A COMBINED STATISTICAL-PROCESS BASED APPROACH FOR MODELLING STORM-DRIVEN, MEDIUM-TERM, BEACH MORPHOLOGY

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Abstract

The ability to predict beach stability in the medium-term (annual to decadal) time scale has clear coastal engineering and management significance. The use of process-based models to determine beach morphodynamics is becoming increasingly popular. This paper discusses the combination of a statistical framework with a process-based, coastal morphodynamic model (XBeach), to allow modelling of medium-term, cross-shore, beach stability. This combined statistical process-based approach (SPA), models storm driven recession and post-storm recovery to determine overall beach variability. A number of sensitivity tests were carried out to assess various parameters that control model performance for erosion and accretion, with outputs assessed using a Brier Skill Score (BSS). This allowed for an accurate and efficient XBeach set up to be determined for both simulation types. The results from this study provide basis for the modelling of medium-term beach stability using the SPA.

The methodology is demonstrated by applying this procedure to Narrabeen Beach in New South Wales, Australia.

Introduction

As the use of process-based, coastal morphodynamic modelling is becoming more prevalent, the time constraints associated with such models have to be overcome, allowing for successful simulations at medium-term time scales. This paper demonstrates a method that combines a statistical framework for modelling extreme storm climate with a process-based model (XBeach), forming a modelling framework for simulating medium-term cross-shore beach morphology, known as SPA herein. The SPA is a novel method that allows for the successful use of a process-based model for analysing beach stability at this time scale. Narrabeen Beach, NSW, Australia is used as a case study.

Until now the use of XBeach has been curtailed at the storm length time scale (hours to days) (de Alegria-Arzaburu et al., 2010; Bolle et al., 2010; McCall et al., 2010). Here it will be shown how, by accounting for the different processes that govern accretion, the model can also produce predictions of post-storm recovery morphology.

The XBeach modelling is divided into two phases, storm-induced erosion and post-storm accretion with the model being set up and validated for each of these forcing conditions and the accuracy assessed using a BSS. The model was run in 1D with the wave forcing orthogonal to the shoreline (i.e. one directional bin).

Upon validation of XBeach an explanation is provided as to how the two procedures are combined, including methods to increase the computational efficiency of the procedure.

Field site

Narrabeen Beach

Narrabeen Beach is located approximately 20 km north of Sydney and is a 3.6 km long embayed beach (Figure 1). The beach is described as an intermediate beach with a transverse bar and rip (Short, 1984) that experiences semi-diurnal, microtidal conditions (spring tide range ≈ 1.25 m). The beach material consists of sediment with grain diameters in the range 0.25mm to 0.50mm (Wright and Short, 1984). An average D_{50} value of 0.37mm has been implemented in the model simulations.

Offshore wave data

The wave data used for the study span approximately 25 years, from 1st January 1981 to 31st December 2005 and were measured using a wave rider buoy near Long Reef Point, NSW, Australia (Figure 1). For additional and more detailed information on the NSW wave climate see Harley et al., (2009); Kulmar et al., (2005); Lord and Kulmar, (2000); Short and Trenaman, (1992).

Cross-shore Beach Profiles

Cross-shore profiles at five different sections of Narrabeen Beach (Figure 1) have been surveyed between 1978 and 2006 (Short and Trembanis, 2004). In this study, Profile 4 data were used to demonstrate the methodology.

All elevations are given relative to Australian Heights Datum (AHD).

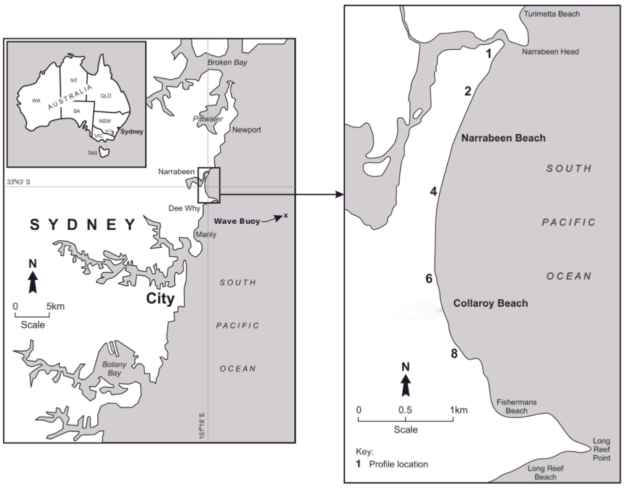

Figure 1: Location and details of the Narrabeen Beach field site (modified after Harley et al., 2011).

