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Probabilistic estimation of storm erosion using analytical, semi-empirical, and process based storm erosion models

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ABSTRACT

Probabilistic estimates for coastal storm erosion volumes are increasingly being sought by contemporary risk based coastal zone management frameworks. Such estimates can be obtained via probabilistic models that incorporate a structural function element which calculates storm erosion (i.e. storm erosion model). Intuitively, the more sophisticated the storm erosion model embedded in the probabilistic model, the more accurate and robust the probabilistic storm erosion volumes should be, albeit at significant additional computational cost. This study assesses the relative performance of three storm erosion models with varying levels of complexity when embedded within Callaghan et al.'s (2008a) probabilistic framework for estimating storm erosion. The storm models tested are: the analytical Kriebel and Dean (1993) model, the more complex semi-empirical SBEACH model and the highly complex and process-based XBEACH model.

The probabilistic model is applied at data rich Narrabeen beach, Australia. Kriebel and Dean (1993) and SBEACH are used 'on-line' in the probabilistic simulations, while XBEACH is used with an innovative off-line tabulation approach to facilitate reasonable computational times. SBEACH is calibrated for a mid-range erosion event while XBEACH is validated for the same single erosion event as well as for all measured storm erosion volumes during the 30 year study period. The Kriebel and Dean (1993) model is used with recommended parameter settings and therefore does not require calibration.

When both SBEACH and XBEACH are calibrated against the single erosion event, SBEACH provides the most accurate and robust probabilistic estimates of storm erosion. However, when XBEACH is calibrated using the entire erosion volume data series, the results improve significantly raising the accuracy and robustness of the probabilistic estimates of storm erosion volumes obtained with XBEACH to be on par with those obtained with SBEACH. However, only XBEACH predicts storm erosion volumes with the physically more plausible behaviour of a downward concave tail shape when plotted as cross-shore beach-erosion volume on a vertical linear axis against return period on a horizontal logarithmic axis.

The simulation time (on a standard single processor) when using the simple Kriebel and Dean (1993) model is about 1 day, whereas for SBEACH (on-line) and XBEACH (tabulation), the simulation time is about 1000 h. However, the physically more plausible and the more accurate and robust results that can be obtained with SBEACH or XBEACH justifies the additional computational cost.

1. Introduction

Coastal zone managers are increasingly seeking beach erosion hazard predictions within a probabilistic framework to facilitate risk informed decision making (Woodroffe et al., 2012). Probabilistic frameworks for coastal erosion typically provide return periods for coastline changes from storm erosion. The major advantage of probabilistic coastal erosion estimation methods is that they enable robust risk assessments (risk = hazard × consequence) while taking into account forcing uncertainty. Information from probabilistic frameworks could be integrated to determine economic implications of coastal hazards and/or adaptation options along with associated uncertainties. Recent examples of probabilistic coastal erosion frameworks include Callaghan et al. (2008a), Corbella and Stretch (2012), Cowell (2006) and Nielsen and Adamantidis (2007) with Jongejan et al. (2011) being an example where risk is optimised through economic arguments.

Callaghan et al (2008a) presented the first attempt of estimating storm erosion probabilities using a rigorous probabilistic framework. Similar frameworks have been developed, for example, for coastal flooding (Garrity et al., 2006; Hawkes et al., 2002) which Callaghan et al. (2008a) extended and applied to storm erosion. Upon reviewing

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several probabilistic frameworks, Callaghan et al (2008a) recommend the full temporal simulation of the Joint Probability Method (JPM) for obtaining probabilistic coastal erosion estimates. Their framework is referred herein as probabilistic modelling or simulation for brevity. They implemented and provided initial justification of their recommended probabilistic model using 30 years field measurements at Narrabeen beach, Australia.

The recommended approach by Callaghan et al. (2008a) involves temporally simulating dominant forcing parameters for storm erosion and using these parameters and a structural function to estimate storm erosion (Fig. 1). The forcing parameters (wave parameters of height, period and direction, storm parameters of duration, surge and interval) are simulated from their joint probability distribution (Fig. 1, orange elements) and used by the structural function (the structural function comprises of all elements with green-dashed box) to derive a time series of storm erosion. The storm erosion probabilities are then estimated from this time series. Their structural function employs wave propagation over the actual bathymetry, refraction and shoaling processes across the continental shelf, an equilibrium based convolution method (Kriebel and Dean, 1993) for storm erosion and an exponential beach accretion model.

Callaghan et al. (2008a) used the Kriebel and Dean (1993) storm erosion model as it is simple and consequently enabled fast computations. Their predictions using Kriebel and Dean (1993) were quantitatively similar to measurements albeit with an upwards concave tail shape (on a plot where storm erosion volume is plotted vertically on a linear scale against return period on a horizontal logarithmic scale), implying very large erosion estimates for rare low probability events. While a rigorous theoretical argument for an upper limit on beach erosion may not exist in the engineering literature, it is reasonable to us that one would exist on the basis that there is a finite amount of energy available to drive geophysical systems (atmospheric events generating erosion). While it is entirely possible that a break in curvature could occur (e.g., due to an offshore rock reef capping wave heights), there were no indications of this occurring in predictions up to 100 year return period in the results presented by Callaghan et al (2008a).

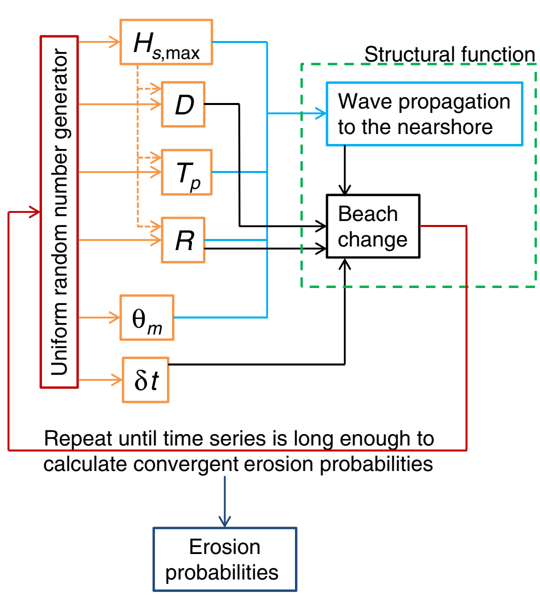

Fig. 1. Flow chart illustrating Callaghan et al.'s probabilistic model, which implements their full temporal simulation approach employing the Joint Probability Method (JPM, red and orange elements) for estimating synthetic storms, the structural function to estimate cross-shore beach change (elements within the green dashed box). Storm parameters included in the JPM are peak significant height $H_{s,max}$, storm duration D, typical peak wave period T_p, maximum storm surge R and typical mean wave direction θ_m, and event sequencing parameter is duration between storms (δt).

Callaghan et al. (2008b) extended their original model by replacing the storm erosion element of the structural function that previously adopted Kriebel and Dean (1993) with SBEACH (Larson, 1988). SBEACH is a one-dimensional (profile) beach erosion model for storm erosion that uses an equilibrium argument that whereby net sediment transport occurs when the local wave dissipation rate is different from the equilibrium rate. SBEACH, while based on similar principals as Kriebel and Dean (1993), represents a significant increase in model complexity compared to the former. These additional complexities include random wave propagation across the surf zone and determination of profile changes by integrating the sediment continuity equation using locally estimated non-cohesive sediment transport rates. This replacement of Kriebel and Dean (1993) by SBEACH did lead to better quantitative and qualitative beach erosion probabilities. The tail shape estimated was, however, still upwards concave but was less so when compared to Kriebel and Dean (1993) and was almost linear when plotted as cross-shore beach-erosion volume on a vertical linear axis against return period on a horizontal logarithmic axis.

