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A Flexible Approach to Forecasting Coastline Change on Wave-Dominated Beaches

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ABSTRACT

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Standard methods of predicting coastline change typically rely on the analysis and extrapolation of historical trends, or simple geometric rules that consider the response of idealised coastal morphology to environmental change – *e.g.* the Bruun rule of coastline retreat due to sea level rise. In practice, predictions based on such methods are often challenged, due to the limited capacity to characterise natural geomorphic complexity, and consequently, the inability to satisfy restrictive assumptions. While statistical simulation methods offer a means to manage uncertainty in environmental forcing, datasets, and predictive models, the continued reliance on simple geometric rules introduces unnecessary error into forecasts. The increasing coverage and detail of geomorphic datasets, provided by modern remote sensing techniques (*e.g.* LiDAR, GPR), means that more rigorous approaches are now achievable in many settings. This paper presents a simple yet flexible approach to forecasting coastline change on wave-dominated beaches. The method combines a Monte Carlo simulation approach with a volumetric coastline response model that features a parameterised sediment budget. Model complexity reflects the levels of topographic and geomorphic data typically available for beaches in southeastern Australia, allowing for the sediment budget parameterisation to be broad or refined. A volumetric implementation of all components of coastline variability and change ensures that forecasts are sensitive to the complex coastal geomorphology of individual beaches. Application of the method demonstrates the sensitivity of forecast coastline change to three-dimensional beach and dune morphology, irregular substrates comprising mixed hard and soft materials, and complex shoreface surfaces featuring submerged reef structures.

ADDITIONAL INDEX WORDS: *Coastal hazards, Probabilistic modelling, Sediment budget, Southeast Australia.*

INTRODUCTION

The average position of the shoreline on wave-dominated beaches is a product of sea level (affected by waves, tides, storm surge and climate variability), and the distribution of sand within the sub-aerial and sub-aqueous beach system. The latter varies in response to fluctuations in energy conditions (*e.g.* waves and currents), sediment supply, and sea level, which collectively control the distribution of sediments within the geomorphic framework (Cowell *et al.*, 2003). Redistribution of sediments in response to permanent change in one or more controls may modify shoreline migration relative to a simple passive response (*i.e.* passive retreat due to inundation by sea level rise only).

While the historical impacts of coastal erosion have been documented at many SE Australian beaches, predicting the potential reach of coastline variability at present, and coastline change into the future, are problems characterised by substantial uncertainty. Uncertainty is unavoidable due to an imperfect understanding of coastal sediment transport processes and future environmental conditions, and limited records of beach volume and shoreline change. Despite having some of the best long-term beach measurement records by global standards (Thom and Hall, 1991; Short *et al.*, 2014; Harley *et al.*, 2015), the diverse coastal geomorphology and beach types of the SE Australian coastline (Short, 2006) present challenges to generalising data and models, and thus assessing coastal hazards (Kinsela and Hanslow, 2013).

However, uncertainty is inherent to risk management and in no way precludes robust forecasts of coastline change. For example, the recent adoption of statistical modelling frameworks within coastal geosciences provides for more rigorous and transparent approaches to identify, manage and communicate uncertainty in predicted coastline response to storms and environmental change (Cowell *et al.*, 2006; Anderson *et al.*, 2015; Simmons *et al.*, 2015). Recognition of the importance of quantifying uncertainty and model error in order to support transparent evidence-based decision making has encouraged the application of probabilistic methods to coastal management and planning in practice (Woodroffe *et al.* 2012, Mariani *et al.*, 2013).

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Here we present a flexible approach to forecasting coastline change on wave-dominated beaches and consider the influence of geomorphic complexity on SE Australian beaches on uncertainty in coastline change predictions.

Regional Setting

The New South Wales (NSW) coastline forms the majority of the mircrotidal wave-dominated SE Australia coastal setting, spanning some 1,500 km at a NE-SW orientation. The coast features over 1,000 km of sandy beaches with reflective to rhythmic bar and beach modes, and longshore bar and trough and dissipative states periodically adopted at the more exposed beaches (Short, 2006). The coast experiences a moderate-high energy SE swell and storm wave climate (Shand *et al.*, 2011).