The profiles were measured across 170m of the beach, from the crest of the dune (+10m) to around -2 to -4m water depth. As XBeach is being used to model the hydrodynamics, the measured profiles were linearly extended to an offshore depth of -85m where the wave rider buoy is located - http://mhl.nsw.gov.au), using a constant 1:83 bed slope (Wright and Short, 1984).

Statistical modelling

Procedure

The statistical modelling of the storm climate follows the Full Temporal Simulation (FTS) procedure described by Callaghan et al. (2008). The following 6 steps give a summary of the modified FTS procedure:

1. Identify meteorologically independent storm events.
2. Fit extreme value distributions to wave height and storm duration.
3. Fit the dependency distribution between wave height and storm duration.
4. Fit the wave period conditional distribution.
5. Fit a non-homogeneous Poisson distribution to the spacing between storms.
6. Simulate the wave climate using the fitted distributions including storm spacing.

The reader is referred to Callaghan et al., (2008) for detailed information about the statistical procedure.

Successful implementation of the FTS allows the generation of random time series of erosion and accretion events for any duration. The synthetic time series of events have parameter values attributed to peak significant wave height, significant period and duration ($H_{s,max}$, T_s and D) of storm events and the spacing between events (S).

FTS results

As the purpose of this paper is to demonstrate the combination of the FTS and XBeach, a synthetic time series of 10 years was generated using the FTS. For the complete modelling and analysis of beach stability over 10 years a number of random time series will have to be generated and modelled to ensure statistical convergence of the morphology results. This is known as wave chronology (Hanson et al., 2003) and implemented by Callaghan et al. (2008) and Ranasinghe et al. (2011) who use the FTS to analyse dune erosion over a 100-year period. Figure 2 shows an example of a single 10-year synthetic time series generated by the FTS.

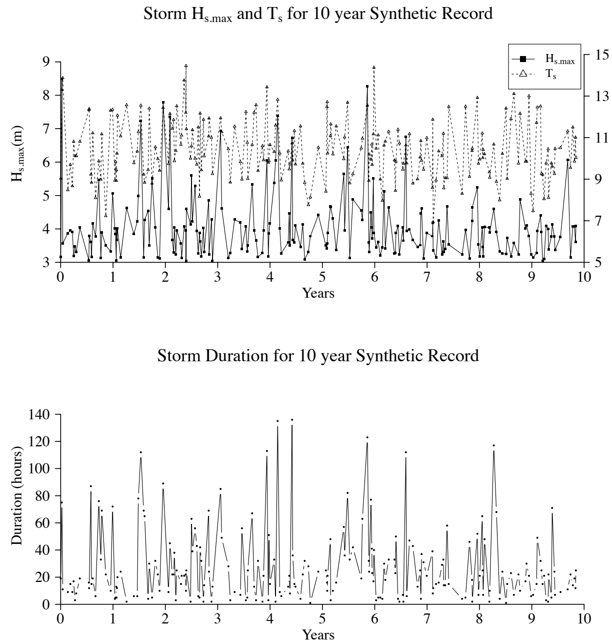

Figure 2: Example of a 10-year synthetic storm record from FTS. $H_{s,max}$, T_s (top) and D (bottom).

XBeach model

XBeach is a 2DH morphodynamic model developed to simulate dune erosion due to hurricane impacts, based on the regimes outlined by Sallenger (2000).

The model solves nonlinear shallow water equations (NSWE) at wave group scale to determine Eulerian flow velocities that drive the sediment transport and bed update modules.

The model resolves swash dynamics by employing a 2DH description of the wave groups and corresponding infragravity motions. The sediment transport module uses a depth averaged advection-diffusion equation (Galappatti and Vreugdenhil, 1985) to determine the sediment concentration (C_s) using an equilibrium concentration (C_{eq})

as a source term. C_{eq} is determined from, either, the Soulsby-van Rijn formula (SvR) (Soulsby, 1997) or the van Rijn formulae (van Rijn, 2007a; van Rijn, 2007b), with the change in bed level being computed using an avalanching technique from the sediment transport gradients. For all simulations given in this paper, the SvR transport equations were used to determine C_{eq}.