The structural function element for wave propagation across the continental shelf used in conjunction with both Kriebel and Dean (1993) and SBEACH (Larson, 1988), included wave refraction and shoaling based on the actually bathymetry. Callaghan and Wainwright (2013) replaced this wave propagation model with a more comprehensive model that included wave breaking, bottom friction, wave diffraction (approximately), refraction and shoaling, wave directional spreading and water surface variations. This replacement lead to marginally better estimates with, for example, reduced rare beach erosion predictions for Kriebel and Dean (1993). While Callaghan and Wainwright (2013) did not present storm erosion probabilities estimated with their more comprehensive wave propagation model and SBEACH as the structural function, we show below that those predictions have an approximately linear tail shape; an improvement from the concave upwards tail predicted by the Kriebel and Dean, 1993 model.

Intuitively, the more sophisticated the storm erosion model embedded in the probabilistic model, the more accurate and robust the probabilistic storm erosion volumes should be. However, whether this is in fact the case has never been tested rigorously. Furthermore, with a very conservative estimate of 5 storms per year, a 1000-year probabilistic simulation will require 5000 simulations of the storm erosion model. Therefore, as the level of sophistication of the storm erosion model increases, the computational effort required will also increase. Thus, the cost/benefit of embedding a highly sophisticated storm erosion model within the probabilistic model needs to be carefully evaluated. Therefore, this study was undertaken with the overarching objective of assessing how the level of sophistication of the storm erosion model influences the accuracy and robustness of the probabilistic estimates of storm erosion volumes. The performance of three different storm erosion models is tested: the analytical Kriebel and Dean (1993) model, the more complex semi-empirical SBEACH model and the highly complex and process-based XBEACH model. XBEACH (Roelvink et al., 2009) was selected as the process-based model herein as it is emerging as the industry standard nearshore coastal dynamics model. Additionally, for XBEACH, two different model calibration approaches are investigated in which the calibration is to either a single mid-range storm or measured erosion statistics. The computational cost, accuracy and robustness associated with the probabilistic storm erosion volume estimates derived with the three different storm erosion models will be compared and contrasted.

A further aim is to investigate whether it is possible to predict a downward concave tail shape using XBEACH. This very specific aim arises from our previous argument that an upper limit on storm erosion volume must exist. An upper limit would imply that beach erosion volumes should either be linear (i.e., able to transition at higher return periods to a constant upper limit) or downwards concave (starting to transition to a constant upper limit) when plotted vertically on a linear scale against return period on a horizontal logarithmic scale. Quantitative accuracy changes between the various storm erosion probability estimates from different erosion models will also be analysed.

SBEACH was previously calibrated and applied to estimate storm erosion probabilities (Callaghan et al., 2008b), however, calibration details were never published and those estimates used the less comprehensive wave propagation model. Herein, all erosion models will be applied using the more comprehensive wave propagation model implemented by Callaghan and Wainwright (2013).

The paper is arranged as follows. Section 2 summarises the field measurements from Narrabeen Beach that are suitable to test storm erosion probability predictions. Our probabilistic modelling approach is briefly described in Sections 3 and 4. Section 3 concentrates on all aspects of the probabilistic modelling except storm erosion. Section 4 discusses how Kriebel and Dean (1993) and SBEACH were previously implemented and details on the calibration and validation of both SBEACH and XBEACH and how XBEACH was implemented into the probabilistic simulation. Section 5 summarises results and conclusions are drawn in Section 6.

2. Narrabeen Beach field measurements

The Collaroy/Narrabeen beaches (Fig. 2) are located approximately 18.5 km north of Sydney central business district (Hoffman and Hibbert, 1987; Short and Trembanis, 2004). For simplicity and brevity, these beaches are collectively referred to as “Narrabeen Beach”.

The Coastal Studies Unit at the University of Sydney, under the direction of Professor Short, have surveyed Narrabeen Beach since 1976 using eight profiles taken at approximately monthly intervals using the Emery (1961) method. The Emery survey approach, as implemented by Short, involved manually measuring (without water craft) each profile at regular 10 m intervals from a constant back beach location. The surveys typically extend to approximately 2 m below mean sea level as surveys were normally conducted near low tide. It should be noted that while the survey method is appropriate for estimating bulk profile properties, the constant cross-shore measuring increment precludes the identification of small scale features such as back beach dune scarps. Another limitation is that there are multiple wave storm events between consecutive surveys. Hence, while we identify one particularly substantial wave storm between consecutive surveys, there can be other smaller wave storms or long periods after the wave storm of interest in which the beach may have accreted.

The Narrabeen Beach is also subjected to beach rotation from the slowly varying imbalance between northerly and southerly directed longshore sediment transport and long-shore variations in cross-shore transport (Harley et al., 2011; Ranasinghe et al., 2004) resulting from wave climate oscillations that are linked to El Niño/Southern Oscillation. Short and Trembanis (2004) both quantified the magnitude and the arrangement of this beach rotation from field measurements and concluded that profile four is the beach rotation fulcrum. Consequently, we concentrate on profile four and exclude the other profiles as being impacted (to some extent) by longshore processes. During a particular short period of several days during stormy conditions, it is reasonable to assume that cross-shore processes will dominate long-shore processes (in the absence of small scale longshore features like rip cells). However, the time between consecutive surveys at Narrabeen Beach are typically large enough to include some effects from longshore migration of rip systems, even at profile four.

Measured non-directional and directional wave parameters were available at Botany Bay (1971–) and Long Reef (1992–) respectively, with both located in water depth of approximately 80 m (Fig. 2b). Narrabeen Beach wave climate, characterised by these measurements include rapidly changing sea states arriving from northerly, easterly and southerly directions and swell predominately arriving from southerly directions. The average significant wave height for sea and swell are 2.1 m and 1.6 m respectively. Water surface levels that excludes wave set-up and run-up, were measured at Fort Denison (1914–, Fig. 2b). The interested reader is referred to Short et al. (2007) for more particulars of Narrabeen Beach, Short and Trenaman (1992) for Sydney wave climate including generation fields and meteorological forcing and Nielsen (2011) for discussions on water levels and contributions to tidal anomalies.

Table 1 lists the major erosion events, ranked by erosion amount and offshore wave height, at Narrabeen Beach since directional wave measurements commenced at the offshore (Long reef) measurement site. The largest recorded storm in the state of New South Wales, where Narrabeen is located, is also included in Table 1 as this storm is frequently used as a design condition in local coastal hazard definition studies. However, a post storm measured profile is unavailable for the May 1974 storm and therefore this event is only included herein in terms of estimated eroded volume. While it is accepted that wave direction is critical in conjunction with wave height and period for determining nearshore wave conditions that drive beach erosion, there are other factors affecting local erosion characteristics which may influence the measured beach profiles. It is suggested that the most dominant of these factors may well be beach accretion between storms and alongshore rip cell migration (Holman et al., 2006 observed up to 20 m/day longshore rip migration on the next beach south of Narrabeen Beach). For example, in situations where the profile measurements are several

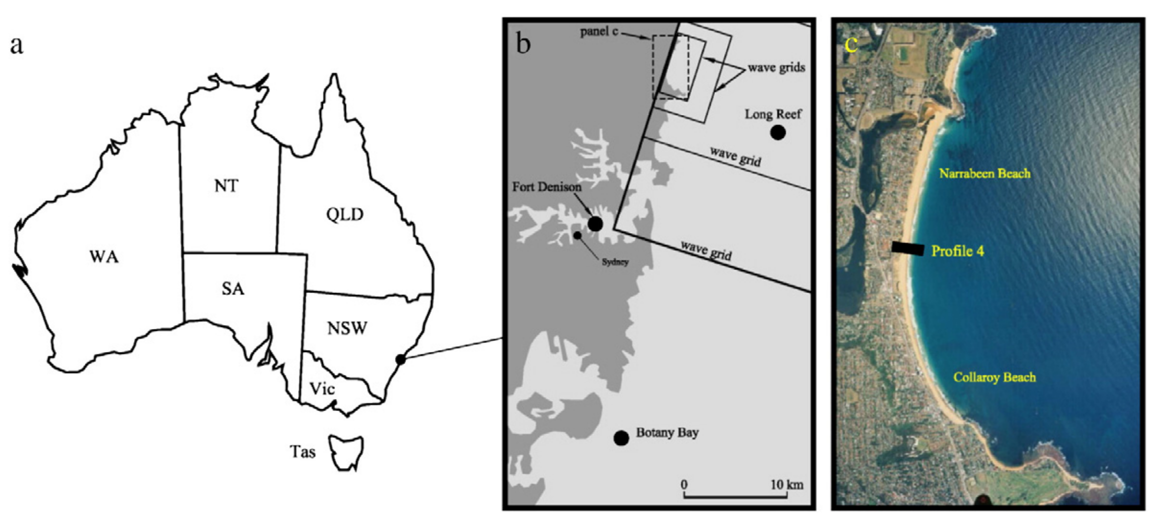

Fig. 2. Narrabeen Beach and measurements locality maps. a. Location of Sydney within Australia; b. the Botany Bay and Long Reef wave buoy locations and the Fort Denison tidal recording station along with the wave propagation model grid extents for scale and panel c extents indicated by the dashed rectangle; and c. the location of long term beach profile surveys at Narrabeen Beach (profile 4) (Short and Trembanis, 2004).

