MODELING BEACH PROFILE EVOLUTION – A STATISTICAL–PROCESS BASED APPROACH

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This paper presents a new combined statistical-process based approach for modeling storm driven, cross-shore beach profile response. The approach discussed here involves combining detailed statistical modeling of offshore storm data and a process based morphodynamic model (XBeach), to assess the medium to long-term morphodynamic response of cross-shore beach profiles. Up until now the use of process-based models has been curtailed at the storm event timescale. This approach allows inclusion of the post-storm recovery, in addition to individual event impacts, thus allowing longer-term predictions. The calibration of XBeach for modeling, both, storm induced erosion and post-storm recovery, taking Narrabeen Beach, NSW, Australia as a case study; and the approach used to combine XBeach with the statistical framework to develop the approach are discussed.

Keywords: extreme storm statistics; XBeach; erosion and accretion; morphodynamics; medium-term beach change

INTRODUCTION

As the use of process-based morphodynamic models is becoming more prevalent within coastal engineering research, there is requirement for the time constraints associated with such models to be extended. This paper discusses how a statistical framework is combined with the process-based model XBeach (Roelvink et al., 2009), to form the statistical-process based approach (SPA). The SPA is a novel approach that allows successful use of a process-based model to forecast beach change beyond storm event time scales.

Quantifying beach morphodynamic variability using a benchmark 1:*N* year event has inherent limitations. Hawkes et al., (2002) show that, for a forcing system with two or more variates, the return period of the individual variates do not necessarily match those of the results. The formation of a new equilibrium profile requiring a finite time, meaning erosion is dependent on duration (Kriebel and Dean, 1993), is one such reason for the difference. A benchmark event is also unable to account for two (or more) storms occurring in quick succession and effectively merging into one erosive event. Should this occur, there is greater erosive impact on the beach than if separated by a time sufficient enough to allow for natural recovery (accretion). In order to combat these issues, Callaghan et al., (2008) developed a statistical framework for modeling extreme storm climate, known as the Full Temporal Simulation (FTS). Their model combines the multivariate statistical modeling of individual storm events with a non-homogeneous Poisson process for modeling event spacing. Inclusion of event spacing allows for the prediction of a time series of storm (erosion) events and calm (accretion) periods, leading to a more accurate quantification of beach change. Ranasinghe et al., (2011) used the FTS model along with a simplified dune erosion model (Larson et al., 2004) to estimate dune erosion at Narrabeen Beach over a 110 year period, incorporating sea level rise. In this approach, offshore wave forcing conditions are transformed to the nearshore using a SWAN model and the post-storm recovery of the dune is determined by empirical means.

By breaking down the time series generated by the FTS, and modeling erosive and accretive events individually and in sequence, the SPA allows for the use of a process-based model for predicting beach variability at longer time scales.

This paper will describe the calibration and validation of XBeach, at Narrabeen Beach, NSW, Australia, and the combination with the FTS to form the SPA. The use of XBeach for modeling, both, erosion and accretion means that, unlike the empirical structural functions used by Callaghan et al., (2008) and Ranasinghe et al., (2011), the SPA will provide a fully numerical model of medium-term beach variability by including antecedent beach profiles. Validation of the full SPA is not demonstrated in this paper as the primary aim is to describe the procedure and show effective XBeach calibration.

FIELD SITE

Narrabeen Beach is located approximately 20 km north of Sydney, NSW, Australia (Figure 1). It is a 3.6 km long embayed beach that experiences semi-diurnal, microtidal conditions with a mean spring tidal range of approximately 1.25 m (Short, 1984). The region is subjected to highly variable, moderate

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to high energy wave conditions as the wave climate is driven by cyclonic sources with storms reaching the beach throughout the year (Short and Trenaman, 1992; Short, 2006).

The sediment are quartz and carbonate sands with median diameter (D_{50}) ranging from 0.25 to 0.50 mm (Wright and Short, 1984). The morphodynamic variability has been regularly and extensively monitored during the last few decades with beach profiles being surveyed at five locations (Figure 1) along the beach by the Coastal Studies Unit, University of Sydney (Short and Trembanis, 2004). The beach profiles surveyed at section 4, where long term longshore transport effects are minimal (Ranasinghe et al., 2004), are used in the present study.

