Can we reliably estimate dune erosion without knowing pre-storm bathymetry?

Kristen D. Splinter[1,2], Darrell Strauss[1], and Rodger B. Tomlinson[1]
[1] Griffith Centre for Coastal Management, Griffith University, Gold Coast Campus, Gold Coast, QLD
[2] Water Research Laboratory, School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW; k.splinter@unsw.edu.au

Abstract
Pre-storm bathymetry is a required boundary condition for processed-based dune erosion models but is often out of date, extremely coarse resolution, or in the worst case, non-existent. Despite these limitations, coastal engineers and managers are being called upon to provide estimates of dune erosion to vulnerable coastal communities in light of changes in storm conditions and longer term climate projections. Here we calibrate and then use a state of the art dune erosion model (XBeach) to predict a range of possible erosion volumes for the May 2009 East Coast Low that impacted the Gold Coast, Australia. Using pre-storm bathymetry surveys the model required minimal calibration. Predicted erosion volumes, as well as shoreline retreat were in good agreement with observations. To account for errors in nearshore bathymetry, the suite of available surveys was used to estimate a range of erosion volumes. The model results were relatively insensitive to the range of available bathymetry. Milder sloping and terraced/barred profiles resulted in less dune erosion, while steeper foreshores and non-barred profiles were more vulnerable.

Keywords: Dune erosion, bathymetry, model sensitivity.

1. Introduction

Much of Australia's coastline is lined with sandy beaches backed by dunes that both accrete and erode due to changes in sediment supply, sea level and storminess. While the dune building processes occur on time scales of years to decades, dune erosion tends to be episodic and linked to single (or closely spaced) storm events. Despite this, coastal dunes can be used to provide a certain level of 'soft' protection for adjacent infrastructure against the direct impact of waves and storm surge if they are sufficient in size to withstand the design storm.

In order to assess dune resilience, coastal engineers rely on dune erosion models to predict erosion volumes and determine vulnerable areas of coastline. The simplest example of a dune vulnerability model is the *Storm Impact Model* [11]. Geometric variables, such as the vertical elevation of the dune toe, D_{low}, and dune crest, D_{high}, are compared against total water levels, R_{low} and R_{high} to estimate vulnerability and the possibility of inundation and overwash. Although erosion volumes are not explicitly calculated, erosion is assumed to scale with regime. Additionally, the model includes no time dependence and therefore feedbacks between the dune and swash zone are neglected. However, the simplicity of the model makes it ideal for large scale coastal vulnerability assessments [15].

Processed-based profile models are more commonly used for design and engineering purposes to estimate profile evolution during storms. These include models such as *EDune* [4], *SBeach* [5], and *XBeach* [8] and explicitly model the wave transformation into the shoreline and sediment transport below the mean water line, however, rely on geometric principals to evolve the dune. For example, dune erosion in XBeach is based on a user-defined critical slope term.

Unlike the Storm Impact Model that only requires information about the upper beach profile, offshore wave conditions and water levels, the processed-based models also need sediment characteristics and cross-shore bathymetry. While sediment characteristics can be obtained via a sediment grain size analysis, accurate pre-storm bathymetry is much harder to obtain due to the cost and logistics of *in situ* surveys and the temporal variability of the nearshore. For instance, along the Gold Coast, Qld, Australia, cross-shore profiles between the dune crest and ~ -15 m water depth contour are typically surveyed on an annual basis and offer only a snapshot of the dynamic nearshore system.

It can be argued that this sampling interval is potentially sufficient for the Storm Impact Model because the dune is also assumed to evolve over much longer time scales. Additionally, the upper (dry) beach information that is needed for these models is far more accessible and can be surveyed more frequently if time and money allow. Unfortunately, the inter-tidal and surfzone bathymetry needed for the processed-based models is not only difficult to measure, it is also highly dynamic; evolving between offshore longshore uniform sand bars and relatively alongshore uniform shorelines during storms to alongshore two-dimensional (2D) crescentic sand bars, rip-terrace systems and beach cusps during milder waves [17].

