport, which determines the profile shape in those parts of the active profile that are out of equilibrium, as illustrated in Figure 8.

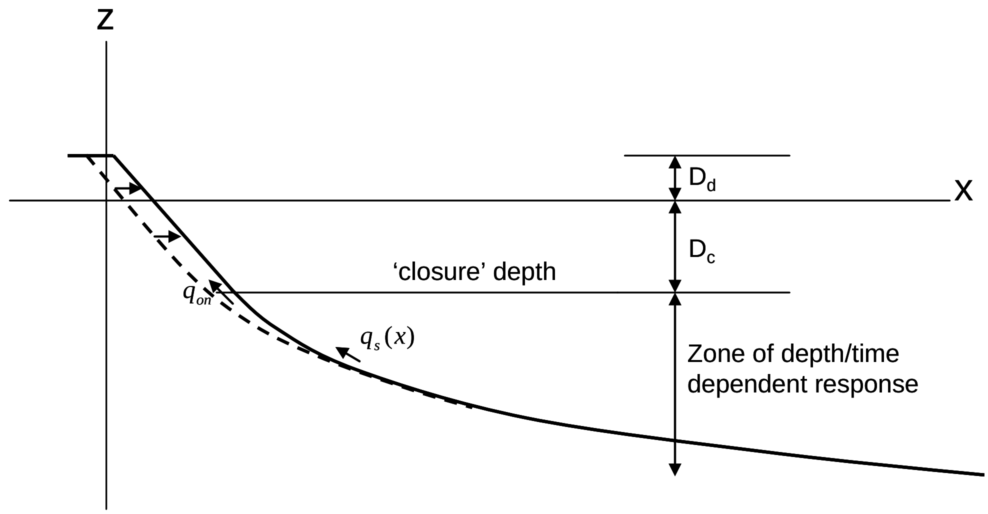


Figure 8: Model framework for cross-shore profile evolution

Below D_c as defined in the 1-line models, gradients in $q_s(x)$ lead to time-dependent evolution of the profile shape due to vertical changes in bed level (z_b), given by equation (2), assuming that there are no alongshore gradients in sand transport below D_c.

$$\frac{\partial z_b(x)}{\partial t} = -\frac{\partial q_s(x)}{\partial x} \qquad (2)$$

Equation (2) provides the direct link between profile bed level response and gradients in the net cross-shore sand transport. Because net cross-shore transport and, particularly, gradients in the net transport, decrease with depth, so too does the bed level response of the profile.

Significance of dune profile evolution

Where sea level rise is involved, an assumption must be adopted also about the dune shape. The natural long term behaviour is that stable beaches not experiencing aeolian sand losses, will have a dune height and width built by wind-borne sand transport from the beach and its trapping by dune vegetation, which maintains its stable shape over time despite being eroded and subsequently rebuilt from time to time. In the long term, that shape is maintained relative to the shoreline as it recedes, otherwise it will overtop and sand will be moved landward by direct wave action.

Model schematisation may thus adopt a geometric dune shape, with a specified crest height and width, which is maintained relative to the shoreline position as it moves both vertically with sea level change and horizontally, as illustrated in Figure 9. This shows that the dune will effectively roll back over itself onto the hind-dune land, requiring accommodation of a beach system sand volume that affects the extent of shoreline recession.

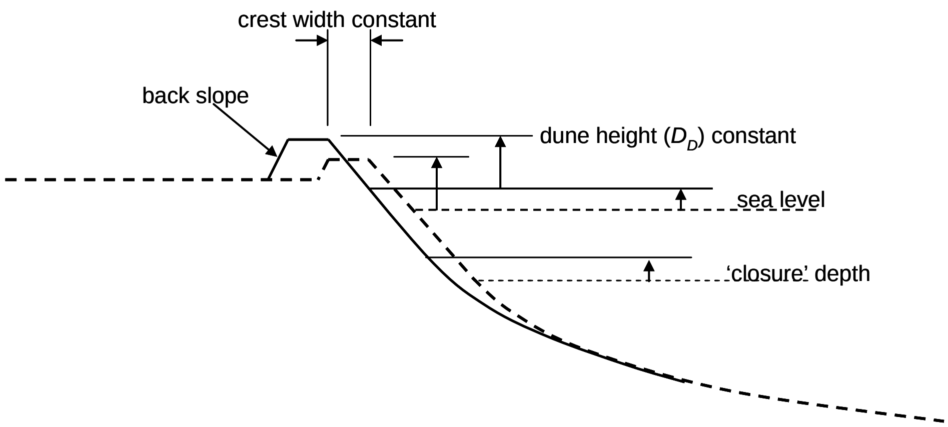


Figure 9: Schematisation of the active dune profile with sea level rise

However, this too is dependent on response time-scale and it may be argued that full development of the dune profile will lag behind the effects of projected sea level rise over a time-frame of one or two centuries.

