DOES A MORE SOPHISTICATED STORM EROSION MODEL IMPROVE PROBABILISTIC EROSION ESTIMATES?

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Abstract

The dependency between the accuracy/uncertainty of storm erosion exceedance estimates obtained via a probabilistic model and the level of sophistication of the structural function (storm erosion model) embedded in the probabilistic model is assessed via the application of Callaghan et al.'s (2008) Joint Probability Model (JPM) at Narrabeen beach, Australia with three different structural functions: (a) Kriebel and Dean (1993) (analytical); (b) SBEACH (semi-empirical); and (c) XBeach (fully process based). Results indicate that the accuracy is greatest for JPM-SBEACH and lowest for JPM-XBeach. The most uncertain results are given by JPM-XBeach while the most robust results are given by JPM-SBEACH. Thus, it appears that increasing the level of sophistication of the structural function beyond the semi-empirical SBEACH model, may not always lead to better results and may even be counter-productive.

Key words: storm erosion, probabilistic model, XBeach, SBEACH, Kriebel and Dean, Narrabeen

1. Introduction

The coastal zone is the most heavily populated and developed land zone in the world. The insatiable human attraction to the coast has resulted in rapid expansions in settlements, urbanization, infrastructure, economic activities and tourism in the 20th century and is likely to continue to increase in the 21st century. Thus, future coastal hazards such as storm erosion will result in massive losses, may they be tangible or intangible.

To avoid such losses, it is imperative that risk informed and sustainable coastal planning/management strategies are developed and implemented sooner rather than later. This requires comprehensive coastal risk assessments which combine state-of-the-art consequence (or damage) modelling and coastal hazard modelling. However, generally applicable coastal risk assessment approaches have not been developed to date. This is mainly due to two reasons: a lack of vision and initiative within the coastal engineering/management/planning sectors, and the lack of numerical models that can provide accurate, probabilistic estimates of potential coastal hazards at spatio-temporal scales relevant for coastal zone planning/management (tens of kilometers and decades).

While the damage caused by storm erosion and protecting coasts can be very costly, so is foregoing land-use opportunities in coastal regions. Developing appropriate policies and strategies for land-use planning purposes is therefore a balancing act. A ‘zero risk’-policy would often have severe economic consequences. On the other hand, high risk policies could lead to risks that are unacceptable to society and individuals. Efficient and socially acceptable coastal zone management/planning thus require the optimisation of risk via comprehensive risk assessments. While risk based management/planning has been common practice in spheres such as flood protection, inexplicably, this way of thinking has only recently emerged in coastal zone management/planning. Historically, far reaching coastal management/planning decisions have been made based only a single extreme hazard estimate with no consideration given to the uncertainty in the hazard nor the potential consequences (damage) caused by the hazard. More often than not, this has led to very conservative management/planning decisions which, ultimately, have resulted in

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forgoing lucrative land-use opportunities (Jongejan et al., 2011). Apart from being of crucial importance to coastal managers/planners, this type of risk quantification will also be invaluable to the insurance and re-insurance industries for the determination of optimal insurance premiums, which will undoubtedly have a follow-on effect on coastal property values. Ultimately, the question that decision makers will have to address is 'how safe is safe enough?'.

Emerging contemporary risk based coastal management/planning frameworks therefore require probabilistic estimates of storm erosion to facilitate risk informed decisions (e.g. to establish coastal setback lines) (Jongejan et al., 2011). Thus, the traditional approach of forcing a process based model with design storm conditions (e.g. 1 in 100 yr storm wave height, worst recorded storm in history) to obtain a single deterministic estimate of storm erosion is no longer sufficient. Probabilistic estimates of storm erosion that also take into account the stochastic nature of coastal forcing, and preferably climate change impacts, are now increasingly being sought by coastal zone managers/planners. Callaghan et al. (2008) presented an innovative statistical model (Joint Probability Model - JPM) that could provide such probabilistic storm erosion estimates.