Wave data collected between 1981 and 2006, offshore of Botany Bay (Fig. 1) at a water depth of 85 m, using a waverider buoy have been used in this study. During the recording period the mean H_s and T_s were approximately 1.5m and 10s respectively, with the overall wave climate being highly variable. More information on the NSW wave climate can be found in Harley et al., (2010); Kulmar et al., (2005); Lord and Kulmar, (2000); Short and Trenaman, (1992).

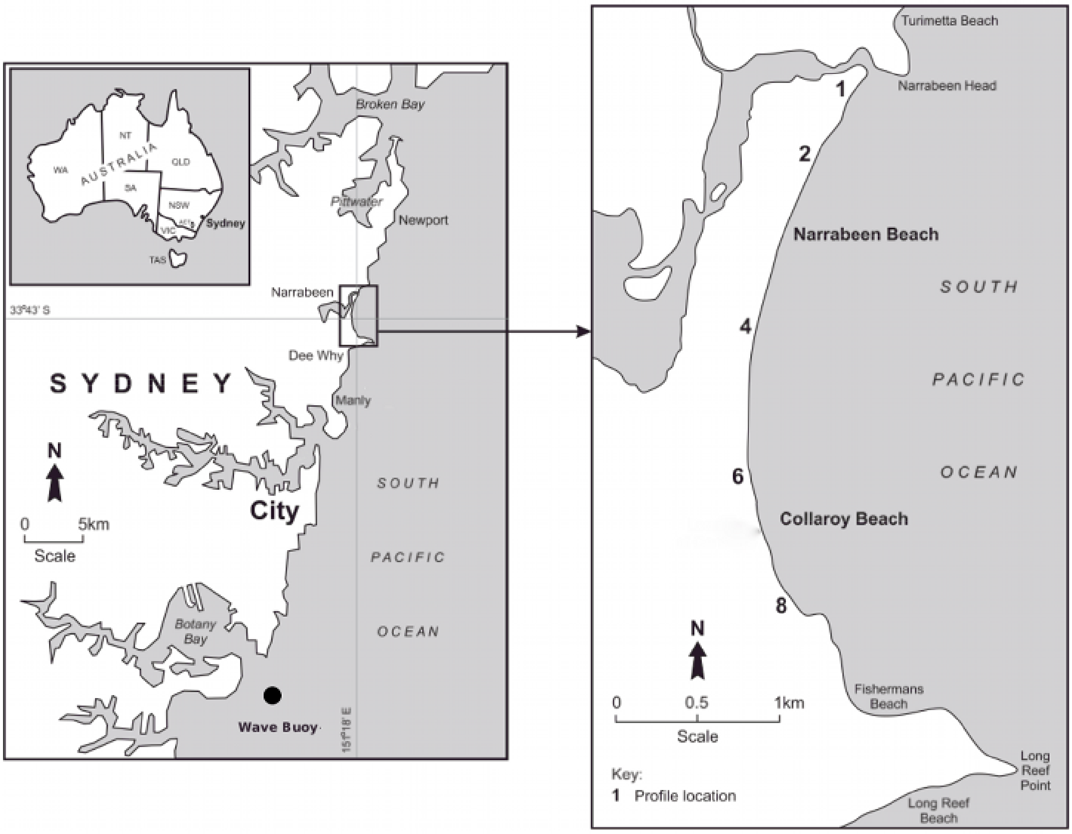

Figure 1. Location of Narrabeen Beach, waverider buoy and measured profiles. Modified after Harley et al., (2010)

STATISTICAL MODELING OF NARRABEEN STORM CLIMATE

Statistical modeling of the storm climate at Narrabeen Beach follows the FTS procedure developed by Callaghan et al., (2008). An overview of the FTS procedure used in the present study is given here with this approach differing from that used by Callaghan et al., (2008) by fitting pairs of peak significant wave height ($H_{s,max}$), of the storm events, and the corresponding period ($T_{s,max}$) rather than pairs of H_s and T_s. This modified FTS therefore requires data of individual storm events only. These data are $H_{s,max}$, $T_{s,max}$, duration (D) and spacing (S) between the events. These storms are abstracted from the wave data time series by clustering data into individual events. This was achieved using a threshold wave height of 3.0m (Kulmar et al., 2005); a criterion of 24 hours to ensure event independence; and a minimum storm duration of one hour. Following this approach, 539 storm events were identified for the 25-year wave record. Figure 2 shows the actual storm events D vs. $H_{s,max}$ (a); $T_{s,max}$ vs. $H_{s,max}$ (b).