Implications of depth-dependent transport potential for natural profile evolution

Patterson (2012; 2013) derived an exponential depth-dependent relationship for potential shoreward sand transport across the shelf and shore-face applicable to northern NSW and SE Queensland. This was used in conjunction with a disequilibrium bed slope function to develop a shoreline evolution modelling capability that explicitly caters for the variation in profile response with depth. The model adopts a fixed geometric shape for the dune, with effectively assuming no time lag in dune building with sea level rise.

When applied at a regional scale to the coastline of northern NSW and SE Qld over a geological time-frame, the model can simulate the time-dependent shore-face and inner shelf profile evolution in response to major sea level change. Figure 10 shows an example of transgressive coastline development covering the past 10,000 years for a location between Byron Bay and Brunswick Heads. This illustrates the consistency of shore-face shape above 15m depth where the response time is relatively short and the progressive slow response after 5,000-6,000 years BP below that depth where the lower shore-face transitions to the inner shelf. The final evolved situation is one approaching dynamic balance with slight shoreline recession due to a littoral zone gradient in the alongshore sand transport offset partially by a residual shoreward sand supply from the inner shelf.

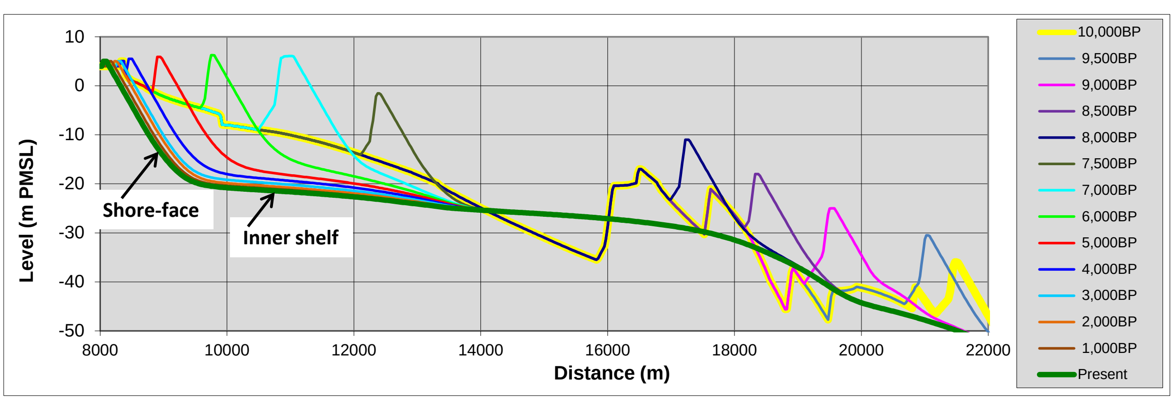


Figure 10: Modelled profile evolution over past 10,000 years (Patterson 2013)

At The Spit, northern Gold Coast, northward migration of the Nerang River entrance left a residual ebb delta lobe in the form of a convex up bulge in the shore-face profile (Figure 2). Surveys from 1966 to 2010 show that this lobe is evolving towards the equilibrium shape and were used to quantify the long term average depth and slope dependent cross-shore sand transport relationship for the region against which empirical analytical methods for predicting wave-dependent transport rates were validated.

Application of the model to simulate the measured historical evolution of the lobe provides validation of the sand transport calculation basis with respect to the adopted equilibrium profile shape (Figure 11 top). Simulation of the future evolution of the lobe, in the absence of changes in sea level or other factors, over the next 5,000 years (Figure 11 bottom) illustrates the decreasing rate of profile change towards the equilibrium condition with depth, predicting the shape of the transition from the equilibrium shape to the inner continental shelf. In this case, the net shoreward transport does not reduce to zero but trends towards the inner shelf rate of about 0.6m^3/m/year.