The JPM involves fitting marginal and conditional distributions to long time series of wave and water level data and subsequently temporally simulating the dominant forcing parameters for cross-shore beach erosion to obtain a storm time series via a Montecarlo approach (**Erreur ! Source du renvoi introuvable.**, orange elements). This storm time series is then used by a structural function (Figure 1, green-dashed box) to obtain a time series of cross-shore beach erosion volumes, which is post-processed to derive erosion probabilities (or erosion exceedance statistics).

The JPM is implemented as follows (see also Figure 1):

1. Assume first storm event at time t
2. Generate random realizations of H_s(storm wave height), D(storm duration), T (storm wave period), θ_p (wave direction), R_s (tidal anomaly) for the storm using data-fitted distributions
3. Transfer the offshore wave climate to nearshore (using the wave model SWAN)
4. Estimate beach erosion using structural function
5. Determine beach recovery till next storm using an exponential function
6. Repeat (2) to (5)

With a very conservative estimate of 5 storms per year, a 1000 year JPM simulation will require 5000 simulations of the structural function (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 JPM needs to be carefully evaluated. This study was undertaken to investigate whether increasing the level of sophistication of the structural function improves the predictive accuracy and/or reduces the uncertainty introduced due to stochastic forcing.

2. Methods

The JPM was applied to Narrabeen beach, Sydney, Australia (Figure 2), located about 20 km North of Sydney. The availability of over 30 years of concurrent wave, water level, and most importantly, monthly beach profile data makes Narrabeen beach an ideal site for this study. Narrabeen Beach has been regularly surveyed since 1976 using eight profiles taken at approximately monthly intervals using the Emery method. The Emery survey approach, as implemented at Narrabeen, 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.