The model fits the Generalized Pareto Distribution (GPD) and the 3-parameter lognormal distribution to the storm events identified, following the procedure outlined by Callaghan et al., (2008) and Coles, (2001). These distributions are used to generate a synthetic storm climate timeseries with parameter values attributed $H_{s,max}$, $T_{s,max}$, D and S of storm events. A Monte Carlo (MC) simulation using a Gibbs sampling technique (Geman and Geman, 1984) and Box-Muller method (Box and Muller, 1958) is employed to generate a random timeseries of erosion and accretion periods. For a full description of the FTS procedure the reader is referred to Callaghan et al., (2008) and references therein.

1. Identify meteorologically independent storm events.
2. Fit the GPD to $H_{s,max}$ and D (marginal distributions).
3. Fit the dependency (logistics) distribution between $H_{s,max}$ and D.
4. Fit the 3 parameter lognormal distribution to $T_{s,max.}$
5. Fit a non-homogeneous Poisson distribution to S.
6. Simulate the storm climate using the fitted distributions including storm spacing.

The number of random storm events required is dependent on the final use of the timeseries. This number has to be large enough to provide accurate estimation of the maximum return level of interest. Generation of more events than required will result in unnecessary computational time. According to Hawkes, (2000), the maximum return period of interest requires a MC simulation size equal to the product of ten, the average number of events per year (Ny) and the return period (RP) (i.e. MC size = 10 x Ny x RP).

As the purpose of this paper is only to demonstrate the methodology of the SPA approach for quantifying medium-term beach change, the maximum return period of interest was taken as 10 years. For 539 events over the 25 year period, Ny = 21.56; and with a maximum return period of 10 year this lead to a random time series of 2156 storm events (corresponding to 100 years) being generated. Figure 2 gives plots of the randomly generated D vs. $H_{s,max}$ (c); $T_{s,max}$ vs. $H_{s,max}$ (d). Comparison between the measured and randomly generated events shows good correlation.