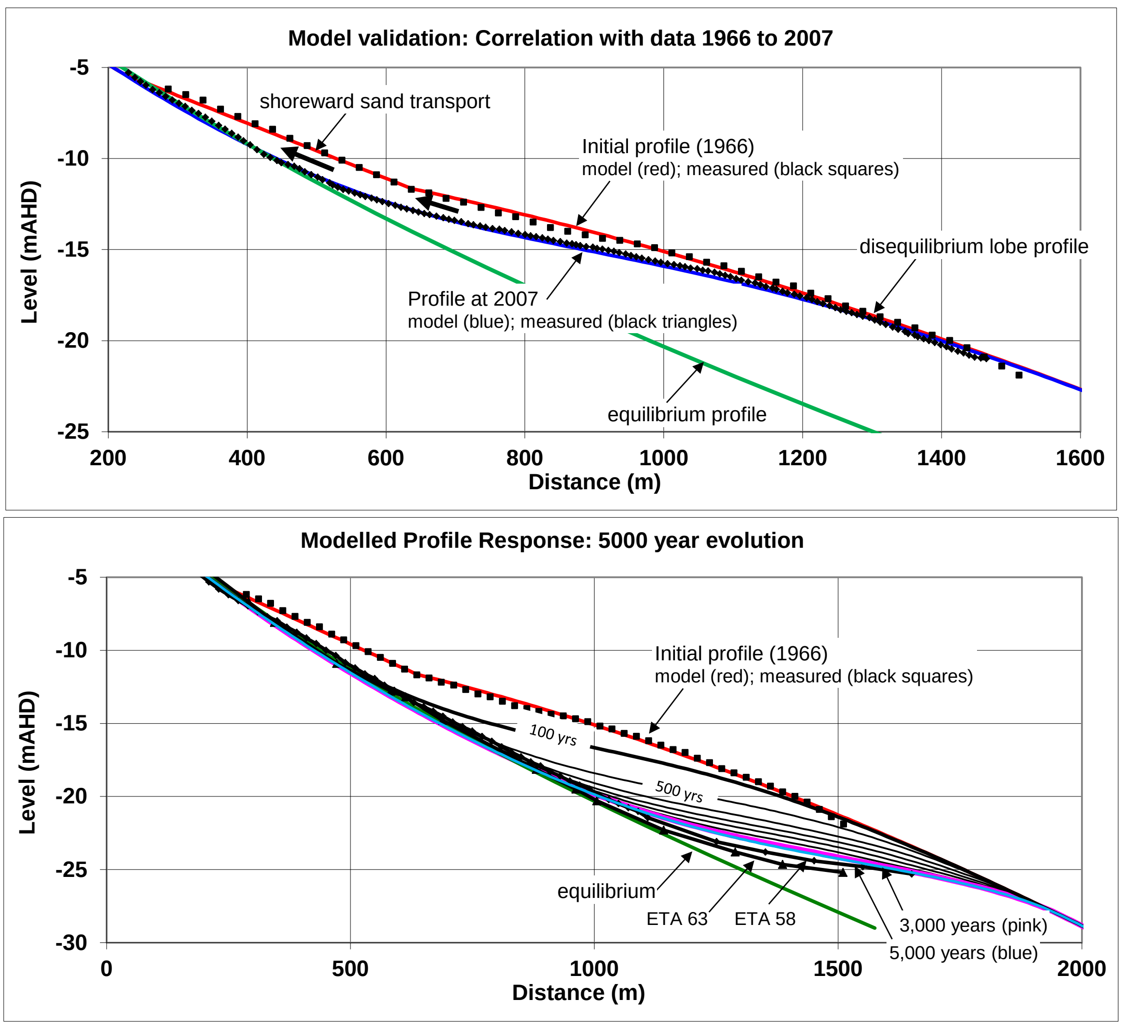


Figure 11: Modelled evolution of The Spit lobe: historical (top) and projected for 5,000 years (bottom) (Patterson 2013)

Profiles subject to different prevailing wave climates and/or with different sand properties will respond differently. Nevertheless, as the modelling illustrates, beach systems generally exhibit a depth dependence on the potential for net cross-shore transport and bed level change such that the rate of profile evolution towards equilibrium reduces with increasing water depth. The shallower parts respond relatively quickly and the equilibrium shape may be determined from repetitive surveys. Deeper parts respond slowly, at a time-scale longer than survey monitoring programs and, in the transition area to the inner continental shelf, may remain out of equilibrium even after centuries or millennia of evolution. In these deeper transition areas, the measured profile shape is not the true equilibrium shape but, instead, reflects predominantly the geological history and wave climate rather than contemporary profile evolution.