For a detailed description of the XBeach model see, Roelvink et al. (2010, 2009) and references therein.

Model accuracy (Brier Skill Score)

The use of a BSS to assess morphological model accuracy has become common practice (de Alegria-Arzaburu et al., 2010; Pedrozo-Acuna et al., 2006; van Rijn et al., 2003). Equation (1) shows formulation of the BSS.

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

Where x_p is the predicted profile from XBeach, x_m is the measured post-storm and x_b is the measured pre-storm profile. The BSS compares the mean square difference between the predicted and measured profiles and the mean square difference between the pre-storm and the measured profiles.

Classification of BSS values is as follows: < 0, bad; 0 – 0.3, poor; 0.3 – 0.6, reasonable/fair; 0.6 - 0.8, good; and 0.8 – 1.0, excellent.

Modelling storm induced erosion

Profiles

By comparing measured profile dates to those of the storm events, appropriate profiles for validation of XBeach were chosen. This led to a storm event that occurred between 04/06/1983 and 08/06/1983 ($H_{s,max}$=3.89m, T_p=12.4s and D=77 hours) along with profile measurements taken on 31/05/1983 and 16/06/1983 being chosen. Figure 3 shows the pre and post-storm measured profiles.

From Figure 3 it can be seen that erosion of the shoreface has taken place during the storm with the total volume of the beach reducing from 941 m^3 to 815 m^3. The storm impact produces a relatively flat section of beach leading up to a newly formed shoreface that is considerably steeper than that of the pre-storm profile.

Sensitivity testing

To set up the erosion model effectively sensitivity tests for a range of Chézy coefficient (C) and permeability of the beach (K) were conducted. As C provides frictional resistance to the flow, altering this will affect the velocity used to determine the sediment transport rate; thus affecting beach erosion. By implementing the groundwater flow module, and altering K, the uprush and return flow will be affected by the infiltration and exfiltration to and from the beach. This, again, will affect the flow velocities used to transport sediment.

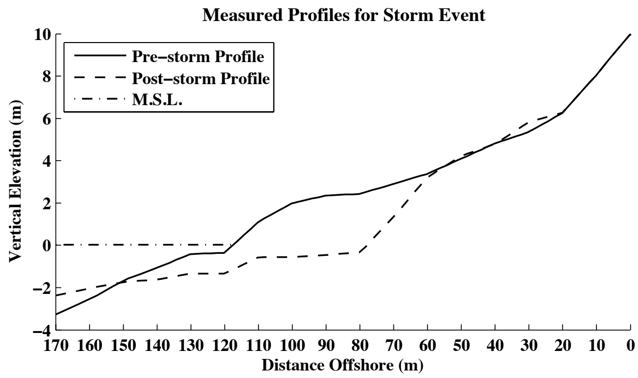

Figure 3: Measured pre and post-storm profiles for the storm occurring between 04/06/1983 and 08/06/1983 ($H_{s,max}$=3.89m, T_p=12.4s and D=77 hours)

Results

From the sensitivity testing of C and K, the optimum model provides a BSS of 0.90, giving an 'excellent' representation of the post-storm profile. The parameter values invoked in the model are provided in Table 1, with Figure 4 showing post-storm morphology.

Table 1: Parameters for final erosion model set up.

Parameter description	XB keyword	Value
Limiting Shields parameter	smax	1.0
Chézy coefficient	C	40
Permeability	k_x, k_y and k_z	0.0031m/s

A C value of 40 corresponds to a flow friction coefficient (cf) value of 0.0061 which relates to a rippled sandy bed (Soulsby, 1997) and is considered valid for Narrabeen based on the studies by Short (1984). Along with this, a K value of 0.0031m/s is also acceptable, as it was determined using a porosity of 0.46, which corresponds to medium to coarse sand (Soulsby, 1997). Additionally, the XBeach model gives a final beach volume of 863m^3, resulting in a 6% difference in beach volumes between simulated and measured profiles.