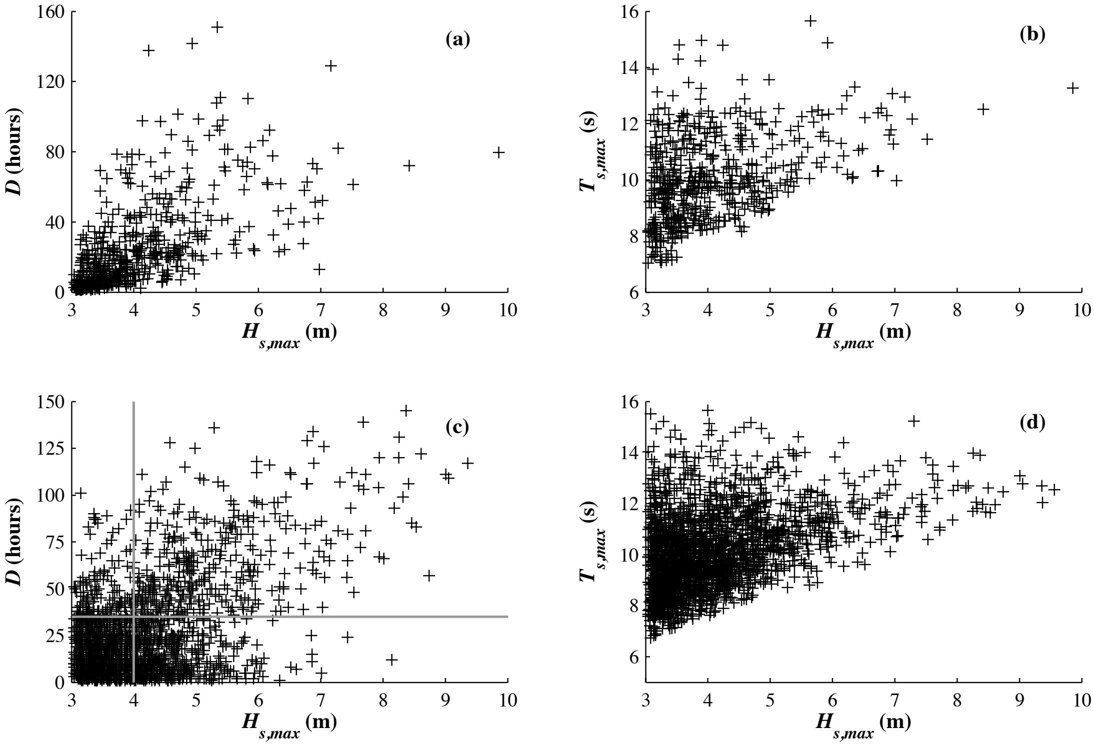

Figure 2. Determined storm events between 1981 and 2006. D vs. $H_{s,max}$ (a) and $T_{s,max}$ vs $H_{s,max}$ (b). Random 100 year storm climate D vs. $H_{s,max}$ (c) and $T_{s,max}$ vs $H_{s,max}$ (d).

XBEACH MODEL

XBeach is a 2DH morphodynamic model developed to simulate the dune erosion regimes due to hurricane impacts (Sallenger, 2000). The model is based on nonlinear shallow water equations and resolves nearshore hydrodynamics by employing a 2DH description of the wave groups and infragravity motions. Wave group forcing is derived from a time varying wave action balance equation, which subsequently drives the infragravity motions and longshore and cross-shore currents. The Eulerian flow velocities (u^E) determined by the model governing equations are used to force the sediment transport module.

The hydrodynamics and morphodynamics of XBeach, as a modeling tool for coastal change, have been extensively validated against numerous flume experiments (1D) and some field case studies (2DH) (Roelvink et al., 2009). The model has been successfully applied to sandy beaches at Assateague Island, Maryland (Roelvink et al., 2009), Santa Rosa Island, Florida (McCall et al., 2010) and Ostend Beach, Belgium (Bolle et al., 2010). More recently, the use of XBeach has been extended to the modeling of gravel beach variability (Jamal et al. , 2010; Williams et al., 2012; de Alegria-Arzaburu et al., 2010). Until now its use has been curtailed at the storm event time scale (hours to days). Although XBeach has been validated extensively for erosive conditions, its use for modeling accretion, especially for sandy beaches, is limited. The calibration provided in this paper provides the first example of an attempt at modeling sandy beach accretion at a time scale of weeks using XBeach.

For more details regarding the formulation of the XBeach model, the reader is referred to Roelvink et al. (2009) and references therein.

MODELING STORM-INDUCED EROSION AND POST-STORM RECOVERY

Overview

The calibration and validation of XBeach for simulating storm induced erosion and post storm recovery are given in this section. The results from this section allow for the model to be used within the SPA for simulating medium-term, storm-induced, beach variability.

The accuracy of the simulations were assessed using a Brier Skill Score (BSS) (van Rijn et al., 2003; Sutherland et al., 2004; Pedrozo-Acuna et al., 2006; Roelvink et al., 2009; Williams et al., 2012) and determining the volumetric error between the simulated and measured beach profiles.
The BSS is given in Eq. 1 for comparing measured and simulated profiles.

$$BSS = 1 - \left[\frac{\left\langle \left| x_p - x_m \right|^2 \right\rangle}{\left\langle \left| x_b - x_m \right|^2 \right\rangle} \right] \tag{1}$$

where x_p is the predicted profile from XBeach; x_m is the measured profile (post-storm) and x_b is the initial (pre-storm) profile. The BSS classification given by van Rijn et al., (2003) states that BSS < 0, bad; 0 – 0.3, poor; 0.3 – 0.6, reasonable/fair; 0.6 - 0.8, good; and 0.8 – 1.0, excellent.

Storm-induced erosion

Calibration of XBeach for modeling storm-induced erosion was achieved by simulating four storm events of varying magnitude (Table 1) and determining the parameter combination that provided the highest average BSS and lowest average volumetric error. The wave conditions were applied to XBeach in the form of a series of hourly JONSWAP spectra using the measured hourly H_s and overall T_p for the storm events.