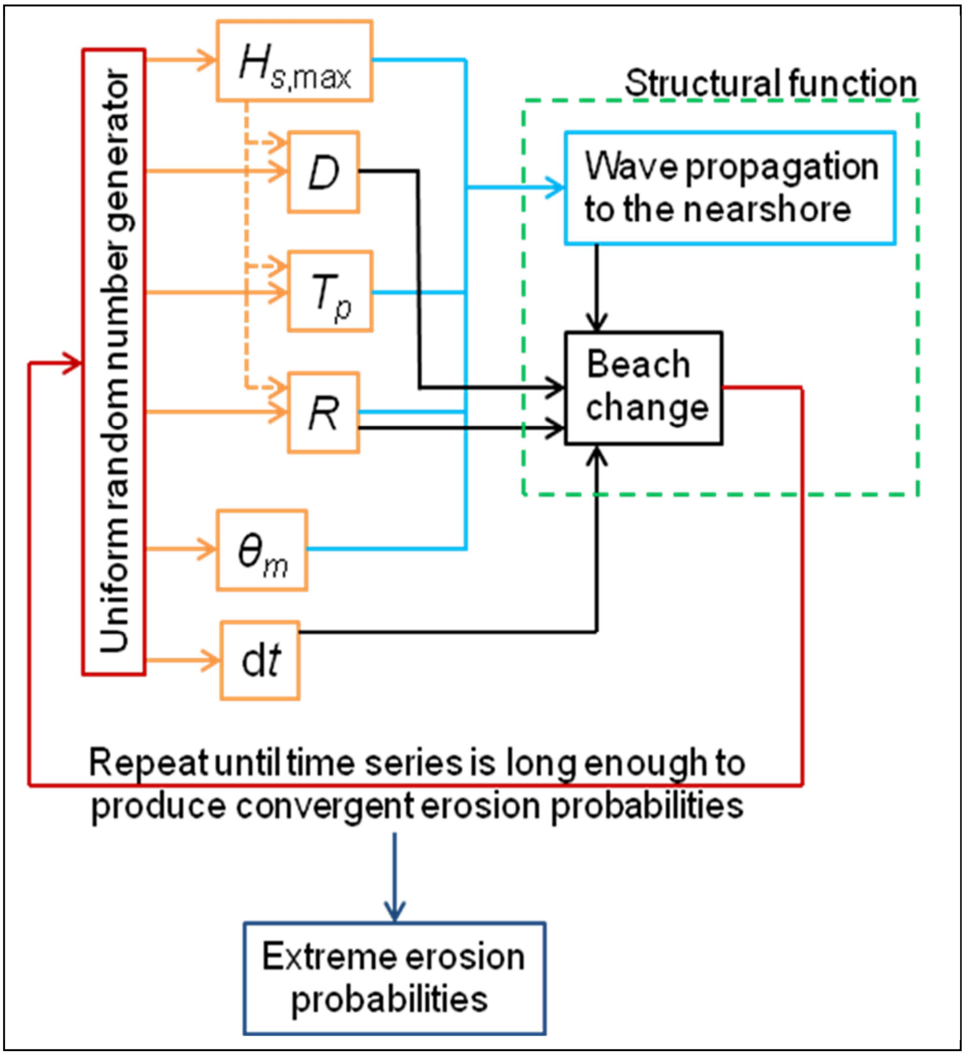

Figure 1. Flow chart showing the operational structure of the JPM (Callaghan et al., 2008). The model employs the Joint Probability Method (red and orange elements) for estimating synthetic storms, a structural function to estimate cross-shore beach change (elements within the green dashed box). The resulting beach changes are used to estimate beach erosion probabilities. 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).

Narrabeen Beach is also subjected to beach rotations 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) quantified the magnitude and the arrangement of this beach rotation from field measurements and concluded that profile four (at the centre of the embayment) 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 the cross-shore processes will dominate long-shore processes.

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 (**Erreur ! Source du renvoi introuvable.**b). 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 (waves approaching steepness limit) 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—, **Erreur ! Source du renvoi introuvable.**b).

In this study the JPM was applied to Narrabeen beach with three different structural functions with varying levels of complexity: (a) The Kriebel and Dean (1993) model (analytical); (b) SBEACH (semi-empirical) (Larson and Kraus, 1989); and (c) XBeach (fully process based) (Roelvink et al., 2009). The computational effort required increases exponentially from the Kriebel and Dean (KD93) model to SBEACH to XBeach. The values for the free parameters in KD93 were obtained from field observations while both SBEACH and XBeach were calibrated and validated against measured storm forcing/response at Narrabeen beach.