Table 1
Summary of extreme erosion and wave events at Narrabeen Beach profile four.

Event	Erosion[a] [m^3/m]	Peak $H_{s,\max}$ [m]	Rank	
			Erosion	Wave height
July 2001	104	8.4	1	3
May 1974	100[b]	9.2	2	2
June 2007	100	6.1	3	6
July 2004	80	6.8	4	5
May 1997	73	9.9	5	1
April 1999	43	6.9	6	4
August 1996	22	6.1	7	7

[a] Erosion amount is the volume change above mean sea level and bounded by the 2 m contour as used by Callaghan et al. (2008a).
[b] Erosion volume estimated from Hoffman and Hibbert (1987) as there is no post-storm profile survey available.

weeks to months apart, or the storms are positioned farther from the initial survey, significant beach recovery may occur between the profile measurement time and the storm. This will be reflected in the post-storm measured profile. We suggest that alongshore rip migration may increase variation seen in measured profiles that are sampled at greater periods than the time taken for a rip channel to migrate past the profile (e.g., see Short and Hesp, 1982, their Fig. 4 where Narrabeen Beach profiles have more variations than beaches with less rip activity). For a survey taken when a rip cell is present, the beach would appear more eroded than a few days later when the rip has migrated alongshore (i.e., signal aliasing).

3. Previous probabilistic modelling of Narrabeen Beach field measurements

Callaghan et al. (2008a) presented a probabilistic model for Narrabeen Beach (Fig. 1), as an example of the application of a probabilistic coastal erosion framework as discussed in Section 1. They identified coastal storms from meteorology events to ensure event independency. These coastal storms were parameterised by peak wave height ($H_{s,\max}$), a storm typical wave period (T_p), typical mean wave direction (θ_m) and storm duration (D), maximum storm surge (R) and time between events (δt). This probabilistic modelling represented coastal storm measurements using generalised Pareto marginal distributions (Coles, 2001) for peak storm wave height, storm duration and maximum storm surge, a modified log-normal distribution for wave periods so as to include a mixture of swell and sea states (i.e., steepness limits) and an empirical distribution for wave direction. Dependency distributions were fitted between peak storm wave height, storm duration and maximum storm surge, with measurements exhibiting partial dependency within the 95% confidence interval. The wave period marginal distribution adopted is conditional on peak wave height and no further dependency between storm duration and maximum storm surge was included. The mean wave direction was assumed independent of wave height based on measurements which showed no decipherable dependency. The wave climate near Narrabeen Beach has more storms during winter compared to summer (Short and Trenaman, 1992), which was modelled using a non-homogenous Poisson distribution for the time between coastal storms, providing a better agreement with measurements than the more traditional approach of assuming that storm durations are small compared to the spacing between events (see de Michele et al., 2007 for a similar approach). Additional testing for storm clustering (Luceño et al., 2006) showed that these measurements exclude any noticeable clustering. However, this does not preclude the scenario of two coastal storms occurring close together and consequently producing severe beach erosion as that form of grouping is already contained in the non-homogenous Poisson distribution.

The storm wave parameters, as measured at the offshore wave buoy, were propagated to the nearshore using the actual bathymetry refraction, shoaling, diffraction, wave breaking, bottom friction, wave directional spreading and water level variations (Callaghan and Wainwright, 2013). The previously used beach erosion approaches (Kriebel and Dean (1993), SBEACH (Larson, 1988) and the probabilistic coastline recession (Ranasinghe et al., 2012a) model or PCR). In this study this uncertain aspect of beach dynamics is accommodated via a simplified exponential beach recovery method using measured accretion rates recently refined by Ranasinghe et al. (2012b). The probabilistic simulation (Fig. 1) uses the Monte Carlo sampling technique and the fitted distributions by repeated random realizations of $H_{s,\max}$, D, T_p, θ_m, R and δt, followed by estimating beach change for each storm and then moving to the next storm. Confidence intervals were estimated using bootstrapping techniques (Markus, 1994) which repeat this probabilistic simulation (Fig. 1) many times with slightly different distributions for $H_{s,\max}$, T_p & D obtained from re-sampling the measurements.

Narrabeen Beach profile measurements (Fig. 2) were previously used to validate, test or apply various combinations of structural function elements (Callaghan and Wainwright, 2013; Callaghan et al., 2007; Ranasinghe et al., 2009a,b, 2012a,c; Woodroffe et al., 2012). Applications before 2013 used the original wave propagation model which was limited to refraction and shoaling. Storm erosion probabilities presented herein will all use the more extensive wave propagation model. Furthermore, these updated predictions (re-run of Kriebel and Dean (1993) and SBEACH models) stemmed from simulations that were 1000-year long, repeated 2000 times. The same simulation approach was used for XBEACH (below) and in all cases, convergence was achieved at exceedance probabilities of 0.001%.

4. Beach change structural function elements

Probabilistic simulations require a structural function that converts forcing to an output. The output here is storm erosion and forcing includes offshore wave parameters and storm surge. Consequently, the storm erosion structural function requires two elements of wave propagation from offshore to nearshore and storm erosion, which requires nearshore wave parameters. In this section, we concentrate on the storm erosion element with the interested reader referred to Callaghan and Wainwright (2013) for particulars of wave propagation element.

All storm erosion models start from the 20 m depth contour, selected as longshore depth contours are approximately parallel shoreward of this point and it is outside the surf zone for reasonably expected wave conditions. Offshore waves are propagated using a two-dimensional wave model to this point. Surveyed profiles where used to developed an equilibrium profile using regular profile measures covering between 2.5 m below to 10 m above mean sea level, combined with a profile measurement out to 20 m below mean sea level.

4.1. Previous beach change structural function element: Kriebel and Dean (1993)

Kriebel and Dean (1993) require geometrical parameters, sediment properties (for estimating the shape parameter A in the equilibrium profile equation) and a time scale for each storm to estimate storm erosion. The shape parameter was estimated using 0.35 mm medium sand grain diameter and Dean and Dalrymple (2002). Each storm's time scale was determined following Kriebel and Dean (1993) recommendation. Consequently, Kriebel and Dean (1993), as applied by Callaghan et al. (2008a), have no calibration parameters. Callaghan et al. (2008a) noted that the good quantitative comparisons with measurements using Kriebel and Dean (1993) were remarkable given this exceptionally simple model with very low computational cost (current simulations taking less than one hour on a single processor).

4.2. Previous beach change structural function element: SBEACH

SBEACH (Larson, 1988) is a one-dimension (profile) semi-empirical beach erosion model specifically designed to simulate profile changes during coastal storms. This model uses the equilibrium argument that net sediment transport occurs when the local wave dissipation rate is different from the equilibrium rate (after adjustment for gravity driven sediment transport). This approach works within the surf zone (from the initial point where waves begin to break to an arbitrary small depth near the still waterline). Outside the surf zone, other methods for estimating sediment transport rate are employed (Wise et al., 1996). For the swash zone, transport rates are estimated using shape function (Madsen, 1991, 1993) and the inner surf zone sediment transport rate. Offshore of the surf zone transport rates are estimated using another shape function (Larson and Kraus, 1989) scaled using the outer surf zone sediment transport rate.