Table 1. Storm events used for XBeach calibration

Storm	Profile dates	$H_{s,max}$ (m)	*D* (hrs)	T_p (s)
1	04/06/83 - 08/06/83	3.89	77	12.4
2	30/10/87 – 27/11/87	6.32	46	9.85
3	19/05/94 – 21/06/94	4.61	53	9.85
4	14/10/94 – 16/11/94	5.33	22	9.85

In all simulations, the Soulsby-van Rijn (SvR) sediment transport formula was used to determine the sediment equilibrium concentration. As the SvR equation cannot model high velocity sheet flow situations a threshold velocity condition was enforced by setting a maximum shields parameter (θ_{max}) (McCall et al., 2010). Along with this sensitivity testing on the Chézy coefficient (*C*); the permeability coefficient (*k*) of the beach; and the maximum gradient of wet cells before avalanching (*wetslp*) were carried out to provide the most accurate model set up. The results from the sensitivity tests are provided in Figure 3 and Table 2.

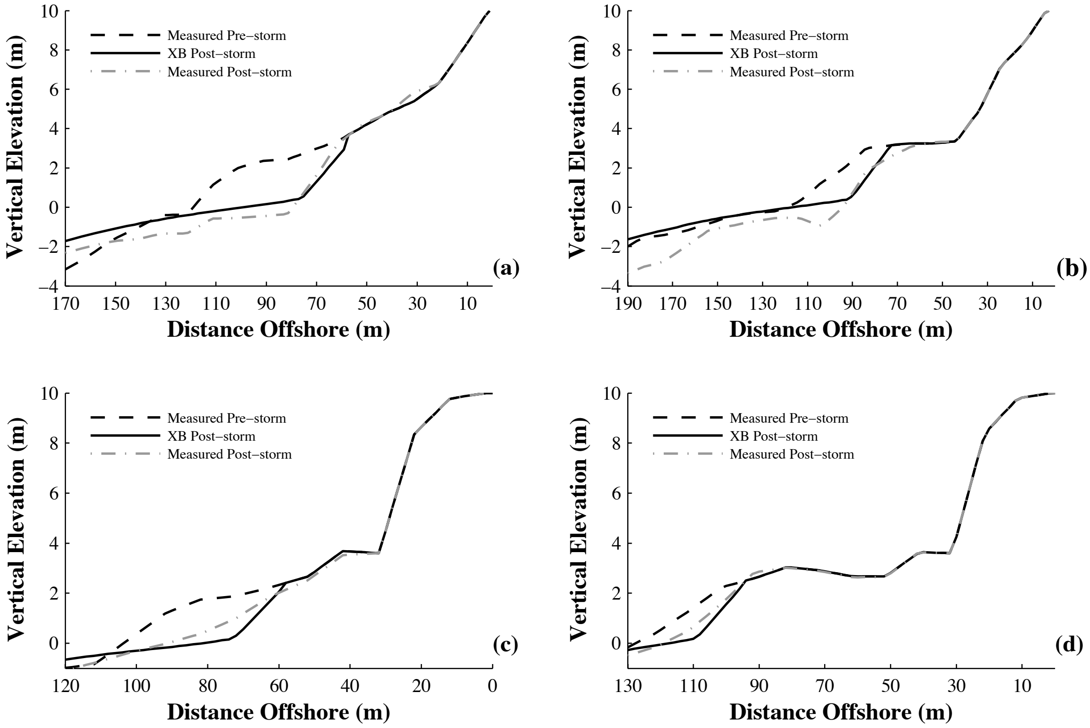

Figure 3. XBeach simulation results for storm model calibration.

Table 2. Storm model calibration results

Storm	BSS	Vol. Err.
1	0.87	+6%
2	0.49	+9%
3	0.77	-1%
4	0.73	-1%

From Table 2 it is evident that Storm 2 produces the lowest BSS (0.49). Although it is considerably less than the others, it is evident in this case that a nearshore bar has formed during the calm period after the event, which may be the reason for lower BSS. Figure 3b shows the nearshore bar, meaning that the profile measurement is not taken soon after the storm. If the profile measurement were taken closer to the end of the storm event the BSS may be considerably higher as the beach would be exhibiting a dissipative state with a wide planar surf zone as in Storm 1 (Figure 3a).