Although sediment transport models are typically more sensitive to tuning parameters than to errors in the boundary conditions [10, 13], high resolution, near real-time bathymetry is needed to accurately predict the wave transformation and wave driven currents [6] in processed-based models. Tuned or best-fit results are rarely presented with a range of possible outcomes to account for the errors in bathymetry associated with sparse sampling. Therefore, this paper explores the sensitivity of modelled dune erosion to errors in bathymetry and examines: *Can we reliably estimate dune erosion without knowing pre-storm bathymetry?*

2. Data

2.1 Site Description

The Gold Coast, Qld, Australia, is located along the east coast of Australia near the Queensland - New South Wales border (Figure 1). This east-facing 35 km stretch of highly developed sandy coastline is exposed to year-round south to south-east swell, as well as infrequent tropical cyclones and East Coast Low (ECL) storm events. Shoreline variability displays a strong annual cycle [1]: during the Australian summer - fall months (Dec. - June), the coast is exposed to larger waves and more frequent storms, resulting in shoreline retreat, while shoreline recovery typically occurs during the milder winter and spring months. The beach is classified as an intermediate [17], double-barred [16] system with the inner bar often evolving into low-tide terrace/rip systems [17].

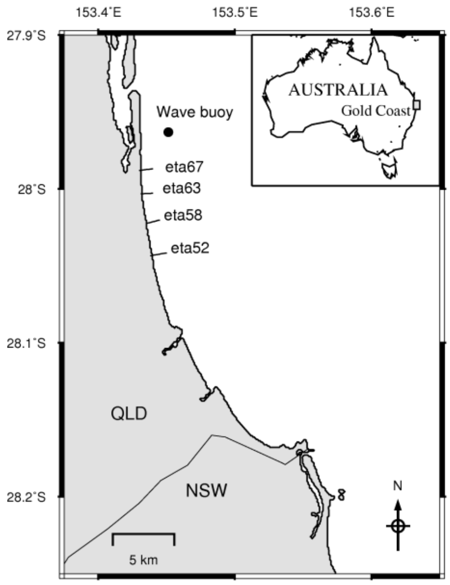

Figure 1. Map of study location.

A primary dune system exists along the majority of the coastline and is vegetated by low-lying dune grasses and coastal bushes. Dune height varies from upwards of 10 m above mean sea level (measured as the Australian Height Datum (AHD) = 0 m) at the northern end to 5 m AHD at the southern end. In most instances, the primary dune system covers a buried sea wall (crest elevation of roughly 5 m AHD) that acts as a last line of defence against storm-induced damage to adjacent infrastructure.

2.2 Storm Description

In May 2009, an East Coast Low storm event impacted the south-eastern Queensland and north-eastern New South Wales coast. The intense low pressure system brought heavy rains, high winds, large waves and storm surge over a week-long period, resulting in significant damage to the beaches. The Gold Coast waverider recorded the 2nd largest significant wave height (H_s = 6.1 m) and 4th largest maximum wave height (H_{max} = 10.6 m) since monitoring began in 1987. Wave periods peaked at 14 s and wave direction was roughly 90^0 N (directly onshore). Maximum recorded surge at the Southport gauge was 0.5 m and the highest recorded water level (surge + tides) was 1.2 m AHD and exceeded the highest astronomical tide. Observations are summarized in Figure 2.