Modelling post-storm recovery

Overview

The processes that govern beach recovery (accretion) are inherently different than those responsible for erosion. This leads to a different model set up requiring sensitivity testing of different parameters.

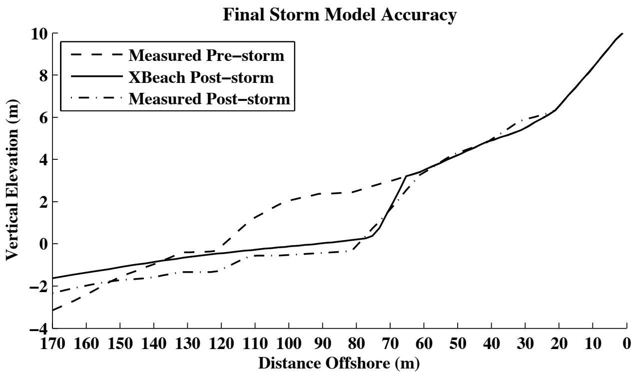

Figure 4: Final erosion profile simulated by XBeach, for the storm even shown in Figure 3.

During accretion periods the permeability of the beach plays a large part in the morphological changes. For this reason, the groundwater flow module was implemented for all simulations with K = 0.0031m/s (as in the storm erosion simulations).

The recovery simulations are forced by bichromatic wave groups with H_{rms}=1.19m, T_{rep}=8.2s and T_{long}=82s.

Measured profiles

Again, storm times were checked against profile measurements to ensure adequate profiles were selected. This comparison lead to profiles measured on 03/05/1989 and 29/05/1989 resulting in a 27-day calm period. Figure 5 shows these measured profiles.

From Figure 5 it can be seen that substantial accretion has taken place on the shoreface as well as the formation of a nearshore bar and runnel. Overall, during the recovery period, the volume of the beach has increased by 54m^3.

Inclusion of tidal variation

The formation of nearshore bars has been the subject of numerous research studies with the most likely hypothesis being that they form near the wave breakpoint, where the onshore transport (due to wave skewness and asymmetry) meets the offshore transport from return flow (Roelvink and Stive, 1989). Tidal variations also play a significant role in the formation and location of nearshore bars. As discussed previously, Narrabeen Beach experiences a semidiurnal tidal variation with the mean tidal level ranging between -0.484m and 0.542m. A simplified, mean, tidal cycle was included in the recovery simulations.

Sensitivity testing

The sediment transport rate in XBeach is determined using a representative velocity (u_{reps}), the sum of the current flow velocity (u_e) and an advection velocity (u_a), from wave skewness and asymmetry (*Sk* and *As*).

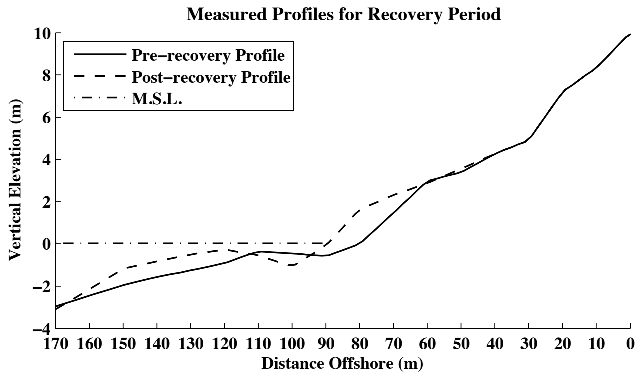

Figure 5: Measured pre and post-recovery period profiles

A strong asymmetric wave motion leads to an increase in the shear stresses imparted on the bed (Walstra et al., 2007), attributed to the front of the waves being steeper than the rear, leading to an increase in onshore sediment flux. In addition, the high crest velocities in the onshore direction attributed to skewed waves in the shoaling zone, mobilise and transport more sediment than the wave troughs (directed offshore); further increasing the net onshore transport of sediment (Grasso et al., 2011).

The velocity, u_{reps},, given by equation (2), where u_e is the wave induced current velocity and u_a is the advection velocity, given by equation (3).

$$u_{reps} = u_e + u_a \tag{2}$$

$$u_a = (facSk \times Sk - facAs \times As)u_{rms} \tag{3}$$

By varying the factors applied to the skewness (*facSk*) and asymmetry (*facAs*), the magnitude and direction of net sediment transport can be altered.