Narrabeen Beach sand has a medium grain diameter of 0.4 mm near the shoreface fining to 0.3 mm at 15 m depth (Short, 1984). A 0.35 mm medium grain diameter was adopted for modelling purposes. Additional SBEACH model parameters were; surf zone cut-off depth adopted at 0.3 m; avalanching trigger angle was 30° (similar to values used by Wise et al., 1996); 2-minute time step (adopted after convergence checks); wave heights were randomised by $\pm 15\%$ as recommended and the transport rate decay coefficient multiplier was set to $\lambda = 0.5$ (Wise et al., 1996). The computational grid had a variable grid spacing from one metre in the surf zone, increasing up to 12 m outside the surf zone, with local grid spacing being approximately equal to the local mean depth (relative to MSL) through the surf zone.

As a measure of relative model complexity, SBEACH probabilistic simulations presented herein take approximately 40 days on a single processor (Intel Xeon L5520), compared with less than one hour for Kriebel and Dean (1993), making SBEACH three orders of magnitude slower than Kriebel and Dean (1993).

The May 1997 storm (Fig. 3) was selected as the single calibration event as it is a mid-range eroded volume coastal storm. Consequently, validation will test lesser and greater eroded volume coastal storms. SBEACH was calibrated with: coefficient for slope-dependent term, $\varepsilon = 2 \times 10^{-3}$ m^2/s (within the normal range of 10^{-3}–4×10^{-3} m^2/s); and transport rate coefficient, $K = 4 \times 10^{-6}$ m^4/N (just above the normal range of 0.25×10^{-6}–2.5×10^{-6} m^4/N).

The model validity has been assessed using the remainder of identified storms (see Fig. 4). The August 1996 validation is poor but explainable as it is expected that a reasonable amount of accretion has occurred between surveys and hence, the erosion signal will only account for a minor portion of the storm erosion. June 2007 and April 1999 validations are poor and fair respectively with over and under predictions due to either model short comings or alongshore rip migration. July 2004 validation is fair. The forcing for this validation includes two large wave storms between surveys and there is limited opportunity for beach accretion between the last storm and the final profile measurement. Hence, the difference between these two surveys captures most of the storm erosion signal. The predicted erosion is however less than that indicated by the measurements with no particularly obvious explanation other than model short comings or possibly alongshore rip migration. July 2001 and May 1974 validations are reasonably good. The erosion obtained from July 2001 surveys is expected to represent the actual storm erosion well and the model is able to predict the correct overall eroded profile shape. The May 1974 storm unfortunately has no post-storm survey from the Narrabeen Beach data set; however, the SBEACH predicted erosion volume of 95 m^3/m for this storm is in very good agreement with the 100 m^3/m aerial photograph based estimate from Hoffman and Hibbert (1987).

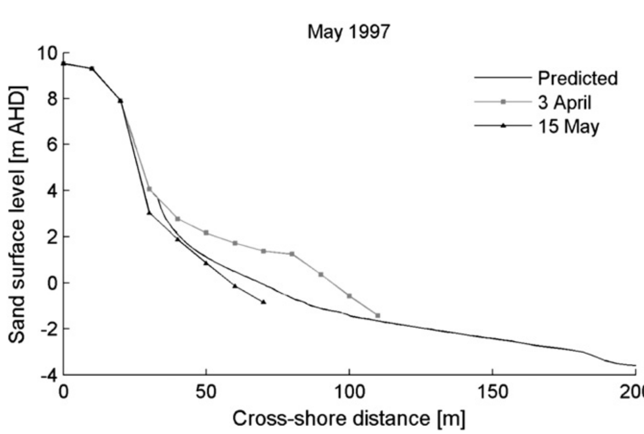

Fig. 3. Narrabeen Beach measured initial and final profiles with SBEACH estimated final profile for the May 1997 storm.

4.3. New beach change structural function element: XBEACH

XBEACH is a nearshore numerical model able to simulate non-cohesive sediment transport and resulting beach change (Roelvink et al., 2009). This model has been used to simulate coastal response including dune erosion and barrier overwash with time-varying forcing conditions. XBEACH is based on a non-stationary wave driver that includes wave directional spreading and can estimate wave-group generated surf and swash zone dynamics and removal of sediment from the dune face using an avalanching technique. The sediment transport estimates are limited to regions inundated by the long waves. Consequently, swash zone transport is excluded from sediment transport estimates but accounted for using avalanching. Sediment transport rates are estimated using the Soulsby–Van Rijn equation (Soulsby, 1997). As a measure of model complexity, if XBEACH probabilistic simulations presented herein were done in a similar manner as either Kriebel and Dean (1993) or SBEACH, it would take approximately four and a half millennia, which is three orders of magnitude slower than SBEACH, which itself is three orders of magnitude slower than Kriebel and Dean (1993).

Our implementation of XBEACH has a grid consisting of 216 cross-shore points using variable spacing of 2 m through the surf zone and increasing to 17 m further offshore, 10° directional resolution, non-stationary wave energy balance model, Chézy coefficient (65 m$^{1/2}$/s) and sediment properties (mean diameter, $d_{50} = 0.35$ mm, 90th percentile diameter, $d_{90} = 0.5$ mm, specific density $s = 2.65$). Calibration involved options and parameters (Table 2) including wave propagation options and parameters, sediment avalanching parameters and wave skewness parameters. Following the testing of some 60 permutations and combinations of the free model parameters/options, the ultimately adopted parameters and options were: non-stationary wave model, wave breaking following Roelvink (1993) with breaker index of 0.56, roller dissipation included, dune erosion using wet and dry avalanching slopes of 0.3 and 0.6 respectively, forced using Pierson-Moskowitz shaped spectrums (Alves et al., 2003; Pierson and Moskowitz, 1964) and increasing acceleration skewness by two and half times (Table 2). The remaining parameters and options were taken as default values. Calibration parameters were generally within recommended ranges other than for critical avalanching slope above water, which was adopted at just below the recommended lower limit. There are no recommended limits on velocity asymmetry adjustment parameter, however, a 2.5 increase above the velocity asymmetry implied by Rienecker and Fenton (1981) appears to be within measurement scatter (Ruessink et al., 2012). The storm erosion estimates were all calculated using an unaltered copy of XBEACH revision 2900 compiled using gfortran 4.5.2 (SUSE Linux) with a Courant–Friedrichs–Lewy time step limit of $CFL < 0.8$. The calibration and validation approach used for SBEACH was repeated for XBEACH (Figs. 5 and 6), where a single event was used to calibrate XBEACH and the remaining events used to validate this calibration.

Validation plots indicate a similar pattern of over and under-estimating beach erosion to that of SBEACH. That is, both models overestimated August 1996, April 1999 while underestimating July 2004 and June 2007. The biggest difference between S/XBEACH validation results is for May/June 1974 storms for which there is no post-storm