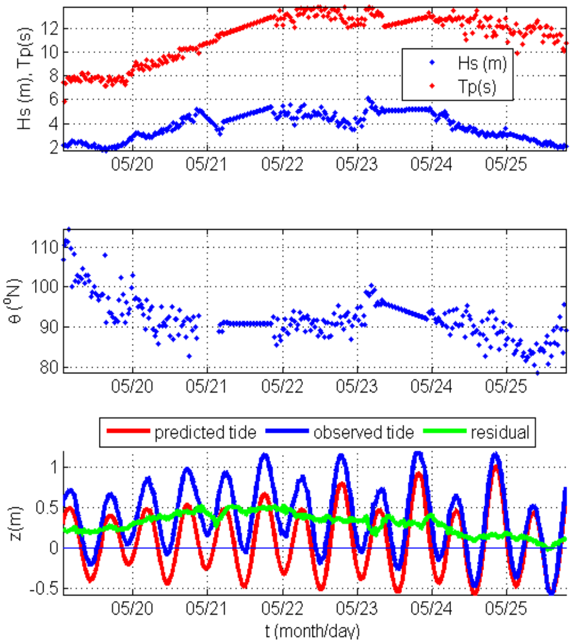

Figure 2. Observations from May 2009 ECL event. (top): Significant wave height, H_s, and peak period, T_p. (middle): Wave direction, *Θ*. (bottom): Water levels.

2.3 Bathymetry

As part of an ongoing coastal monitoring effort, select transects (referred to as ETA lines) are surveyed using standard *in situ* surveying methods (i.e. RTK GPS and echo sounder equipment). This study focuses on the northern end of the coast between Mermaid Beach (ETA 52) and Narrowneck (ETA 67) due to their proximity to the offshore waverider and tidal gauge (Figure 1). The transect lines are spaced between 1.5 and 2.5 km apart. Pre-storm surveys were completed between October (ETA 52, 58) and December (ETA 63, 67) 2008 and post-storm profiles were completed within one week of the storm impact in June 2009 prior to beach reprofiling.

3. Model

XBeach [8], a model designed to estimate eXtreme Beach erosion under storm events, is used to model the May 2009 ECL. The model solves the depth-averaged nonlinear shallow water equations using the wave action balance formulation at the wave group timescale. Wave dissipation is modelled using the formulation of Roelvink [9] for non-stationary waves. The model includes the transfer of momentum due to breaking waves through a similar roller energy balance formulation. XBeach uses the Generalized Lagrangian Mean (GLM) formulation to represent the depth-averaged undertow and its effect on bed shear stresses and sediment transport [7]. The Eulerian depth-averaged velocities are replaced by their Lagrangian equivalent. This results in the GLM momentum equations:

$$\frac{\partial u_L}{\partial t}+u_L\frac{\partial u_L}{\partial x}+v_L\frac{\partial u_l}{\partial y}=-\frac{\tau_{E,bx}}{\rho h}-g\frac{\partial \eta}{\partial x}+\frac{F_x}{\rho h},$$
$$\frac{\partial v_L}{\partial t}+u_L\frac{\partial v_L}{\partial x}+v_L\frac{\partial v_l}{\partial y}=-\frac{\tau_{E,by}}{\rho h}-g\frac{\partial \eta}{\partial y}+\frac{F_y}{\rho h}, \quad (1)$$

where x,y,t = cross-shore, alongshore, and temporal dependencies; u_L,v_L = depth-averaged cross-shore and alongshore Lagrangian velocities, respectively; ρ = density of sea water; $\tau_{E,bx}$, $\tau_{E,by}$ = Eulerian bed shear stresses in the cross-shore and alongshore; h = water depth; g = gravitational acceleration; η = free surface elevation; and F_x, F_y = cross-shore and alongshore wave-induced stresses, respectively.

Sediment transport is modelled using the formulation of Galapatti [2] with the depth-averaged advection diffusion equation:

$$\frac{\partial hC}{\partial t}+\frac{\partial hCu_{av}}{\partial x}+\frac{\partial hCv_{av}}{\partial y}+\frac{\partial}{\partial x}\left[D_h h\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_h h\frac{\partial C}{\partial y}\right]=\frac{hC_{eq}-hC}{T_s}, \quad (2)$$

where C = depth averaged sediment concentration varying on the infragravity time scale; u_{av}, v_{av} = cross-shore and alongshore velocity including the effects of wave skewness and asymmetry; D_h = horizontal diffusion factor; C_{eq} = equilibrium suspended sediment transport concentration; and T_s = adaptation time-scale for the entrainment of sediment. u_{av} is defined as:

$$u_{av}=V_W\cos\theta_m+u_E \quad (3)$$

where θ_m = mean wave angle and V_W = velocity amplitude:

$$V_W=\gamma_{ua}u_{rms}(S_k-A_s). \quad (4)$$

u_{rms} = near-bed root mean square velocity; S_k = wave skewness; A_s = wave asymmetry. S_k and A_s are a function of the Ursell number. γ_{ua} (model parameter *facua*) is a free parameter in the model and determines the impact of short wave properties on sediment transport.