By default *facSk* and *facAs* are set to 0.10, so in order to determine appropriate values, sensitivity tests that varied these parameters from 0.10 to 0.50 were carried out.

Results

By refining the tests it was found that a combination of *facSk*=0.2 and *facAs*=0.2 provided the highest BSS of 0.40, giving a ‘fair/reasonable’ representation of the post-recovery profile. Figure 6, which gives the final accretion profile, shows that, although there is deposition of sediment on the shoreface (as required), the volume of deposition is significantly lower than measured. However, the predicted beach volume from the simulation resulted in a final beach volume of 777m^3, giving only a 2% difference between the measured and simulated values. In terms of assessing the stability of the beach, an accurate prediction in volume change may be as important as the BSS.

Although a BSS of 0.40 may not be considered acceptable for modelling storm impact, it is important to consider the limitations of XBeach. The fact that the model is unable to simulate individual swash events means that the formation of nearshore bars cannot be accurately reproduced using the current XBeach model. With these limitations in mind it can be concluded that the current set up of XBeach is the best available for simulating post-storm recovery. Table 2 provides the parameter values for the accretion model set up.

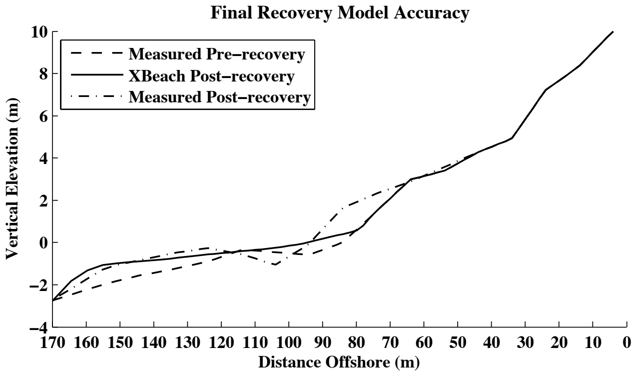

Figure 6: Final accretion model profile.

Table 2: Parameters for final accretion model set up.

Parameter description	XB keyword	Value
Limiting Shields parameter	*smax*	1.0
Factor on Asymmetry	*facAs*	0.2
Factor on Skewness	*facSk*	0.2
Permeability	*kx, ky* and *kz*	0.0031m/s

Computational Efficiency

One of the main limitations of process-based modelling is the large computational times associated with simulations. In order to reduce the simulation times in XBeach, a morphological acceleration factor (*morfac*) can be implemented. This factor updates the bed level changes *morfac* times in a single hydrodynamic time step. Equation (4) shows the use of *morfac* in the bed-updating module of XBeach.

$$\frac{\partial z}{\partial t} + \frac{morfac}{(1-p)}\left(\frac{\partial q_x}{dx} + \frac{\partial q_y}{dy}\right) = 0 \tag{4}$$

Where q_x and q_y are the sediment transport fluxes in the x and y directions respectively. Details of the *morfac* factor can be found in Roelvink (2006) and Ranasinghe et al. (2011).

In order to attempt to reduce simulation time associated with the SPA, a range of *morfac* values (1, 2, 5 and 10) were tested for the post-storm recovery. Table 3 provides the results.

Table 3: Reduction in computational time results.

Morfac	Run time	BSS	Vol. (m^3)	Vol. Diff.
1	8 hrs 32 mins	0.40	777	≈ -2%
2	4 hrs 7 mins	0.49	775	≈ -2%
5	1 hr 39 mins	0.54	786	< -1%
10	51 mins	0.40	806	≈ + 2%

The profiles for each XBeach simulation (Figure 7) show that although Table 3 shows acceptable results for *morfac* values up to 10 the final profiles do not necessarily agree. This illustrates why, during complex morphodynamic situations, simply using a BSS or volumetric error is not adequate.

However, the results do show that it may be acceptable to use a *morfac* value up to 5, which will reduce the computational time by approximately 80%.