The geological framework of the coastline varies from north to south: the northern region features broad embayments, low relief and a shallow shelf; the southern region features deeper pocket embayments, rugged relief and a steeply sloping shelf (Roy and Thom, 1981). As such, compartmentalisation is more developed within the central to southern regions. Further to defining sediment accommodation, the framework has shaped beach types by modifying local energy regimes, resulting in considerable regional- and local-scale variability (Short, 2010). Additional geomorphic complexity is introduced by nearshore reefs and consolidated or cemented beach-dune substrates.

Sediment connectivity via littoral and shoreface sand transport means that many NSW beaches cannot be considered isolated features that vary independently from surrounding beaches (Goodwin *et al.*, 2013). Rather, most beaches are elements of larger *sediment-sharing systems*, and respond to the redistribution of sand within the system due to evolving forcing conditions, such as the energy climate or sea level (Cowell *et al.*, 2003). The magnitude and timescales of beach change reflect not only variability in forcing conditions, but also the spatial scales and connectivity (by sediment transport) of adjacent beaches within each sediment-sharing system.

METHODS

Informed decision-making in the face of uncertainty, necessitates a risk management approach to assess the costs and benefits of management options and planning strategies, in the context of the likelihood and consequences of impacts.

Here we use a statistical simulation method to characterise uncertainty in model inputs, and describe the likelihood of hazard scenarios within the feasible uncertainty space. Nested within the simulation framework is a volumetric coastline response model that uses detailed terrain data and a parametrised sediment budget (consistent with available data) to predict the potential range of present and future coastal erosion hazards.

Statistical simulation approach

The Monte Carlo method is a standard modelling approach that is typically used to explore the potential range of solutions where the precise values of model inputs is poorly defined. The method has been previously applied to manage uncertainty in forecasting coastline change, with uncertainty in model predictions typically described in terms of the probability of exceeding potential coastline positions, or as confidence intervals (Cowell *et al.*, 2006; Mariani *et al.*, 2013; Anderson *et al.*, 2015).

Key to the process is appropriately capturing the uncertainty space (*i.e.* feasible range of values) of model parameters and variables that are randomly sampled for each model iteration. Here we express the uncertainty space for most inputs as a triangular probability density function (pdf), which is suitable where the bounds of the uncertainty space can be estimated but little data exists to define the precise shape of the distribution. Triangular pdfs are defined by fixed lower and upper bounds, and a modal value that controls probability density (Figure 1).

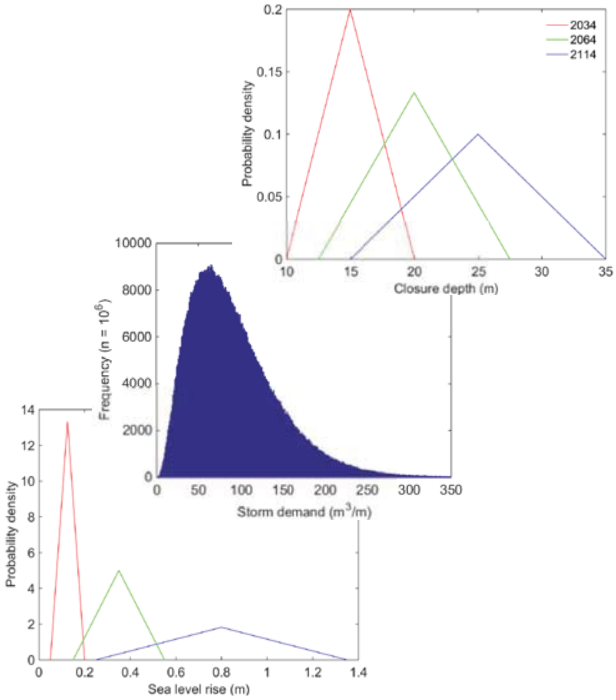

Figure 1. Triangular pdfs for sea level rise and closure depth for three forecast periods, and 10^6 samples from the storm demand gamma pdf.