Implications for shoreline response to coastal structures

A groyne impact assessment case is used to illustrate the implications of the depth and time dependent shore-face profile response with respect to the downdrift shoreline recession. A 400m long groyne located on a straight beach with about 500,000m^3/year net transport was simulated (Figure 12) and the profile about 500km downdrift used as an indicator of the shoreline recession response. Three cases were modeled, namely:

a) with zero cross-shore transport below D_c=10m, equivalent to a GENESIS one-line model analysis;
b) equivalent to a) but with the Patterson model shore-face response parameters; and
c) with a D_c value of 15m.

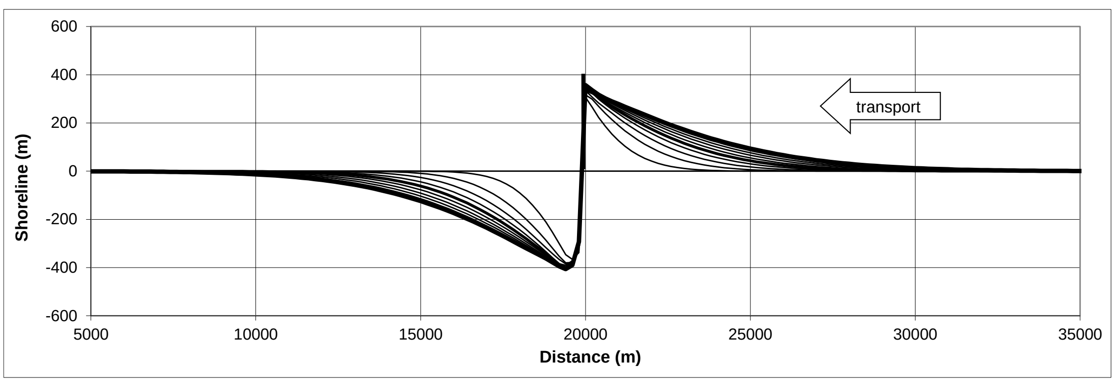


Figure 12: Modelled shoreline evolution with 400m long groyne

The modeled shoreline erosion responses are presented and compared in Figure 13 and Figure 14. It can be seen that:

- Recession of the shoreline with translation of the profile above D_c set at a depth of 10m with no interaction with the lower shore-face is up to about 450m;
- Increasing the depth of D_c to 15m decreases the initial recession rate and the final recession distance to about 380m;
- Introducing cross-shore sand transport interaction with the lower shore-face moderates the shoreline recession rate and the extent of shoreline recession (Figure 13 bottom and Figure 14 respectively) by progressively extending the volume loss to deeper parts of the profile (Figure 13 top). Over time it approaches the shoreline recession associated with D_c = 15m, but with different and more realistic evolution history (Figure 14).