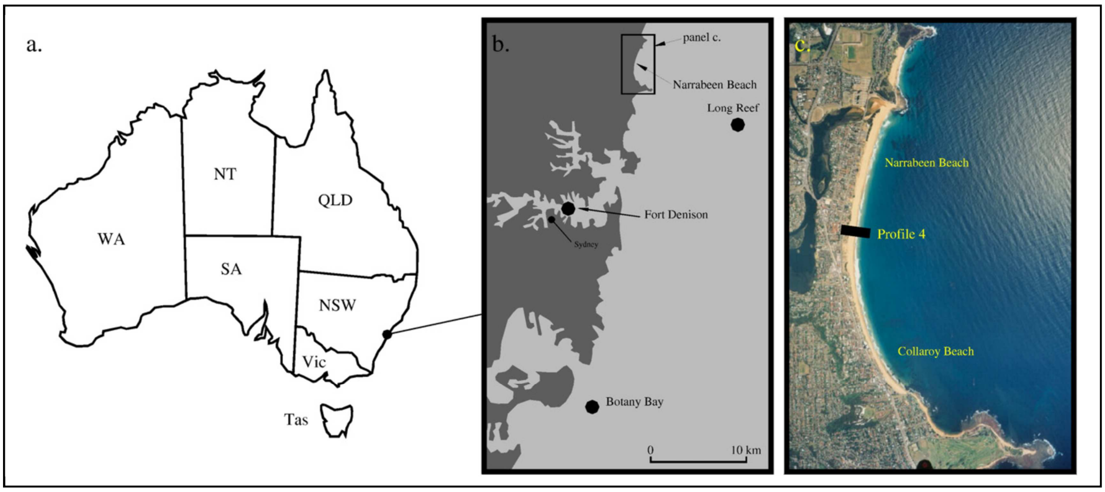

Figure 2. Narrabeen Beach and measurements locality maps. a. location of Sydney within Australia; b. the Botany Bay and Long Reef wave buoy locations and the Fort Denison tidal recording station; and c. the location of long term beach profile surveys at Narrabeen Beach (profile 4)

The May 1997 storm was selected as the calibration event for both SBEACH and XBeach as it is a mid-range eroded volume (of the extreme erosion events recorded since 1974 - see Table 1) coastal storm. Consequently, validation tests assess model performance for lesser and greater eroded volume coastal storms. SBEACH and XBeach calibrations are shown in Figure 3 and 4 respectively.

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

Event	Erosion[1] [m^3/m]	Peak $H_{s,\max}$ [m]	Rank	
			Erosion	Wave Height
July 2001	104	8.4	1	3
May 1974	100[2]	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

[1]erosion amount is the volume change above mean sea level and bounded by the 2 m contour as used by *Callaghan et al.* (2008a).

[2]erosion volume estimated from *Hoffman and Hibbert* (1987) as there is no post-storm profile survey available.

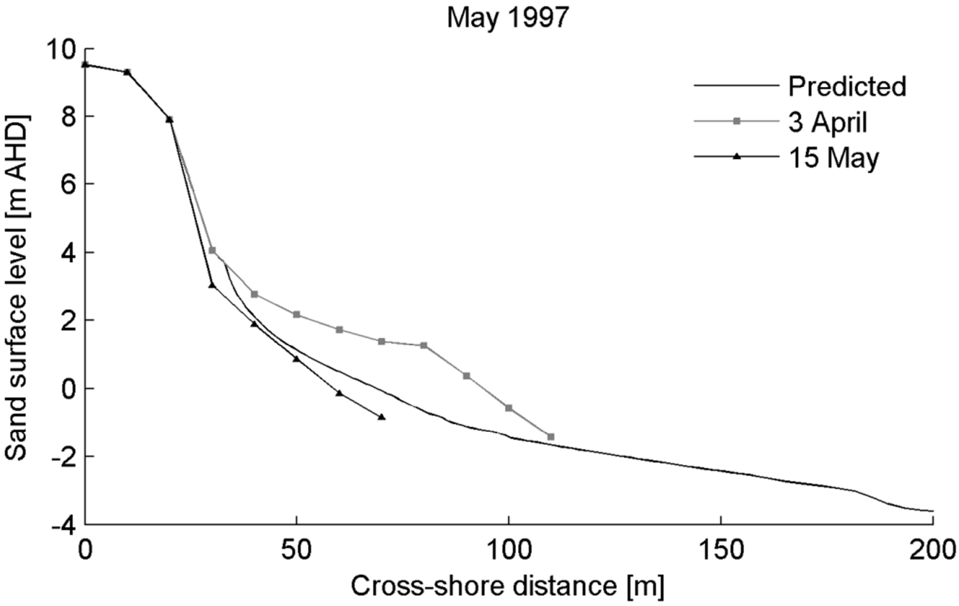

Figure 3. SBEACH calibration result for the May 1997 storm

After calibration, both models were validated against the remaining 6 recorded extreme erosion events (Figures 5 and 6). Note that there is no post-storm measured profiles for the 1974 storm, the most extreme storm ever recorded, and hence for this event only the estimated and modelled erosion volumes were compared. Both models perform reasonably well providing confidence in the single event calibration.