The simulation method is carried out as follows (for further detail refer to Cowell *et al.*, 2006):

1. Input pdfs are defined using available data and expert reasoning to reflect the nature of the uncertainty space
2. The coastline response model is run many times (*e.g.* 10^6) with inputs sampled at random, unless correlation between particular inputs suggests proportionate sampling
3. A frequency histogram of model predictions is constructed
4. A continuous probability distribution (such as Generalised Extreme Value or Gaussian) is then fitted to the predictions
5. The cumulative probability function of the fitted distribution is derived to determine exceedance probabilities
6. Model predictions corresponding to relevant exceedance probabilities are derived from the fitted cumulative function
7. The zone of forecast coastline change is mapped for selected exceedance probabilities or confidence intervals

Volumetric coastline response model

The coastline response model treats each component of coastline variability and change as a sediment volume. For the chosen forecast period (*t* years), coastline change is solved as the sum of sediment volume flux per metre of beach (V_T):

$$V_T = C_F(V_F) + C_R\left[(q_x + q_y)t + C_S(V_S) + \left(\frac{A_D \cdot S}{L}\right) + \left(\frac{V_O + V_A + V_M + V_C}{L}\right)t\right]$$

q_x = historical shore-normal sediment flux rate [m^3/m/yr]
q_y = historical alongshore sediment flux rate [m^3/m/yr]
V_F = fluctuating erosion from storms and variability [m^3/m]
V_S = theoretical shoreface accommodation volume [m^3/m]
V_O = sediment loss via barrier overwash [m^3/yr]
V_A = sediment loss via aeolian transport to dunes [m^3/yr]
V_M = sediment loss via mega-rips during storms [m^3/yr]
V_C = carbonate sediment dissolution or production [m^3/yr]
A_D = surface area of marine (flood-tide) delta [m^2]
S = sea level change over forecast period [m]
L = alongshore length of sediment cell [m]

The parameterisation of all potential contributors to coastal erosion as volumetric sediment budget components allows for the distinctive morphology of each beach to be accounted for in coastline change predictions. The coastline change distance (R_T) is calculated by applying V_T to a beach profile derived from LiDAR topography (Figure 2), and includes an allowance for dune slumping (Nielsen *et al.*, 1992). Ideally, an alongshore-averaged beach profile is used where homogeneity of processes and morphology is satisfied, to account for the redistribution of sediments within the beach system (Cowell *et al.*, 2003).

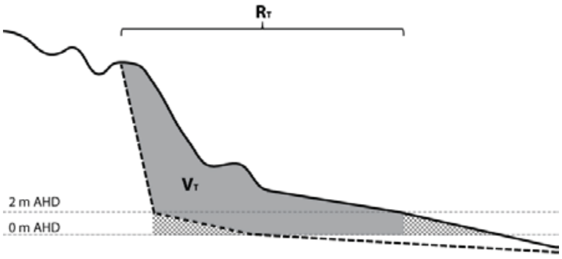

Figure 2. The forecast coastline change distance (R_T) is calculated by applying V_T above mean sea level and landward of 2 m elevation.

The solution features three scaling coefficients: *fluctuating* erosion (C_F) and coastline *recession* (C_R) account for reduced exposure to wave energy, or substrate resistance, for fluctuating and recession components; and, *shoreface* response (C_S) accounts for shoreface reefs that occupy space in the water column and reduce the theoretical sediment accommodation volume.

Fluctuating beach erosion due to storms (V_F) is handled using a gamma pdf (Figure 1), which better captures the frequency of occurrence of severe erosion events as estimated from historical records (Gordon, 1987). Where sufficient data (historical or geological) exists, shoreface-beach (q_x) and alongshore sediment exchange trends (q_x) can be included.