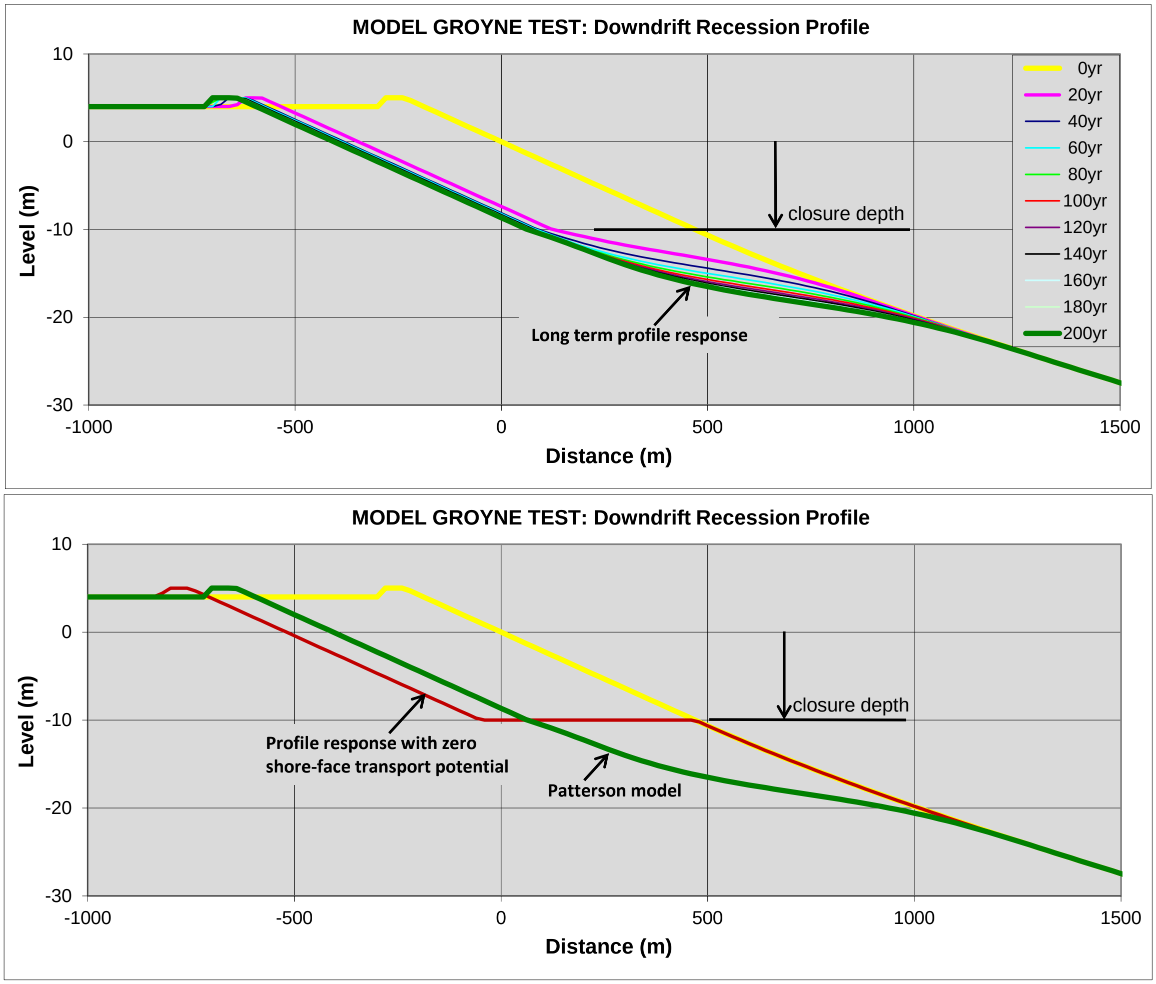


Figure 13: Modelled groyne impacts: downdrift erosion profile with progressive shore-face response (top); comparison at 200 years with zero shore-face cross-shore transport potential below D_c (bottom)

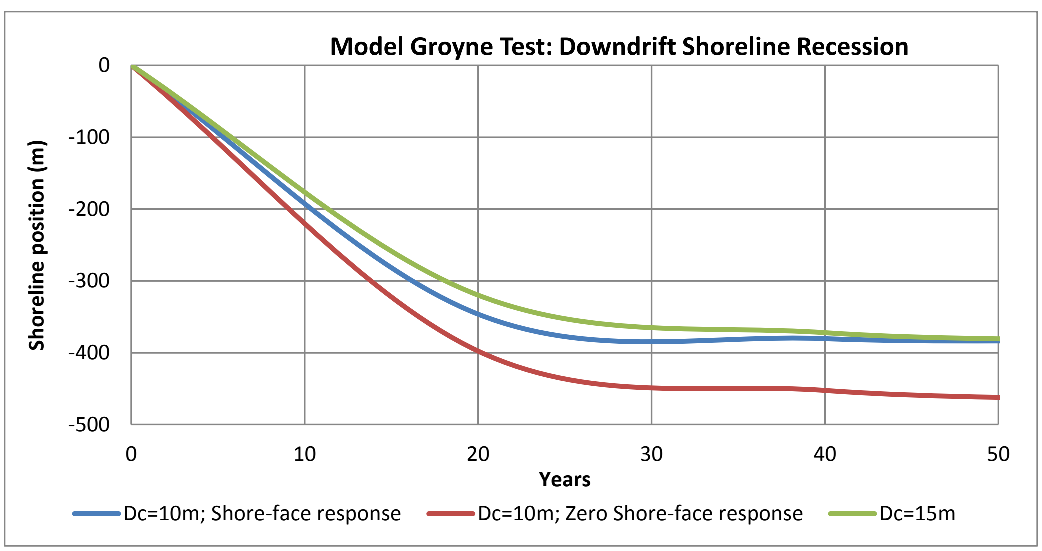


Figure 14: Comparison of predicted downdrift recession with different profile response options

Implications for shoreline recession due to sea level rise

The depth dependent response time-scale has significance for the shore-face translation concept as used for prediction of shoreline recession due to sea level rise using the Bruun Rule in two important and related ways:

1. It requires difficult and sometimes controversial decisions about the depth of 'closure' to be adopted; and
2. It requires proper definition of the 'equilibrium' profile shape to the adopted depth of closure, as potentially distinct from the lower shore-face transition away from equilibrium to the inner shelf slope.