At current computational speeds, Kriebel and Dean (1993) and SBEACH—applied directly (or online) within the probabilistic JPM 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 online within the JPM would take four and a half millennia to complete using one processor—an unfeasible time frame. Consequently, XBeach was implemented via linearly-interpolated cross-shore beach erosion values obtained for a pre-run tabulation of beach erosion predictions. Tabulations consisting of 1875 to 64 entries (representing the various possible combinations and permutations of the five (5) main variable forcing parameters (H_s,T_p,D,θ_m,R) were systematically tested to determine the optimum number of table entries, which in this case appeared to be 384. While this approach is many orders of magnitude quicker than implementing XBeach online into the JPM, the computational time to build the 384 entries tabulation still involves around 1,000 computing hours using a single processor.

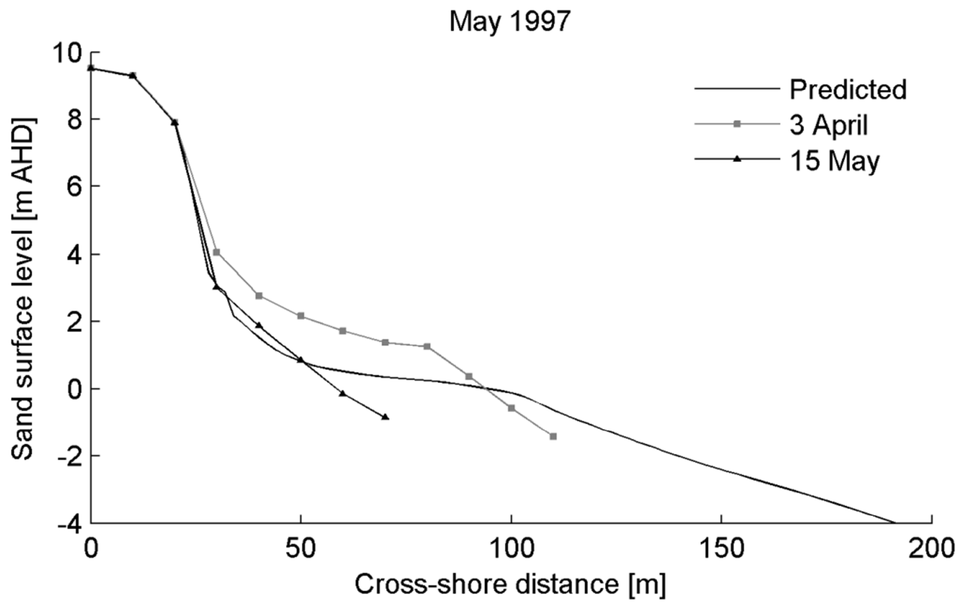

Figure 4. XBeach calibration result for the May 1997 storm

3. Results

To ensure convergence at the 100yr ARI erosion volume, all JPM computations were continued for 1000 years. Each 1000 year simulation was repeated 2000 times (bootstrapping) to enable the computation of confidence limits. The recurrence intervals (from 1 to 100 ARI) of storm erosion volumes predicted by the 3 different structural functions are shown in Figure 7. All beach change models compare reasonably well with measurements. SBEACH results in 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 measurements at all return periods.

The 95% confidence intervals developed by simulating 1,000 years 2,000 times indicate that they were narrowest for SBEACH and widest for XBeach for return periods less than 100-years. KD93 falls 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 to 100-year) slimmer than those obtained with KD93. The probabilistic simulations with KD93, SBEACH and XBeach enclose 52, 97 and 14% respectively of field measurements.

Intuitively an upper limit should exist for storm erosion, although this has never been proven. The JPM-XBeach exceedance curve does show a downward concave tendency in the tail shape for ARI events beyond 70 years supporting the existence of such an 'ultimate erosion volume'. There are no indications of downwards concave predictions up to 100 year return period for either JPM-KD93 or JPM-SBEACH. JPM-KD93 shows an upwards concave tail and JPM-SBEACH shows a linear tail.