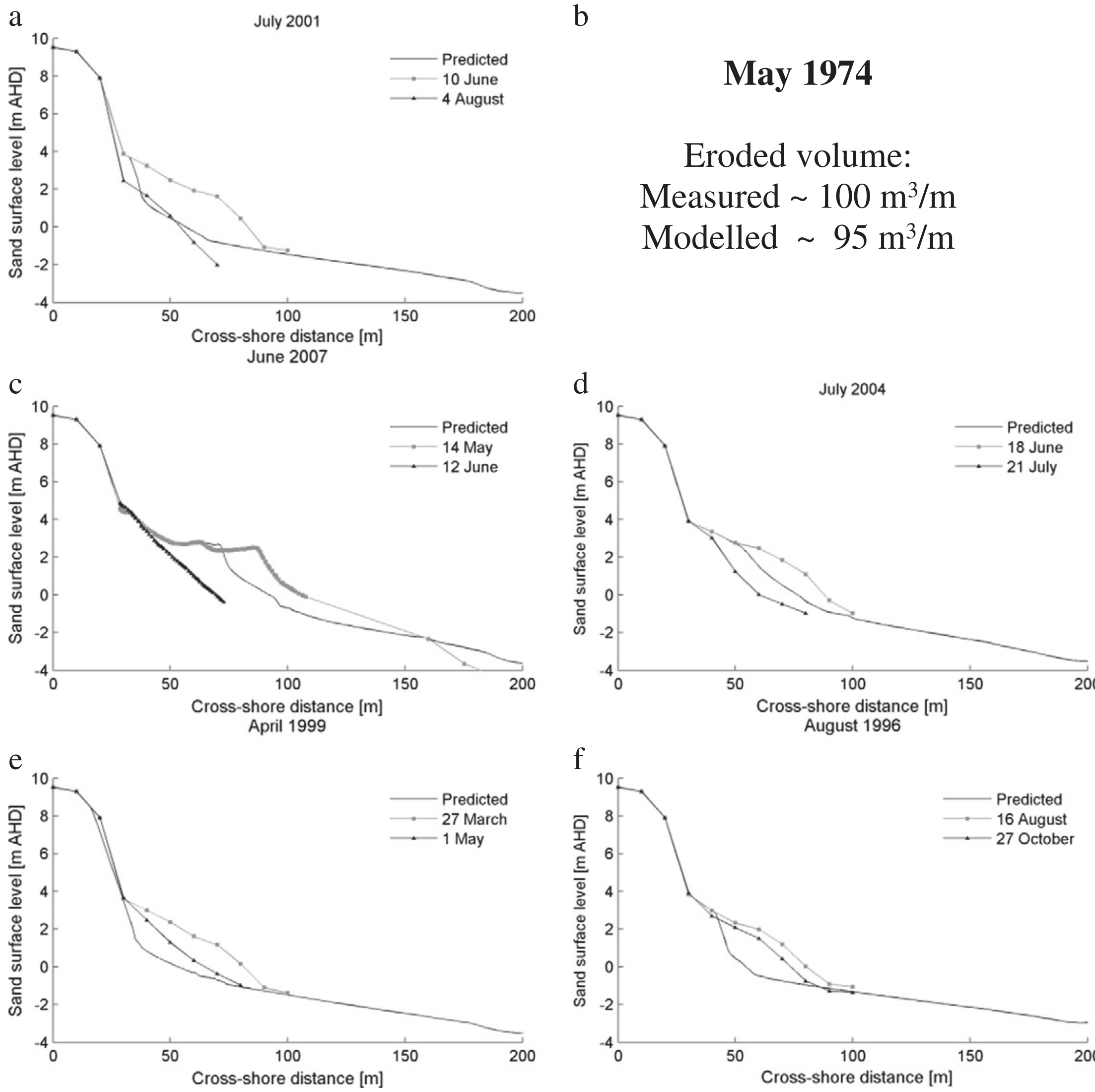

Fig. 4. Narrabeen Beach measured initial and final profiles with SBEACH estimated final profiles for the following validation events; a. July 2001, b. May 1974, c. June 2007, d. July 2004, e. April 1999 and f. August 1996.

profile. XBEACH predicted more than twice the estimated erosion volume of 100 m^3/m whereas SBEACH predicted 95 m^3/m. It would appear that XBEACH requires additional calibration when extrapolating to this storm event. While it is speculative, the XBEACH model maybe generating a flatter surf zone bed slope than that which occurred in nature, allowing significantly more dune erosion (wet and dry avalanching is probably not capturing swash zone dynamics when the bed slope is steep compared to flatter beaches where it has been shown that avalanching handles the swash zone/dune dynamics satisfactory).

The probabilistic model for which XBEACH is being implemented into involves a six parameter distribution. Consequently, the Monte Carlo simulations have to be long in duration (either directly or implied through bootstrapping) to ensure that this six-parameter distribution is adequately sampled in tail regions. At current computational speeds, Kriebel and Dean (1993) and SBEACH—applied directly within the probabilistic simulation (i.e., each storm simulated)—takes less than one hour and approximately 40 days respectively using one processor (Intel Xeon L5520). While it has never been attempted, we estimate applying XBEACH directly in our probabilistic model would take four and a half millennia to complete using one processor—an unfeasible time frame. Consequently, XBEACH was implemented by linearly-interpolating storm erosion values obtained for a pre-run structured grid of beach erosion predictions. Interpolated beach erosion is obtained by

$$\vec{Q}_I = \sum_{i'=0}^{1}\sum_{j'=0}^{1}\sum_{k'=0}^{1}\sum_{l'=0}^{1}\sum_{m'=0}^{1}\left(f_{i,i'}+f_{j,j'}+f_{k,k'}+f_{l,l'}+f_{m,m'}\right)\vec{Q}_{i+i',j+j',k+k',l+l',m+m'} \tag{1}$$

where $\vec{Q}_I$ and $\vec{Q}_{i+i',j+j',k+k',l+l',m+m'}$ are vectors containing the interpolated and tabulated beach erosion respectively, i, j, k, l and m are the locations in the tabulation of beach erosion which is the first point lower than the target position (i.e., five dimensional position of H_s, T_p, D, θ_m, η) and f is the relative position between the target position and table vertices of

$$f_{q,q'} = 1-q' + \left(2q'-1\right)\frac{W_{\text{target}}-W_q}{W_{q+1}-W_q} \tag{2}$$

where W is any of the five quantities (i.e., H_s, T_p, D, θ_m, η) from tabulated storm erosions and q is any of the five indices (i, j, k, l, m) used to defined the tabulation.

Table 2
XBEACH trialled and adopted options and parameters during model calibration to Narrabeen Beach profile measurements for 1997 storm event.

XBEACH key word	Description	Trialled values or option selections	Adopted value or option	Remarks
Break	Wave breaking energy dissipation model	1 or 3, both options use Roelvink (1993) with option 1 (3) excluding (including) local wave height to water depth effects	1	Wave breaking proportional to wave height squared
Roller	Roller energy balance	included or excluded	Included	
Beta	Breaker slope coefficient in roller model	0.1 to 0.35	0.15	Within physical range
Gamma	Relative wave height at breaking	0.35 to 0.75	0.56	Mid of the physical range (Power et al., 2010; Raubenheimer et al., 1996)
hmin	Minimum depth for which flow velocities or sediment concentrations are estimated	0.05 to 0.2 m	0.05 m	Reasonably close to zero
dryslp[a]	Critical avalanching slope above water	0.8 to 1.3	0.6	Just below recommended range
wetslp[a]	Critical avalanching slope under water	0.25 to 0.39	0.3	Within recommended range
hswitchx	Water depth at interface from wet to dry avalanching	0.05 to 0.1 m	0.1 m	Recommended value
facAs	Velocity asymmetry (or acceleration skewness)	0 to 1	0.25	

[a] Facilitates sediment transport from the numerically dry zone into the surf zone, which physically represents transport from either the dune or the high frequency swash zone into surf zone.

Riesenkamp (2011) undertook analysis of how dense the tabulated erosion volumes (i.e., number of XBEACH simulations required to fill the table) should be and found that more detailed tables (up to 8800 entries) were only marginally more accurate as tables with 162 entries. In particular, the 162 tabulation resulted in approximately only a 5% difference in storm erosion volume compared to those estimated using 8800 entries. However, Riesenkamp (2011) provided limited detail regarding this conclusion. The computational saving highlighted here makes implementing XBEACH within our probabilistic model feasible. However, Riesenkamp (2011) analysis did not compare storm erosion probabilities obtained from tabulations of various densities. To check that results are independent of tabulation density, predictions have been obtained from lower density tabulations generated by reducing values used for each parameter individually (Fig. 7A–E & 1875 or full table defined in Table 3). This checks that each parameter has enough definition for independent predictions of tabulation density. Using lessons learnt from these comparisons, we build eight smaller tables and compare the predictions to those from the 1875 or full table to see how much smaller our table can be while not compromising on accuracy (Fig. 7F and Table 3).