Figure 15 illustrates the effect on the Bruun Rule slope factor of adopting different depths of closure with respect to the shore-face to inner shelf transition. If a response time in the range 100 to 500 years is reasonable for application to assessment of potential recession over the next 100 to 200 years, Figure 15 suggests a depth of closure of about 18-22m is appropriate, corresponding to a Bruun Rule slope factor of about 45:1.

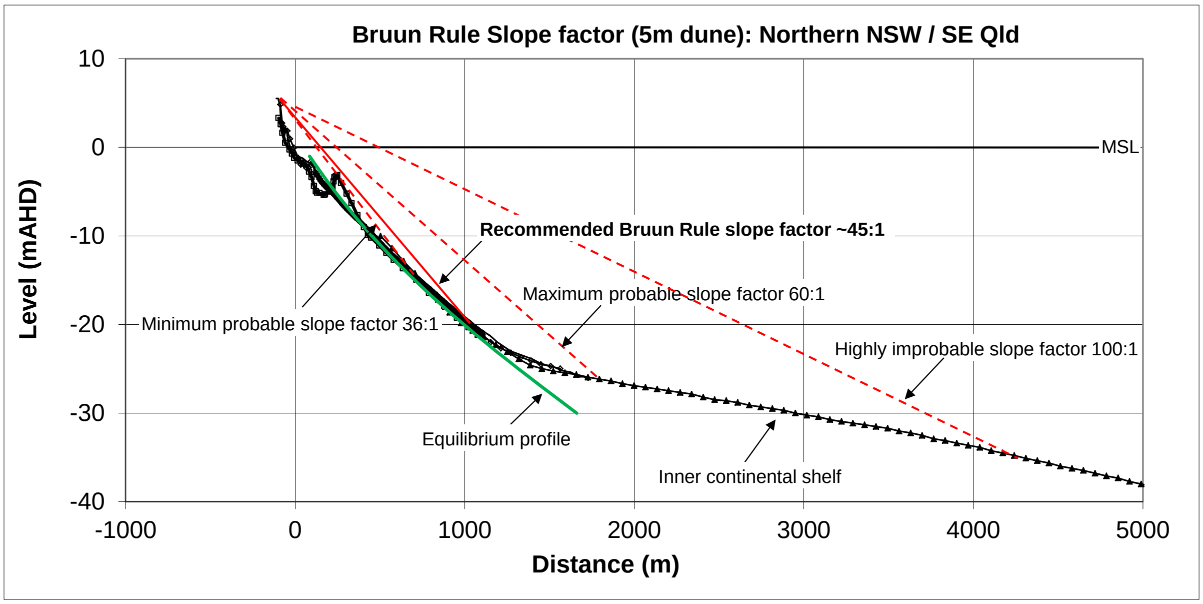


Figure 15: Bruun Rule slope factor variation with adopted closure depth

Significantly, a depth greater than 25m and up to the Hallermeier h_i depth of about 35m for the open coast would yield factors in the range 60:1 to 100:1 if the measured profile is taken to have the equilibrium shape that would be maintained as sea level rises. However, that would ignore both the depth limitation on profile response and the true shape of the equilibrium profile. Nevertheless, adoption of a depth of 35m would yield a slope factor of about 50:1 if applied to the extrapolated equilibrium profile rather than the measured shape, not too different from that derived taking account of the response limitation.

The depth influence on profile response has been recognized previously by various researchers. Nicholls *et al* (1996; 1998) and Cowell *et al* (2000) note that profile 'closure' occurs at greater depth as the time-scale increases. Wright (1995) suggests that there should be thinning of profile change near the closure depth as it adjusts to sea level rise. Cowell *et al* (2006) deal with this probabilistically in terms of the profile toe accumulation response in the range ‘full accommodation’ to ‘full dilation’ to account for the uncertainty involved.

The limited available data suggests that the Hallermeier h_i depth over-estimates the appropriate closure depth. A closer approximation for this data would be given by $H_{sm}T_{sm}(g/8000d_{50})^{0.5}$, of the same form but different scaling factor giving about 80% of the Hallermeier h_i.value.