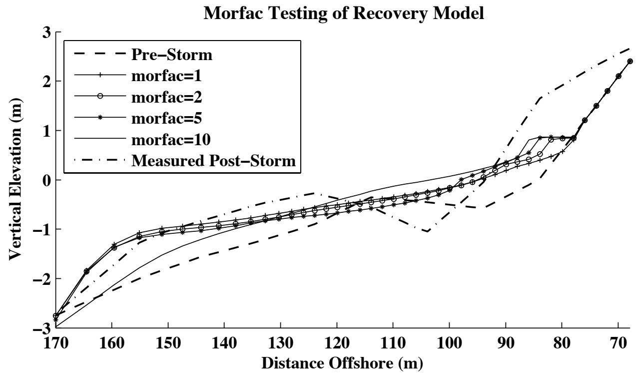

Figure 7: Accretion model - *morfac* testing profiles.

Modelling medium-term beach stability

Now that the XBeach model has been set up adequately for modelling cross-shore storm induced erosion and post-storm recovery, the model can be used to simulate beach variability for time series generated by the FTS. As discussed previously, a number of random time series were generated in order to ensure the final exceedance probabilities converge. Usually this can be achieved with around 30 simulations (Lopez de San Romano and Southgate, 1998). Once the modelling of the erosion/accretion time series are complete this will provide an assessment of the 10-year stability of Narrabeen Beach in response to statistically generated erosion and accretion periods.

Conclusions

The XBeach model is able to simulate storm induced beach erosion at Narrabeen Beach with a BSS of 0.90 and with only 6% difference in the volumetric change of the beach.

It can also be seen that XBeach provides simulations of post storm accretion during calm periods by varying the advection velocity associated to wave skewness and asymmetry. Although the BSS value (0.40) is not as good as that associated with the storm events, it does provide accurate representation of volumetric beach change, with an error of approximately 2%.

It should be noted that the modelling of beach recovery using XBeach has inherent limitations due to the method of model formulation. By using wave group averaged values it cannot simulate individual swash events, meaning nearshore bar and runnel features cannot be simulated accurately. The results given in Figure 6 show that the formation of the bar has been created primarily due to the onshore transport of sediment rather than the converging of onshore and offshore transport. This can again be attributed to the wave group averaging of the return flow. Although there are inherent limitations associated with XBeach when modelling post-storm recovery, it can be concluded that, by accounting for the varying hydrodynamic process, the set ups shown provide adequate predictions for both, erosive and accretive events.

The results presented in this paper provide a basis for modelling of medium-term beach stability using the SPA.

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References

de Alegria-Arzaburu, A. R., Williams, J. J., & Masselink, G. (2010). Application of XBeach to Model Storm Response on a Macrotidal Gravel Barrier. *32nd International Conference on Coastal Engineering*. Shanghai, China.

Bolle, A., Mercelis, P., Roelvink, D., Haerens, P., & Trouw, K. (2010). Application and Validation of XBeach for Three Different Field Sites. *32nd International Conference on Coastal Engineering*. Shanghai, China.

Callaghan, D., Nielsen, P., Short, A., & Ranasinghe, R. (2008). Statistical simulation of wave climate and extreme beach erosion. *Coastal Engineering*, *55*(5), 375-390. doi:10.1016/j.coastaleng.2007.12.003

Galappatti, G., & Vreugdenhil, C. B. (1985). A depth-integrated model for suspended sediment transport. *Journal of Hydraulic Research*, *23*(4), 359-377.

Grasso, F., Michallet, H., & Barthélemy, E. (2011). Sediment transport associated with morphological beach changes forced by irregular asymmetric, skewed waves. *Journal of Geophysical Research*, *116*(C3), 1-12.

Hanson, H., Aarninkhof, M., Capobianco, M., Jiménez, J. A., Larson, M., Nicholls, R. J., Plant, N G, et al. (2003). Modelling of coastal evolution on yearly to decadal time scales. *Journal of Coastal Research*, *19*(4), 790-811.

Harley, M.D., Turner, I.L., Short, A.D., & Ranasinghe, R. (2009). Interannual variability and controls of the Sydney wave climate. *International Journal of Climatology*

Harley, M.D., Turner, I.L., Short, A.D., & Ranasinghe, R. (2011). Assessment and integration of conventional, RTK-GPS and image-derived beach survey methods for daily to decadal coastal monitoring. *Coastal Engineering*, *58*(2), 194-205.