The individual parameter tests show that predictions are density independent (black +, blue and green lines agree) for all parameters except for mean wave direction which was slower to converge (black + and blue line agree with green diverging from full at high return periods). The panel legend show the values used when varying each parameter density individually. Consequently, similar predictions to that obtained from the full tabulation are possible using reduced numbers of entries or table density. Eight different tabulations (Table 3) have been tested (Fig. 7F and Table 3), of which, comparable results are obtained for carefully selected parameter values as low as 384 entries. This test included two tabulations comprising of 384 entries, with 384A reducing surge and increasing storm duration densities compared to 384B. It seems reasonable to conclude from this analysis that storm duration is more important at Narrabeen Beach than storm surge. However, this may not be the case at sites which have significantly larger storm surges compared to this beach (e.g., North Sea beaches). These probabilistic results obtained by varying tabulation density provide some guidance for other sites (or erosion models), however, similar tests to these would be needed to ensure predictions are independent of tabulation density.

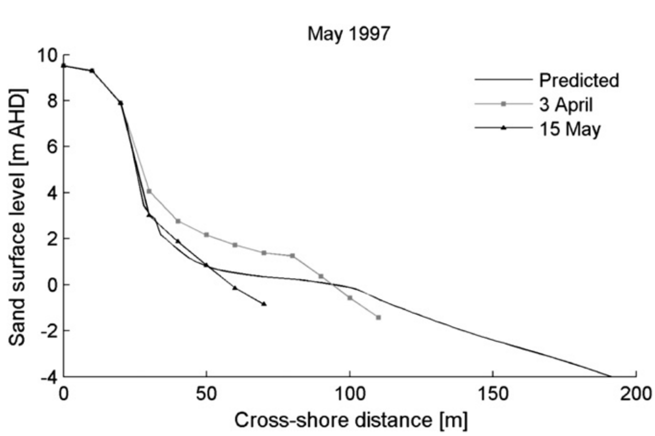

Fig. 5. Narrabeen Beach measured initial and final profiles with XBEACH estimated final profile for the May 1997 event.

While this approach is many orders of magnitude quicker than directly implementing XBEACH into our probabilistic model, computational time to build the 384 entries tabulation, for example, involves around 1000 computing hours using a single processor (significant wall-time reductions are achievable as each entry can be run separately).

XBEACH predictions, shown in section 5 below however, use the 1875 entries or full tabulation as they already exist. Nevertheless, for practical applications, using lower density tabulations (i.e., 384 entries) would save computational time without substantial accuracy losses.

5. Results

The probabilistic model results obtained with the three storm erosion structural function elements of Kriebel and Dean (1993), SBEACH and XBEACH are shown in Fig. 8 along with measurements from Narrabeen beach. Note that the wave propagation model that includes refraction, shoaling, diffraction, wave breaking, bottom friction, wave directional spread and water surface variations was used in all simulation reported herein. All beach change models compare reasonably well with measurements. SBEACH shows a minor overestimation, whereas Kriebel and Dean (1993) shows a slight underestimation for more frequent events (return periods less than approximately 8 years) with the opposite occurring for rare events (low probability events). XBEACH overestimates erosion volumes at all return periods. For this “simple beach”, using an equilibrium approach such as SBEACH appears to have its advantages. However, this may not hold for more complex beaches where equilibrium profile models would be less adaptive than XBEACH.

Despite the absence of a rigorous theoretical argument for an upper limit on storm erosion in the engineering literature, it is reasonable to expect that one would exist on the basis that there is a finite amount of energy available to drive geophysical systems (atmospheric events generating erosion). The XBEACH results do indeed show a break in curvature with the tail shape becoming downward concave for return periods greater than 70 yrs. There are no such indications of downwards concave predictions up to 100 year return period for either Kriebel and Dean (1993) or SBEACH. Kriebel and Dean (1993) show an upwards

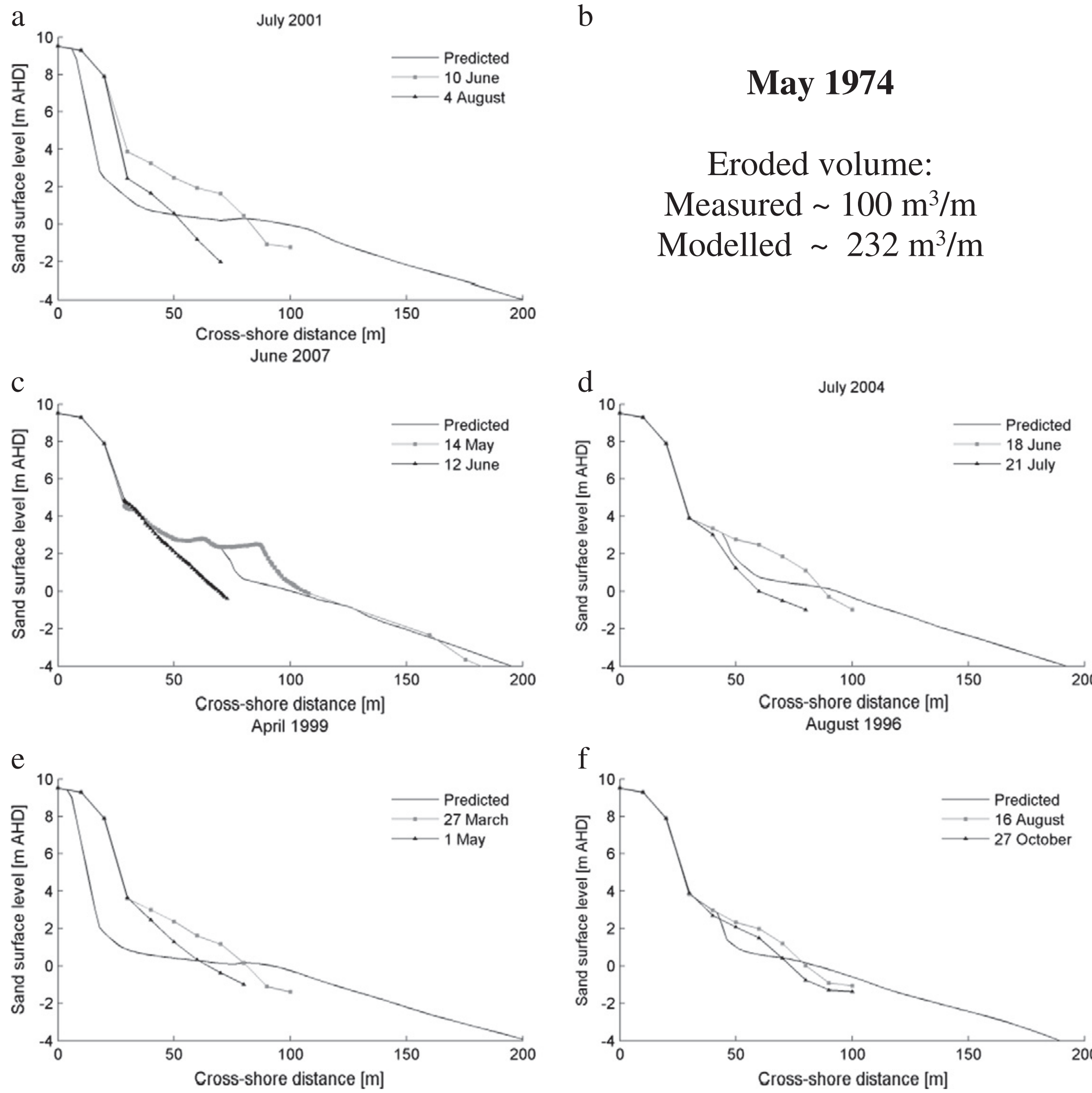

Fig. 6. Narrabeen Beach measured initial and final profiles with XBEACH estimated final profile for the following validation events; a. July 2001, b. May 1974, c. June 2007, d. July 2004, e. April 1999 and f. August 1996.

concave tail and SBEACH shows a linear tail (Fig. 8). The tail shape for SBEACH remains linear for return periods as long as 1 in 1000 year (not shown).

The 95% confidence intervals (Fig. 8) determined by simulating 1000 years of beach erosion repeated 2000 times using bootstrapping techniques (Callaghan et al., 2008b) indicate that they are narrowest for SBEACH and widest for XBEACH for return periods less than 100-years. Kriebel and Dean (1993) fall between S/XBEACH. The confidence intervals obtained with SBEACH are approximately 30% (1 and 100-year) to 50% (20-year) slimmer than those obtained with XBEACH. Similarly, SBEACH confidence intervals are between 0% (2-year) and 35% (20 through to 100-year) slimmer than those obtained with Kriebel and Dean (1993). The probabilistic simulations with Kriebel and Dean (1993), SBEACH and XBEACH enclose up to 52, 97 and 14% respectively of field measurements processed with either block averaging or consecutive volumes approaches above 1in 1 year return period. Therefore, in this application, it appears that SBEACH is the structural function element that provides the most accurate and most robust (least uncertain) erosion estimates.