Coastline response to sea level rise is also considered as a volumetric component. First, an idealised shoreface profile of the form $h = Ax^m$ is fitted to available hydrographic data (Figure 3). For each model run, the profile is raised by the sea level rise sampled from the input pdf, and the area between the initial and raised profiles is calculated, although only to the limit of the sampled closure depth (Figure 1). The calculated area is then halved to derive V_S, in accordance with basic principles of sediment conservation (Bruun, 1962). Figure 1 shows that the profile closure depth increases with the forecast period, which is consistent with depth-increasing shoreface response timescales (Stive and de Vriend, 1995; Kinsela and Cowell, 2015). Flood-tide delta aggradation due to sea level rise (Eysink, 1990) is also considered using the active delta area (A_D) and sea level rise (S) values sampled in each model run from the respective pdfs.

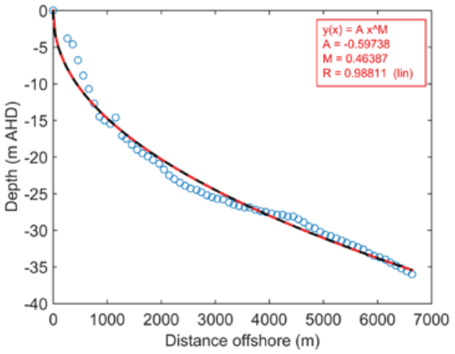

Figure 3. Shoreface profile fitted to hydrographic data (o) from Lake Cathie Beach to calculate the theoretical shoreface accommodation.

Other sediment budget components may be measured or estimated as gross fluxes within the sediment cell. The examples included here (V_O, V_A, V_M, V_C) are not exhaustive but are intended to capture processes relevant to the SE Australian coastal setting.

Application to Lake Cathie Beach

The volumetric coastline response model was applied to Lake Cathie Beach on the mid-north coast of NSW. Historical records from this beach suggest a trend of coastline recession, and properties and infrastructure have been identified as at risk from coastal erosion (SMEC, 2010; Cardno, 2014).

Lake Cathie Beach features geomorphic complexity in the form of indurated sand (coffee rock) within the beach and dune sands, and shoreface reef structures (Figure 4). A recent geotechnical study found coffee rock intermittently throughout the beach and dunes between 0-4 m elevation, with strength ratings ranging from extremely low to moderate (Cardno, 2014). The beach is also situated within a drift-aligned alongshore transport setting, and together these complexities invalidate traditional approaches to predicting coastline change such as the standard Bruun rule of coastline retreat due to sea level rise (Bruun, 1962).

Geomorphic complexity was accounted for by adjusting the response scaling coefficients to reflect the available data (Table 1). Analysis of historical erosion during severe storms (Cardno, 2014) indicates that the storm demand volume at Lake Cathie

Beach is about 70% (135 m^3) of the typical value for exposed NSW beaches (200 m^3), so C_F was set accordingly. However, geotechnical testing suggests that the coffee rock may not withstand prolonged erosion as would be anticipated during coastline recession (Cardno, 2014), and thus C_R allowed for a potential full response to sediment budget redistribution (*i.e.* $C_R = 1$). Detailed mapping of shoreface reefs by marine LiDAR indicated approximately 30% coverage (Figure 4), and so C_S was set accordingly, within a 20% uncertainty space.

Figure 4. LiDAR data showing shoreface reef off Lake Cathie Beach.

Table 1. T*riangular pdf values for coastal response scaling coefficients.*

Scaling coefficient	Lower	Mode	Upper
C_F	0.6	0.7	0.8
C_R	0.6	0.8	1.0
C_S	0.6	0.7	0.8

RESULTS

Applying the volumetric coastline response model using the statistical simulation method generates a frequency histogram of coastline change predictions for each forecast period that reflects the convolution of the various input pdfs. Figure 5 shows the results of a 50-year forecast for Lake Cathie Beach, with 50, 90, 99 and 99.9 percentiles marked in grey. Fitting a continuous probability distribution to the frequency histogram allows for the predictions to be interpreted in terms of exceedance probabilities. The cumulative function of the best-fit distribution - in this case Generalised Extreme Value (GEV) is plotted to show exceedance probabilities for the full range of predictions (Figure 5).