The Patterson model may be used to assess the likely recession due to sea level rise, taking account of both cross-shore and associated alongshore response processes. Its application to simple cross-shore profile response is illustrated in Figure 16 for a 2m sea level rise over 200 years. Examples for fixed dune crest level and for vertical dune growth with rollover to the hind-dune area are shown. They indicate equivalent Bruun Rule slope factors of about 43 and 47 respectively, correlating well with the recommended factor of 45:1 shown in Figure 15. However, care must be taken to account for the effects of coastal structures where significant net alongshore sand transport occurs (Patterson 2009; 2010; 2013).

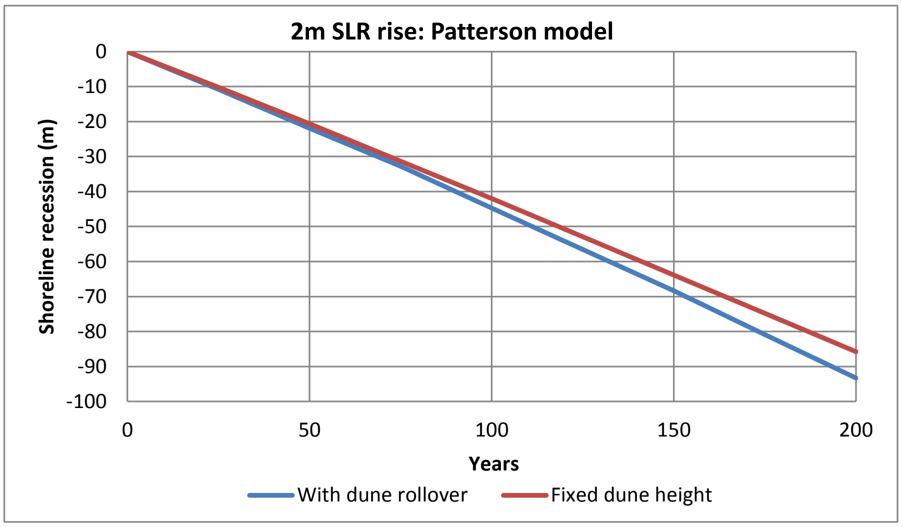


Figure 16: Patterson model shoreline recession due to 2m sea level rise with and without dune rollover

The depth and time dependency of the profile response and the departure of the measured profile from the equilibrium shape are directly linked in the natural Holocene period evolution of the contemporary coastline and shore-face, particularly during the past 5,000 years of relatively stable sea level. As such, the depth of departure of the profile from the equilibrium shape is a good natural indicator of the depth of closure to be adopted as it corresponds to the depth to which the equilibrium shore-face profile has the capacity to evolve for the sediment and prevailing wave climate regime involved.

Conclusions and Recommendations

A quantified depth and slope dependent relationship for cross-shore shore-face sand transport has led to development of a model capability that provides for progressive evolution of the active nearshore profile. This explicitly caters for variation in profile response time-scale with depth, with implications for behaviour of the shoreline in response to perturbations across the active profile, commensurate with the water depths at which they occur.

Implications for application of equilibrium shore-face translation models have been described, particularly with respect to closure depth for sea level rise assessments using the Bruun Rule. The depth-time dependency of profile response and the departure of the measured profile from the equilibrium shape are directly inter-related and provide a good natural indicator of the depth of closure to be adopted.

It is recommended that further investigation be undertaken of equilibrium profile shapes, including dependence on sediment characteristics and wave climate, with identification of transitions from the shore-face to the inner shelf across a range of locations and wave climates. This may be used to assess the applicability of the Hallermeier h_i depth as a predictor of the Bruun Rule closure depth for sea level rise shoreline impacts. The limited available data suggests that a modified scaling factor given by $H_{sm}T_{sm}(g/8000d_{50})^{0.5}$ may be more suitable.

References

Bruun P. (1954). Coast erosion and the development of beach profiles. Beach Erosion Board Technical Memorandum No. 44, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Mississippi.

Bruun P. (1962). Sea level rise as a cause of shoreline erosion. Journal of Waterways and Harbors Division, American Society Civil Engineering, Vol. 88: pp117-130.

Bruun P. (1986). The Bruun Rule of erosion by sea-level rise: A discussion on large scale two and three-dimensional usages. Journal of Coastal Research, Vol. 4(4), pp527-648. Charlotteville.

Chapman D.M., Geary M., Roy P.S. and Thom B.G. (1982). Coastal evolution and coastal erosion in New South Wales. Report prepared for the Coastal Council of New South Wales, ISBN 0 7240 6582 2.