Kulmar, M, Lord, D, & Sanderson, B. (2005). Future Directions for Wave Data Collection in New South Wales. *Coasts and Ports: Coastal Living - Living Coast; Australasian Conference*.

Lopez de San Romano, B., & Southgate, H.N. (1998). *The Effects of Wave Chronology in Beach Planshape Modelling*. HR Wallingford Report TR67.

Lord, D, & Kulmar, M. (2000). The 1974 Storms Revisited: 25 Years Experience in Ocean Wave Measurement Along the South-East Australian Coast. *27th International Conference on Coastal Engineering* (pp. 559-572). Sydney, Australia.

McCall, R.T., Van Thiel de Vries, J.S.M., Plant, N.G., Van Dongeren, A. R., Roelvink, J.A., Thompson, D. M., & Reniers, A. J. H. M. (2010). Two-dimensional time dependent hurricane overwash and erosion modeling at Santa Rosa Island. *Coastal Engineering*, *57*(7), 668-683.

Pedrozo-Acuna, A., Simmonds, D. J., Otta, A. K., & Chadwick, A. J. (2006). On the cross-shore profile change of gravel beaches. *Coastal Engineering*, *53*(4), 335-347.

Ranasinghe, R, Callaghan, D., & Stive, M.J.F. (2011). Estimating coastal recession due to sea level rise: beyond the Bruun rule. *Climatic Change*.

Ranasinghe, R, Swinkels, C., Luijendijk, A., Roelvink, D., Bosboom, J., Stive, M., & Walstra, D. (2011). Morphodynamic upscaling with the MORFAC approach: Dependencies and sensitivities. *Coastal Engineering, 58(8), 806-811.*.

van Rijn, L.C. (2007a). Unified View of Sediment Transport by Currents and Waves. I: Initiation of Motion, Bed Roughness, and Bed-Load Transport. *Journal of Hydraulic Engineering*, (June), 649-667.

van Rijn, L.C. (2007b). Unified view of sediment transport by currents and waves. II: Suspended transport. *Journal of Hydraulic Engineering*, 668-689.

van Rijn, L.C., Walstra, D.J.R, Grasmeijer, B., Sutherland, J., Pan, S., & Sierra, J. P. (2003). The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based Profile models. *Coastal Engineering*, *47*, 295 - 327.

Roelvink, J.A., & Stive, M.J.F. (1989). Bar-generating cross-shore flow mechanisms on a beach.pdf. *Journal of Geophysical Research*, *94*(C4), 4785-4800.

Roelvink, J.A., Reniers, A., van Dongeren, A., van Thiel De Vries, J., Lescinski, J., & McCall, R. (2010). *XBeach Model Description and Manual* (p. All). Deltares, Delft, The Netherlands.

Roelvink, J.A., Reniers, A., van Dongeren, A., van Thiel De Vries, J., McCall, R., & Lescinski, J. (2009). Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering*, *56*(11-12), 1133-1152.

Roelvink, J.A. (2006). Coastal morphodynamic evolution techniques. *Coastal Engineering*, *53*(2-3), 277-287.

Sallenger, A.H. (2000). Storm Impact Scale for Barrier Islands. *Journal of Coastal Research*, *16*(3), 890-895.

Short, A D. (1984). Beaches and Nearshore Facies: Southeast Australia. *Marine Geology*, *60*, 261-282.

Short, A., & Trembanis, A. (2004). Decadal scale patterns in beach oscillation and rotation Narrabeen beach, Australia: time series , PCA and wavelet analysis. *Journal of Coastal Research*, *20*(2), 523-532.

Short, A.D., & Trenaman, N.L. (1992). Wave climate of the Sydney region, an energetic and highly variable ocean wave regime. *Australian Journal of Marine and Freshwater Research*, *43*(4), 765.

Soulsby, R.L. (1997). *Dynamics of Marine Sands* (1st ed.). London: Thomas Telford.

Walstra, D.J.R., van Rijn, L.C., van Ormondt, M., Brière, C., & Talmon, a M. (2007). The Effects of Bed Slope and Wave Skewness on Sediment Transport and Morphology. *Coastal Sediments '07*, *239*, 11-11.

Wright, L.D., & Short, A.D. (1984). Morphodynamic Variability of Surf Zones and Beaches: A Synthesis. *Marine Geology*, *56*, 93-118.