Given that the average BSS all 4 storms considered here still results in a 'good' (0.72) and an excellent average volumetric error (+3%) it can be said that the XBeach model has been effectively calibrated for modeling storm erosion at Narrabeen Beach.

The final calibrated parameters for modeling storm erosion are provided in Table 3.

Table 3. Calibrated parameters for modeling storm-induced erosion

Parameter description	Value
Sediment transport regime	SvR
Limiting Shields parameter (θ_{max})	1.0
Chézy coefficient (C)	40
Coefficient of permeability (k)	0.0031 m/s
Wet cell max gradient (*wetslp*)	0.15

Post-storm recovery

For simulation of post-storm recovery using XBeach, two extended periods when no storm events occurred between profiles measurements were used. Figure 4 shows the measured initial and final profiles, indicating that substantial accretion of the shoreface had taken place transforming the beach from dissipative to reflective states.

Analysis of the wave climate showed that these periods satisfied the calm wave criteria with all measured wave heights being below the 3.0m storm threshold. Details of the wave conditions during the recovery periods are provided in Table 4.

As with the storm models the simulations were forced using JONSWAP spectra of 24-hour duration that varied in line with the measured daily wave conditions.

Table 4. Recovery periods used for XBeach calibration

Recovery	Profile dates	$H_{s,mean}$ (m)	D (days)	T_p (s)
1	25/08/81 - 23/09/81	1.16	29	9.5
2	25/07/87 - 16/08/82	1.11	20	9.5

In all simulations, the van Thiel-van Rijn (vTvR) sediment transport formula was used to determine the sediment equilibrium concentration.

The sediment transport rate (q_t) in XBeach (Eq. 2) is determined using a representative velocity (u_{reps}) (Eq. 3), the sum of the current flow velocity (u^E) and an advection velocity (u^a) from wave skewness and asymmetry (Eq. 4). It is the asymmetric motion and skewness of the waves that are primarily responsible for the onshore transport of sediment (Grasso et al., 2011; Walstra et al, 2007).

$$q_t = C_s u_{reps} - D_h h \frac{\partial c}{\partial x} - 1.6 C_s v_{magu} \frac{\partial z}{\partial x} \tag{2}$$

where C_s is the sediment concentration, u_{reps} is the Eulerian transport velocity, D_h is the sediment diffusion coefficient, h is the water depth and v_{magu} is the Lagrangian transport velocity.

$$u_{reps} = u^E + u^a \tag{3}$$

$$u^a = (facSk \times Sk - facAs \times As) u_{rms} \tag{4}$$

The factors applied to skewness (*facSk*) and asymmetry (*facAs*) determines the magnitude and direction of net sediment transport. Varying these factors therefore determines the predominant sediment transport direction. The permeability of the beach also plays a significant role in berm formation during the accretion phase (Jensen et al., 2009). For this reason, the groundwater flow module was activated for all post-storm recovery simulations with the permeability of the beach taken from the storm erosion tests (0.0031m/s). In addition, simplified semi-diurnal tidal cycles were included based on tidal levels provided by Manly Hydraulics Laboratory for the Sydney region (Table 5). The high tidal range corresponds to the High Water Spring Solstice and the Indian Spring Low Water.

Table 5. Tidal variations for Sydney region

Tide	Low level (m)	High level (m)
Mean	-0.484	0.524
Spring	-0.607	0.647
High	-0.856	0.995

Unlike the storm models, it is less likely that sheet flow conditions will occur due to the smaller incident wave heights. For this reason the θ_{max} criterion was not implemented in the recovery model simulations.

Due to the desire for the SPA to be as computationally efficient as possible, the recovery models use a morphological acceleration factor (*morfac*) (Roelvink, 2006; Ranasinghe et al., 2011) of ten.

The sensitivity testing was carried out systematically with the set up producing the highest BSS without tidal variation then having tidal cycles introduced. As earlier, BSS and volumetric errors between measured and simulated profiles were used to assess model accuracy. Table 6 provides the results for the sensitivity testing and Figure 4 shows the simulated profiles.