Cowell P.J., Stive M., Roy P.S., Kaminsky G.M., Buijsman M.C. Thom B.G. and Wright L.D. (2000). Shore-face sand supply to beaches. Proc. 27th Int. Conf. on Coastal Engineering, ASCE, pp2496-2508.

Cowell P.J., Thom B.G., Jones R.A., Everts C.H. and Simanovic D. (2006). Management of uncertainty in predicting climate-change impacts on beaches. Journal of Coastal Research, 22(1), pp232-245.

Dean, R.G. (1977). Equilibrium beach profiles: US Atlantic and Gulf Coasts. Ocean Engineering Report No. 12, Dept. Civil Engineering, University of Delaware, Newark, DE.

Dean R. (1987). Coastal Sediment Processes: Toward engineering solutions. Proc. Coastal Sediments, ASCE, pp1-24.

Dean R. and Dalrymple R. (2002). Coastal processes with engineering applications. Cambridge University Press.

Dean R., Kriebel, D., Walton, T. (2002). Coastal Engineering Manual: Cross-Shore Sediment Transport Processes. Coastal and Hydraulics Laboratory – Engineering Research and Development Center Waterways Experiment Station – Vicksburg Mississippi

Delft Hydraulics Laboratory (1970). Gold Coast, Queensland, Australia – Coastal erosion and related problems. Delft Hydraulics Laboratory, Netherlands, Report R 257.

Hallermeier, R.J. 1977. Calculating a yearly limit depth to beach erosion. Proc. 16th Int. Conf. on Coastal Engineering, Hamburg, Germany, pp1493-1512.

Hallermeier R.J. (1981). A profile zonation for seasonal sand beaches from wave climate. Coastal Engineering, Vol. 4(3), pp253-277.

Hanson, H. (1987). GENESIS: A generalised shoreline change model for engineering use. PhD Thesis, Report No. 1007, University of Lund, Sweden.

Huxley C D (2009). Shoreline Response Modelling: Assessing the Impacts of Climate Change. Proc. 18th NSW Coastal Conference, Ballina, November.

Jackson J. (2007). Long term modelling using 1-line models – GENESIS and new extensions. Coastal Portal: http://www.encora.eu/coastalwiki/

Moore B.D. (1982). Beach profile evolution in response to changes in water level and wave height. MCE Thesis, Department of Civil Engineering, University of Delaware, 164pp.

Nicholls R.J., Birkemeier W.A., and Hallermeier R.J., 1996. Application of the depth of closure concept. Proc. 25th Int. Conf. Coastal Engineering, Orlando (USA), pp3874-3887.

Nicholls, R.J., Birkemeier, W.A., and Lee, G., 1998, Evaluation of depth of closure using data from Duck, NC, USA, Marine Geology, 148, pp179-201.

Patterson D.C. (2007). Sand transport and shoreline evolution, northern Gold Coast, Australia. Journal of Coastal Research, Special Issue 50.

Patterson D.C. (2009). Modelling the shoreline impacts of the Richmond River training walls. Proc. 18th NSW Coastal Conference, Ballina, NSW.

Patterson D.C. (2010). Modelling short to geological time-scale coastline response to climate change along the central east coast of Australia. Proc. Conference on Practical Responses to Climate Change, Engineers Australia, Melbourne, December.

Patterson D.C. (2012). Shoreward sand transport outside the surfzone, northern Gold Coast, Australia. Proc. 33rd International Conference on Coastal Engineering, Santander, Spain.

Patterson D.C. (2013). Modelling as an aid to understand the evolution of Australia's central east coast in response to late Pleistocene-Holocene and future sea level change. PhD thesis, University of Queensland.

Roy P.S. (2001). Sand deposits of the NSW inner continental shelf. Geoscience Surveys report.

Roy P.S. and Stephens A.W. (1980a). Regional geological studies of the NSW inner continental shelf. Geological Survey Report No GS 1980/028, Geological Survey of New South Wales, Department of Mines, February.

Roy P.S. and Stephens A.W. (1980b). Nearshore process-response in southeastern Australia. Proc. 17th Int. Conf. on Coastal Engineering, Sydney, Australia, March.

Vellinga P. (1983). Predictive computational model for beach and dune erosion during storm surges. Delft Hydraulics Laboratory publication No 294, February.

Wright L.D. (1995). Morphodynamics of inner continental shelves. CRC Marine Science Series, CRC Press, Inc., pp241.