DISCUSSION

Comparison of the 50-year forecast results shown in Figure 5, with a previous 'best estimate' prediction for 2050 using standard approaches, provides an opportunity to demonstrate the utility of the probabilistic approach in communicating uncertainty in predictions, and to consider the influence of geomorphic complexity at Lake Cathie Beach on forecast coastline change.

Figure 6 compares the 50-year probabilistic forecast (2064) with the 'best estimate' hazard line for 2050, which was derived using extrapolation of historical trends and the standard Bruun rule (SMEC, 2010). It is seen that the 50% exceedance forecast for 2064 (red line) is consistent with the best estimate prediction for 2050. In this case, the geomorphic complexity of Lake Cathie Beach (irregular dune topography, coffee rock, shoreface reefs) accounted for by the volumetric coastline response model moderates forecast coastline change relative to the best estimate, suggesting a potential delay in the magnitude of coastline change experienced of 15-20 years relative to the standard approach.

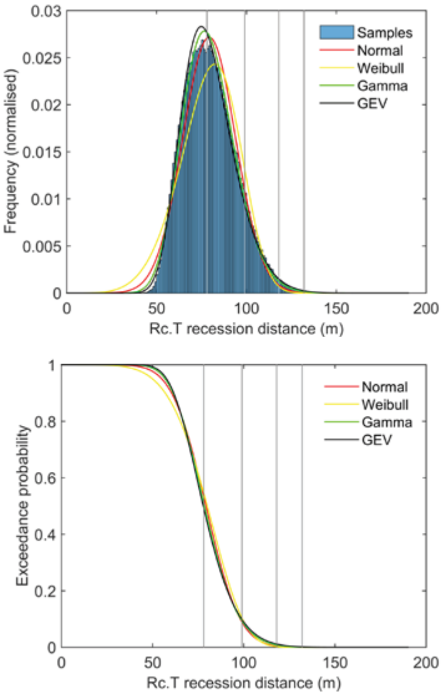

Figure 5. Frequency histogram (upper) and cumulative probability (lower) for a 50-year coastline change forecast at Lake Cathie Beach.

However, the 1% exceedance position marked by the green line indicates that 1% of feasible predictions exceeded that line, and thus some erosion risk exists beyond the 2050 best estimate line, which may need to be considered in future (Figure 6).

The flexibility of the volumetric coastline response model allows for the level of complexity to be adapted to suit the resolution and accuracy of data available to guide the sediment budget parameterisation, or the necessary resolution of forecasts. For example, a sediment cells framework characterising regional variability in coastal geomorphology and sediment transport has been developed for NSW to support regional-scale modelling to inform strategic planning (Hanslow *et al.*, 2016).

CONCLUSIONS

Uncertainty is characteristic of risk management and can be handled in predictions of coastline change through the use of statistical sampling techniques and flexible predictive models that account for the natural complexity of sediment-sharing systems. The method described here provides a pragmatic means to consider complexity due to three-dimensional morphology, multiple sources and sinks, partially resistive substrates, and timescale-dependent shoreface response to sea level change, in a manner consistent with available data and current knowledge.

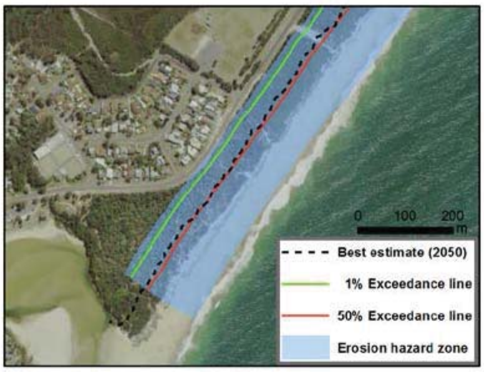

Figure 6. 50-year forecast for Lake Cathie Beach showing potential range of coastline change with 50% and 1% exceedance level lines.

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