Table 6. Recovery model calibration results			
Recovery	**Tide**	**BSS**	**Vol. Err.**
1	Mean	0.88	-2%
1	Spring	0.89	-1%
1	High	0.89	-1%
2	Mean	0.72	-6%
2	Spring	0.73	-5%
2	High	0.71	-5%

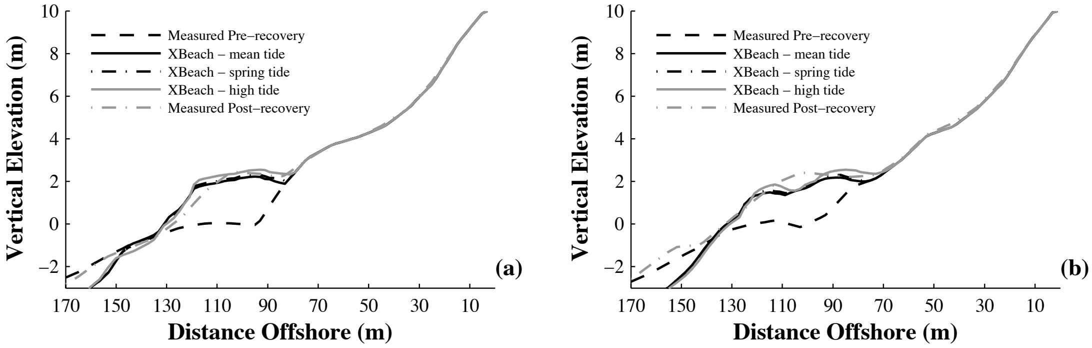

Figure 4. XBeach simulation results for recovery model calibration

From these results it can be seen that all tidal variations provide similar average BSS (0.80, 0.81 and 0.80) and average volumetric errors (-4%, -3% and -3%).

The results provided in Table 6 are extremely encouraging and show that for recovery from a dissipative to reflective beach state, XBeach can produce ‘excellent’ representation of beach accretion.

The final calibrated parameters for modeling storm erosion are provided in Table 7.

Table 7. Calibrated parameters for modeling post-storm recovery	
Parameter description	**Value**
Sediment transport regime	vTvR
Limiting Shields parameter (θ_{max})	NA
Factor on wave asymmetry (*facAs*)	0.80
Factor on wave skewness (*facSk*)	0.50
Coefficient of permeability (*k*)	0.0031 m/s
Tidal variation	yes
Accel. Factor (*morfac*)	10

SPA PROCEDURE

Implementation

Upon calibration of both XBeach set-ups, random erosion / accretion timeseries generated by the SPA will be simulated. The XBeach model has been modified such that the final profile grid is output into a format that can then be read by the next XBeach simulation. The entire timeseries will then be run in sequence, with the initial input bathymetry being the final bathymetry from the previous simulation. In order to further increase the computational efficiency of the SPA, XBeach has been compiled using the Message Passing Interface (MPI) option. The final profiles from each simulation can then be analyzed in order to quantify medium-term erosion levels and assess the stability and position of beach contours.

Example

The following is an example of the SPA procedure using two random storm events and post-storm recovery periods resulting in approximately 46 days of simulation time (Table 8). The initial beach profile for the sequence uses the average levels of profile 4 during the measurement period.

The storm models were set up as in Table 3 and the recovery models as in Table 7 with a high tidal variation.

Table 8. Example SPA procedure details			
Simulation	***H_s* (m)**	***T_p* (s)**	***D* (hrs)**
Storm 1	4.41	11.0	8
Recovery 1	1.50	9.8	120
Storm 2	3.16	15.5	21
Recovery 2	1.50	9.8	960

The beach profiles from the example sequence are provided in Figure 5 and show how the SPA simulates storm event sequencing by transitioning between the two model set ups and transforming the beach from dissipative to reflective states.