XBEACH is the only structural function that results in a physically realistic downwards concave shaped tail of the storm erosion volume exceedance curve, while Kriebel and Dean (1993) and SBEACH resulted in upwards concave and linear tail shapes respectively. This is an indication that the limit state physics of storm erosion is better represented by XBEACH and raises the question whether the approach of model calibration against a single storm event is appropriate for this type of probabilistic estimation of storm erosion volumes which necessitates simulating beach response to storm events that maybe far less and far more energetic than the calibration event. Consequently, a different calibration method was devised for XBEACH. This method (Fig. 9) uses all the empirical estimates in the calibration. An XBEACH model (defined by its parameters) is assumed, and then the statistical simulation is undertaken and the extreme beach erosion estimates are compared to the measurements. At sites which do not have empirical erosion statistics (i.e., similar measurements to Narrabeen Beach), where this calibration approach would be impossible, a series of key events (small to large with return periods estimated) could be used to calibrate XBEACH in a similar but less rigorous manner.

When XBEACH is calibrated using the above alternate approach (note: all model parameters were the same as those adopted in the single event based calibration excepting the breaking index which was reduced to 0.5 from 0.56), erosion volume predictions are more consistent with measurements for return period less than 10 years, while overestimation is shown for greater return periods. This approach preserves the previously

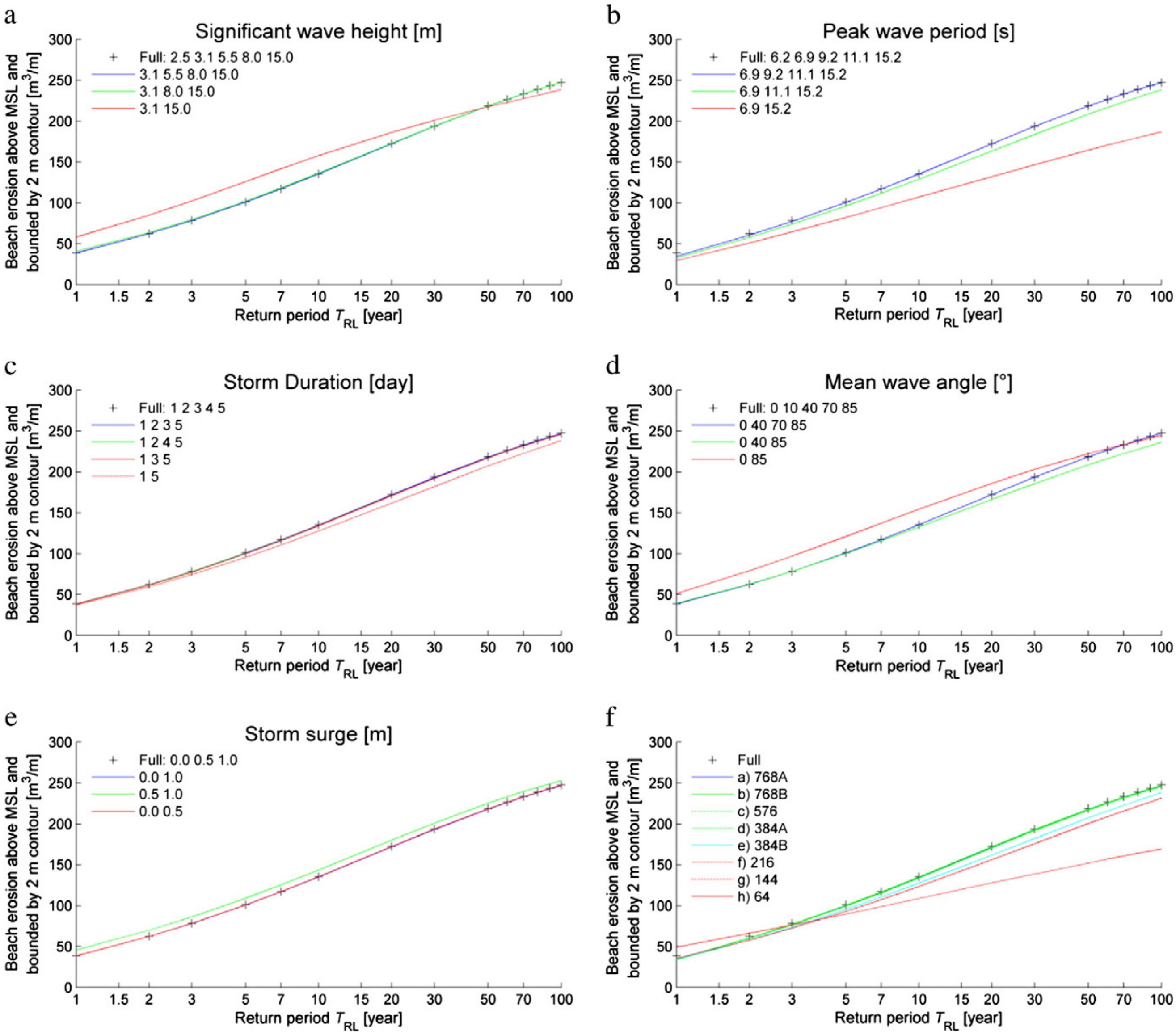

Fig. 7. The eroded sand volume above MSL at Narrabeen Beach from simulating 1000 years of beach erosion repeated 2000 times to ensure probabilistic model converged using various XBEACH (Roelvink et al., 2009) tabulations against return period. The black crosses (+) result from using 1875 entries or full tabulation defined by Table 3 with table density decreasing from black crosses to blue, to green, to cyan and to red, with panels A through to E reducing tabulation density in forcing parameter of A) significant wave height [m], B) peak wave period [s], C) storm duration [day], D) mean wave angle [° shore normal] and E) storm surge [m] with selected values for various tables used for that parameter shown in each legend. Panel F) simultaneously reduces several forcing parameters with legend showing each tabulation size (complete definition is given in Table 3). In cases where predictions with lower densities are the same as those from higher densities, the lower density colour is shown (i.e., plotted from highest density to lowest density).

observed downward concave tail shape and also results in slightly slimmer 95% confidence intervals at lower return periods than before, with SBEACH confidence intervals now being approximately 44% (20-year) slimmer than those obtained with XBEACH. The percentage of field measurements enclosed by 95% confidence intervals of the probabilistic simulation with XBEACH increases to 90% (previously 14%). Therefore, this alternate calibration approach for XBEACH raises the accuracy and robustness of the probabilistic estimates of storm erosion volumes obtained with XBEACH to be on par with those obtained with SBEACH (Fig. 10).

Table 3
Tabulation definitions used for beach erosion estimations[a]. The highlighted column defines lowest tabulation density able to reproduce similar results to the full tabulation.

Storm parameters	Number of tabulation entries								
	1875 or Full	768A	768B	576	384A	384B	216	144	64
Significant wave Height Hs [m]	2.5, 3.1, 5.5, 8, 15	3.1, 5.5, 8, 15	**768A**	**768A**	**768A**	**768A**	3.1, 8, 15	**216**	2.5, 15
Peak wave period Tp [s]	6.2, 6.9, 9.2, 11.1, 15.2	6.9, 9.2, 11.1, 15.2	**768A**	**768A**	**768A**	**768A**	6.9, 11.1, 15.2	**216**	6.2, 15.2
Storm duration D [day]	1, 2, 3, 4, 5	1, 3, 4, 5	1, 2, 3, 5	1, 3, 5	**576**	1, 5	1, 5	**216**	1, 3
Mean wave Direction θm [°]	0, 10, 40, 70, 85	0, 10, 40, 85	**768A**	**768A**	**768A**	**768A**	**768A**	**768A**	**768A**
Surge, R [m]	0, 0.5, 1	All	All	All	0, 1	All	All	0, 1	0, 1

[a] Bold entries indicate that parameter values implemented are the same as those in the table indicated by the bold text.