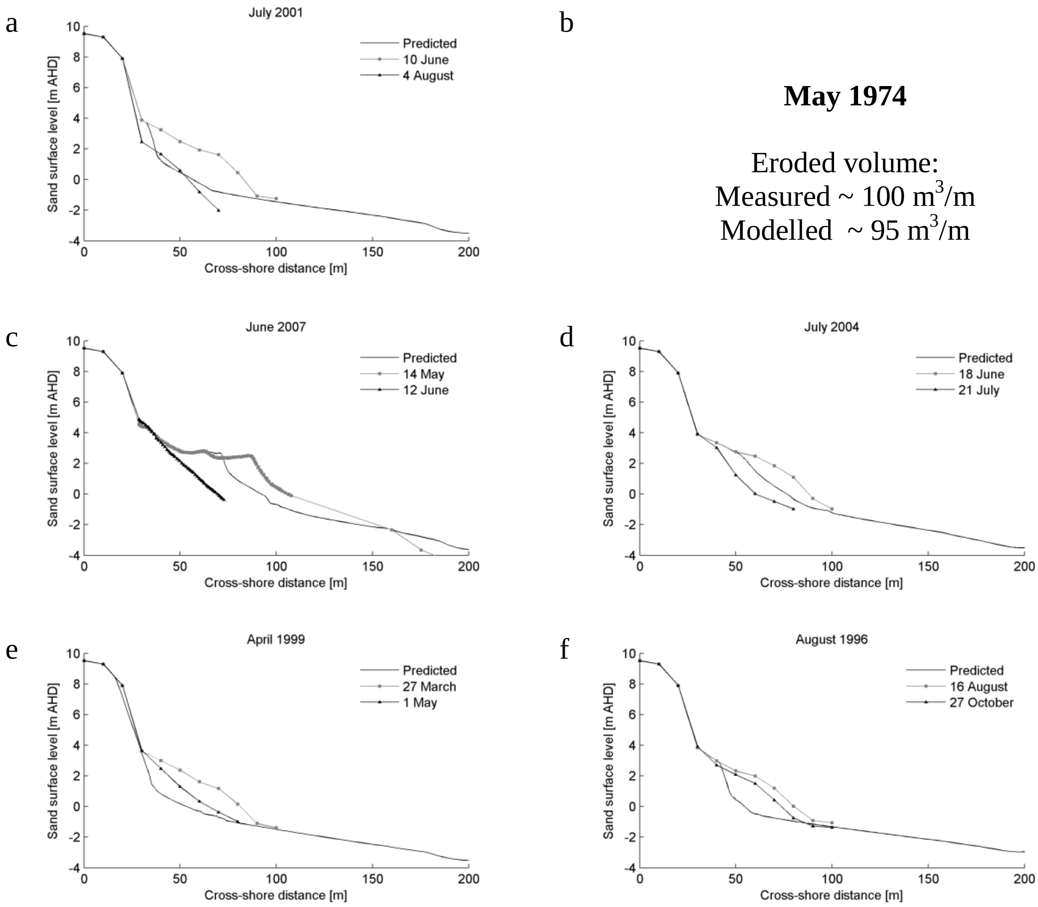

Figure 5. Narrabeen Beach measured initial and final profiles with estimated final profile using SBEACH for the following validation events; a. July 2001, b. May 1974, c. June 2007, d. July 2004, e. April 1999 and f. August 1996