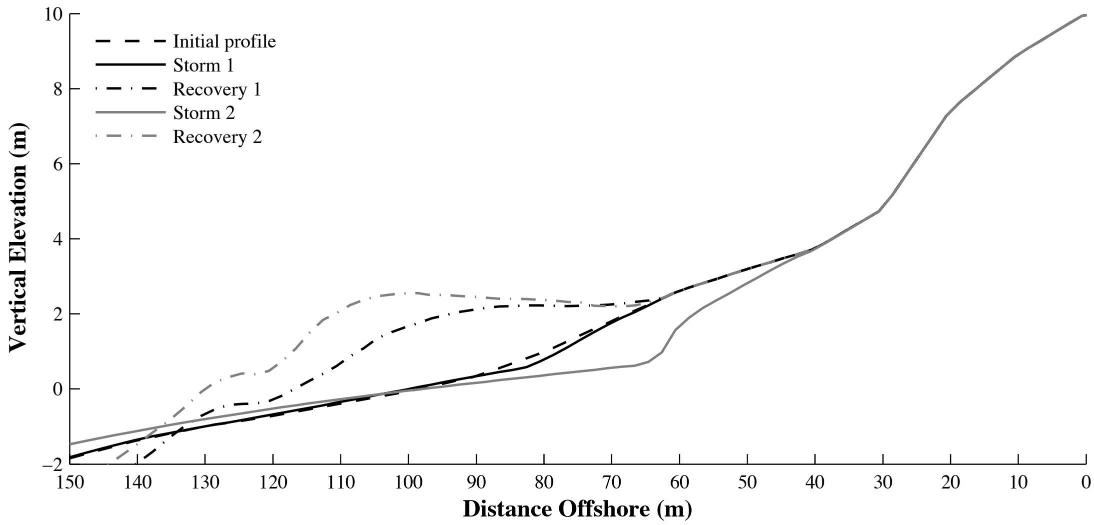

Figure 5. XBeach simulation results for recovery model calibration

Further testing

In order to provide a full assessment of the stability of the SPA, some further testing is required. The longer term stability and accuracy of the procedure will be assessed by simulation of a measured annual time series. Comparison of the results with the measured profile data will provide a more comprehensive validation of the procedure. Along with this, a random 10-year synthetic time series will be modeled. From this the erosion levels will be quantified and compared to those from the measured profile data.

Although the model set ups have provided excellent BSS for individual erosion and accretion periods, the underestimation in beach volume, during recovery periods, may result in stability issues if not enough protection is provided to the beach during these periods.

Upon validation of the SPA procedure for an annual time series the procedure will then be applied to longer-term simulations to provide estimations of medium-term beach variability using fully process-based model.

CONCLUSIONS

This paper has described the novel statistical-process based approach for predicting medium-term beach variability using a fully process-based morphodynamic model.

Accurate calibration of XBeach for modeling, both, storm-induced erosion and post-storm recovery, is presented. Both of the model set-ups provide excellent BSS as well as good volumetric errors when compared to the measure profiles. The calibration of the recovery model is the most important and encouraging result presented. This calibration provides the first attempt at modeling beach accretion using XBeach at weekly time scales. This shows that the XBeach model is a useful tool for modeling erosion and accretion reasonably accurately. The simple erosion / accretion sequence demonstrates the procedure of running the erosion and accretion simulations in sequence to form the SPA.

Although the individual BSS and volumetric errors for the recovery models are acceptable, the accumulation of these errors, may lead to instability when simulating a longer time series. Although profile 4 was determined to be the most stable in the longer term with minimal longshore transport effects (Ranasinghe et al., 2004) these may still play a role in beach accretion at profile 4. Even if directional wave data were to be obtained and used in the FTS, as in Callaghan et al., (2008) and Ranasinghe et al., (2011), the extension of the XBeach modeling into a 2D domain is not computationally viable, in terms of intended long term simulations. Additionally, as XBeach solves the hydrodynamics on a wave group timescale there is no inclusion of individual wave effects in the swash zone. The inclusion of the effects of individual wave run-up may provide a fuller estimation of the berm and reduce the volumetric error.

In order to provide as accurate a model set up as possible sensitivity testing needs to be carried out on annual timeseries of measured data. Final calibration of the entire procedure will allow for the SPA to be implemented and longer-term beach variability to be modelled.

This paper demonstrates successful calibration of XBeach for modeling both storm impact and post-storm recovery at Narrabeen Beach. These calibrations will allow XBeach to be combined with a synthetic erosion / accretion timeseries to form the SPA. Once fully calibrated, the SPA will provide method of quantifying medium-term beach variability using a fully process-based morphodynamic model.

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