Bed updating at each time step is based on the continuity equation:

$$\frac{\partial z_b}{\partial t}+\frac{f_{mor}}{(1-p)}\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}\right)=0, \quad (5)$$

where p = sediment porosity (set to 0.4); f_{mor} = morphological acceleration factor (set to 10); z_b = bed elevation; and q_x, q_y = cross-shore and alongshore sediment transport rate, respectively. An avalanching criterion is also imposed on the bed-updating. When the critical slope, m_{cr}, as defined by the user (*wetslp, dryslp* for wet and dry cells, respectively) is exceeded, the bed is updated as follows:

$$\Delta z_b=\min\left(\left(\left|\frac{\partial z_b}{\partial t}\right|-m_{cr}\right)\Delta x,0.05\Delta t\right),\frac{\partial z_b}{\partial x}>0$$
$$\Delta z_b=\max\left(-\left(\left|\frac{\partial z_b}{\partial t}\right|-m_{cr}\right)\Delta x,-0.05\Delta t\right),\frac{\partial z_b}{\partial x}<0 \quad (6)$$

where Δt = model timestep; and Δx = cross-shore grid spacing. A complete description of the model can be found in Roelvink et al. [8] and the XBeach users manual (www.xbeach.org).

4. Methods

Based on available survey data, all model runs were done in profile mode such that the effects of 2D bathymetry were not considered. The model was initially calibrated using the pre-storm bathymetry for ETA 67 (Dec. 2008) along with the forcing conditions summarized in Figure 2. Good agreement was obtained using the default parameters (XBeach v.18) with γ_{ua} = 0.15. These parameters were then used for the remaining three profiles for the May 2009 event, as well as for the bathymetry sensitivity tests.

For the sensitivity tests, the upper beach (z > 0 m AHD) for each transect was held constant and equal to the pre-storm survey. The lower profile (z < 0 m AHD) was then merged with the upper profile to create a range of possible offshore profiles. A summary of all available surveys used to test model sensitivity is presented in Table 1 and Figure 3.

Table 1. Summary of surveys used in model sensitivity.

ETA line	# of profiles	Date range
52	19	1972-2009
58	6	1994-2009
63	48	1972-2009
67	24	1985-2009

5. Results

Model results were compared for both total eroded upper beach (z > 0 m AHD) volume, ΔV, as well as change in shoreline, Δs, and are summarized in Table 2 and Table 3. The two most northern sites (ETA 67 and 63) had good model – data agreement for the erosion volumes, while the southern transects had larger errors in ΔV. All sites compared well for changes in shoreline (Figure 4).

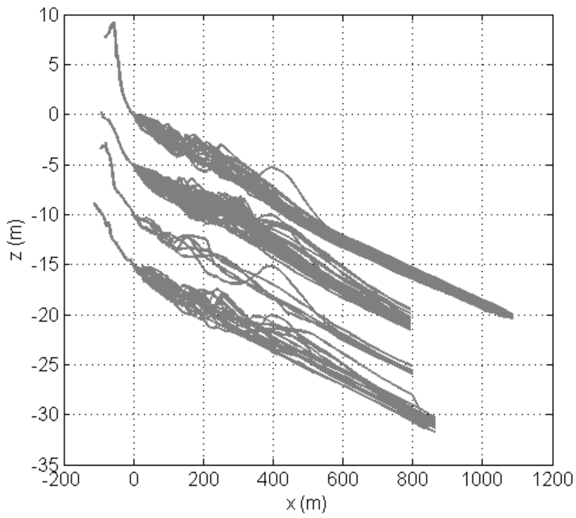

Figure 3. Profiles used to test model sensitivity. Top to bottom are transects ETA 67 - 52. Each transect is offset by 5 m in the vertical. Shoreline is at x = 0 m for all profiles.