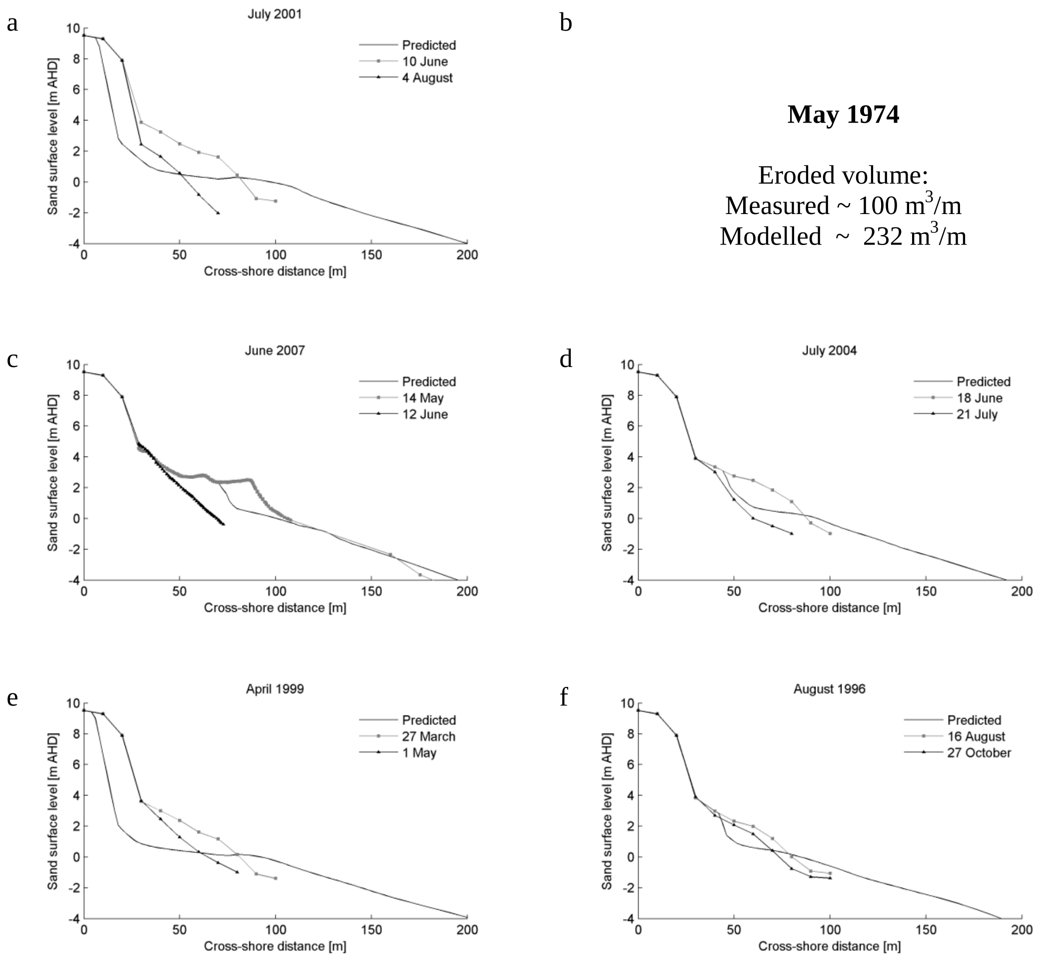

Figure 1. Narrabeen Beach profile four measured initial and final profiles with estimated final profile using XBeach for the following validation events; a. July 2001, b. May 1974, c. June 2007, d. July 2004, e. April 1999 and f. August 1996