6. Conclusions

The contemporary demand for risk based coastal zone management requires probabilistic frameworks for estimating coastal storm erosion volumes. The first such probabilistic framework was presented by Callaghan et al. (2008a) and has since undergone a number of developments including changing the structural function that calculates storm erosion in response to storm forcing (Fig. 1). Further changes include a better wave propagation model and different storm erosion models ranging from the analytical Kriebel and Dean (1993) model, the more

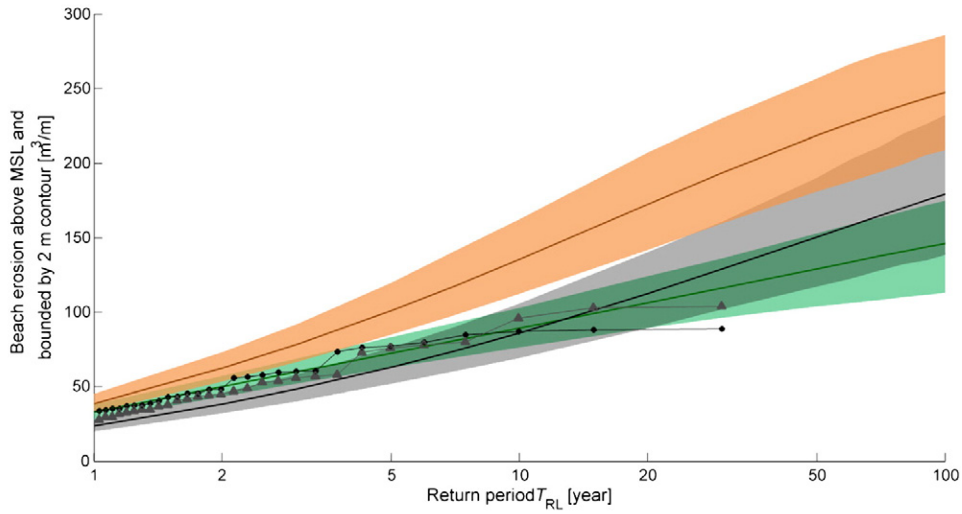

Fig. 8. The eroded sand volume above MSL at Narrabeen Beach from; profile measurements (empirical estimates by block averaging and consecutive volumes); and simulating 1000 years of beach erosion repeated 2000 times to ensure convergent predictions for Kriebel and Dean (1993) (continuous black line), SBEACH (Larson, 1988, continuous green line) and XBEACH (Roelvink et al., 2009, continuous orange line). Shaded areas are estimated 95% confidence intervals calculated by bootstrapping techniques.

complex semi-empirical SBEACH model and the highly complex and process-based XBEACH model. This study was undertaken to assess the relative performance of the 3 above mentioned storm erosion models when embedded within Callaghan et al.'s (2008a) probabilistic framework for estimating storm erosion. With this aim, the probabilistic model was applied at Narrabeen beach, Australia where over 30 years of field measurements of wave, water level, and profile data exist.

Prior to using SBEACH and XBEACH within the probabilistic model, both beach erosion models were first calibrated against the mid-range May 1997 storm, and validated against a number of other smaller and larger storms. While the calibration comparisons were good, the validation comparisons ranged, for both models, from poor to good. The Kriebel and Dean (1993) model was used as recommended by its authors and consequently did not require calibration.

Kriebel and Dean (1993) and SBEACH was used in the probabilistic simulations directly (i.e., probabilistic simulation generates the storm event and then Kriebel and Dean (1993) or SBEACH was used 'on-line' to determine the resulting storm erosion for each storm). This 'on-line' approach was impossible with XBEACH using contemporary computing technology. Therefore, to facilitate XBEACH estimates, a tabulation approach was devised and tabulation densities were tested to obtain guidance on optimal tabulation density to ensure that probabilistic model predictions are independent of the method. This testing indicated that a modest tabulation density of about 400 entries would suffice, which still requires about 1000 computing hours on a standard processor.

For this simple beach, SBEACH provided the most accurate and robust probabilistic estimates of storm erosion. However, only XBEACH predicted storm erosion volumes with the physically more plausible behaviour of a downward concave tail shape when plotted as cross-shore beach-erosion volume on a vertical linear axis against return period on a horizontal logarithmic axis. SBEACH displayed a linear tail shape while Kriebel and Dean (1993) resulted in a concave upwards tail shape.

As the relatively poor performance of the process-based XBEACH model raised the question whether calibration to a single event is appropriate for this type of probabilistic simulations, XBEACH was subsequently calibrated using all empirical erosion volume estimates. When the XBEACH model calibrated using this alternate approach was used in the probabilistic model, the results improved significantly raising the accuracy and robustness of the probabilistic estimates of storm erosion volumes obtained with XBEACH to be on par with those obtained with SBEACH.

The simulation time (on a standard single processor) when using the simple Kriebel and Dean (1993) model was about 1 day, whereas for SBEACH (on-line) and XBEACH (tabulation) the simulation time was about 1000 h; a very significant increase. However, the additional computational cost required with SBEACH or XBEACH is justified by the physically more plausible, more accurate and robust results that would result.

Acknowledgments

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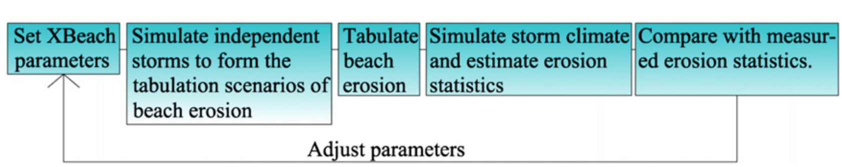

Fig. 9. Alternative XBEACH calibration approach using empirical beach erosion statistics (i.e. using many events to calibrate).

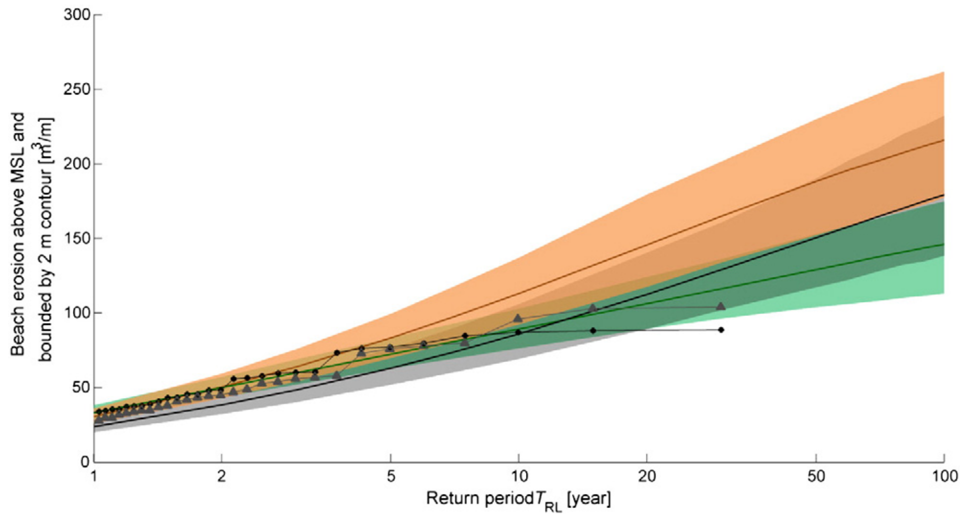

Fig. 10. The eroded sand volume above MSL at Narrabeen Beach from; profile measurements (empirical estimates by block averaging and consecutive volumes); and simulating 1000 years of beach erosion repeated 2000 times to ensure convergent predictions for Kriebel and Dean (1993, continuous black line), SBEACH (Larson, 1988, continuous green line) and XBEACH (Roelvink et al., 2009, continuous orange line) using the alternate calibration procedure using empirical beach erosion statistics. Shaded areas are estimated 95% confidence intervals calculated by bootstrapping techniques.

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