Table 2. Summary of *ΔV* results for May 2009 event.

Site	Obs *ΔV* *(m^3/m)*	Model *ΔV* *(m^3/m)*	Range *(m^3/m)*
ETA 67	-66	-77	-59 - -123
ETA 63	-74	-82	-68 - -113
ETA 58	-109	-87	-73 - -98
ETA 52	-114	-80	-56 - -99

Table 3. Summary of *Δs* results for May 2009 event.

Site	Obs *Δs (m)*	Model *Δs (m)*	Range (m)
ETA 67	-12	-16	-12 - -26
ETA 63	-25	-32	-27 - -42
ETA 58	-23	-28	-25 - -34
ETA 52	-30	-34	-26 - -42

The observed volumes were within the range of modelled erosion volumes for ETA 67 and 63, while observed erosion at ETA 52 and 58 were larger than that predicted by the ensemble of available bathymetry. However, the limited number of profiles available for ETA 58 resulted in a much smaller range of erosion volumes and therefore carries with it a larger degree of uncertainty.

Overall, the range of erosion volumes and shoreline change was not significant (Figure 4), indicating the model is not overly sensitive to small errors in nearshore bathymetry. Although variability in the estimated erosion volumes can be due to several reasons including errors in offshore bathymetry; additional sources of errors include errors in the lower portion of the upper beach (inter-tidal zone) which is highly dynamic and shows a strong seasonal signal at this site; and longshore gradients in transport and/or wave focusing that were not accounted for due to the lack of 2D bathymetry and are discussed in more detail below.

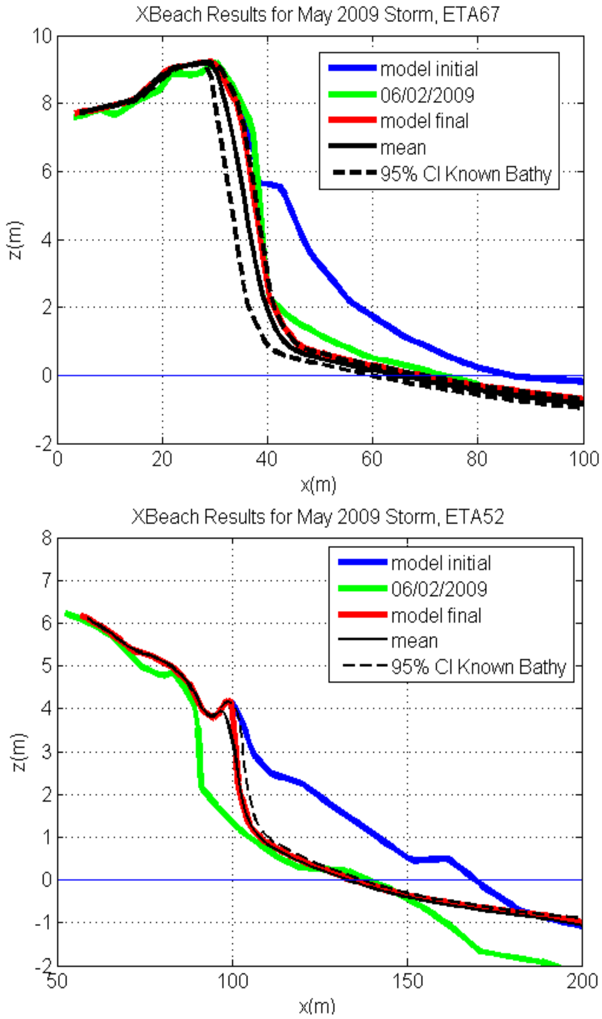

Figure 4. Erosion results for ETA 67 (top) and ETA 52 (bottom). Mean and 95% CI are based on results from all available survey data. 95% CI is calculated as the 0.05 and 0.95 percentile of the cummulative distribution.