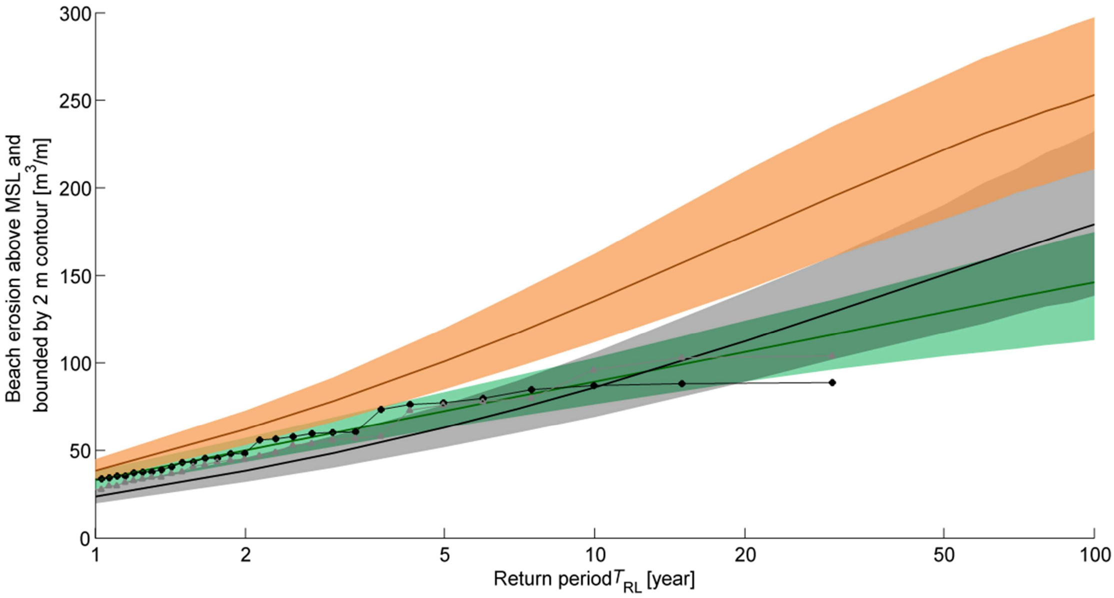

Figure 7. The eroded sand volume above MSL at Narrabeen Beach from; profile measurements (empirical estimates by block averaging —▲— and consecutive volumes —●—); and simulating 1,000 years 2,000 times to ensure convergent predictions for *Kriebel and Dean* (1993, continuous black line), SBEACH (*Larson and Kraus*, 1989, continuous green line) and XBEACH (*Roelvink et al.*, 2009, continuous orange line). Shaded areas indicate the estimated 95% confidence intervals calculated by bootstrapping techniques.

4. Conclusions and future outlook

The accuracy and uncertainty associated with probabilistic predictions of storm erosion volumes obtained when using structural functions (in this case, storm erosion model) with low, medium and high levels of sophistication were assessed by embedding 3 different structural functions the Joint Probability Model (JPM) presented by Callaghan et al. (2008) at Narrabeen Beach, Sydney, Australia. The three different structural functions adopted are: (a) The Kriebel and Dean (1993) model (analytical); (b) SBEACH (semi-empirical); and (c) XBeach (fully process based). The computational effort required for JPM simulations increases exponentially from the Kriebel and Dean (KD93) model to SBEACH to XBeach.

SBEACH and XBeach nmodels were first calibrated against the May 1997 beach erosion storm, and validated against a number of other smaller and larger beach erosion storms. While the calibration comparisons were good, the validation comparisons ranged, for both models, from poor to good. KD93 was used as recommended by its authors and consequently was not calibrated.

The JPM application indicates that the accuracy is greatest for JPM-SBEACH and lowest for JPM-XBe ach. The uncertainty of the predictions, shown by the 95% confidence limits, indicate that the most uncertai n results are given by JPM-XBeach while the most robust results are given by JPM-SBEACH. Thus, at leas t in this application it appears that increasing the level of sophistication of the structural function, at a signif icant computational cost, beyond that of the semi-empirical SBEACH model, is not only unnecessary but is even counter-productive.

However, XBeach is the only structural function that resulted in a physically realistic downwards concave shaped tail of the storm erosion volume exceedance curve, while KD93 and SBEACH resulted in upwards concave and linear tail shapes respectively. This an indication that the limit state physics of storm erosion are 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. Investigations are presently being undertaken to determine whether an alternative calibration approach for XBeach may yield improved results for the JPM-XBeach approach.

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