6. Discussion

In XBeach, modelled dune erosion is dependent on user-defined critical slope values in relation to whether or not a grid cell is considered wet or dry. The vertical limit of wet cells is defined by the total water levels in the model and calculated as the sum of wave runup, tides, and surge. Within each of these model runs water fluctuations due to tides and surge are constant and therefore, changes in modelled erosion are directly related to how effectively the nearshore bathymetry dissipates wave energy and beach slope impacts runup. The Iribarren number $\left(\varepsilon = \beta_f / \sqrt{H_o/L_o}\right)$, where β_f = bed slope; H_o = deep water wave height; and L_o = deep water wave length, can be used to determine the state of the beach. Under dissipative conditions (higher waves and/or flatter slopes, $\varepsilon < 0.3$) both the incident [14] and infragravity bands [12] of swash can become saturated, thus limiting the vertical extent of runup. We can therefore examine the sensitivity of modelled erosion to variations in surfzone and upper beach slope via a runup equation. One well known equation to statistically describe the 2% runup exceedence, R_2, is given by [14]:

$$R_2 = 1.1\left(0.35\beta_f\left(H_oL_o\right)^{1/2} + \frac{\left[H_oL_o\left(0.56\beta_f^2 + 0.004\right)\right]^{1/2}}{2}\right) \quad (7)$$

The first term in (7) represents the contribution due to wave set-up, while the second term represents the incident and infragravity components of runup, respectively.

6.1 Errors in nearshore bathymetry

Pre-storm beach volumes between 0 > z > -5 m contour reveal that the four profiles contained similar amounts of sand (ETA 67 = 689 m^3/m, ETA 63 = 602 m^3/m, ETA 58 = 614 m^3/m, ETA 52 = 618 m^3/m). However, ETA 63 and 67 had a larger bar-trough system, with a distinct bar at 2 m, while ETA 52 and 58 were more terraced and had very mild features. The milder profiles dissipate more energy offshore and would therefore reduce wave energy reaching the foreshore, as well as saturate the swash, resulting in less erosion.

To examine what impact variations in the nearshore bathymetry have on erosion volumes, we compare the range associated with each of the profiles given the same forcing conditions and upper beach profiles. The inter-tidal slopes (0 > z > -2 m) significantly changed between the minimum and maximum observed erosion volumes. Minimum dune erosion was observed when inter-tidal beach slopes were flatter (β_f ~ 0.014) while maximum erosion was associated with much steeper nearshore slopes (β_f ~ 0.039). Substituting nearshore beach slope into (7) with H_o = 1 m, L_o = 156 m gives a range of R_2 between 0.51 and 0.67 m, and therefore a reduced exposure of wave impact on the dune when the nearshore profile is more dissipative due to changes in the nearshore surfzone bathymetry.

In the most extreme cases, we can generate offshore profiles that envelope the minimum and maximum depth observed at each cross-shore location. The maximum depth example is indicative of an unbarred profile at this site, while the minimum depth includes all the bars/terraces and is therefore far more dissipative. As expected, these more extreme cases result in a larger range of possible dune erosion volumes (for ETA 67, -44 > ΔV > -213 m^3/m). While the minimum depth profile results in slightly less erosion compared to the measured profile examples, the unbarred profile results in a significant increase in dune erosion and agrees with field observations of [3].

6.2 Errors in pre-storm upper beach profile

In addition to variability of the nearshore profile, runup (and therefore modelled dune erosion) is sensitive to the upper beach slope. [14] defined β_f as the mean beach slope +/- 2 standard deviations of the swash, while for large storms [15] found better agreement when β_f was measured between the still water line and the base of the dune. Since the upper beach remained constant for each of the profiles tested here, this term cannot be a source of variability in the expected range of erosion volumes but is useful in determining additional sources of error in the results. For a simple comparison, consider again H_o = 1 m, L_o = 156 m and β_f measured as a best fit between the shoreline (z = 0 m) and z =+2 m contour (Table 4). For the flatter slope (more dissipative condition), R_2 = 0.68 m, while for β_f ~ 0.07, R_2 = 0.90 m. Again we find that less modelled erosion occurred for the flatter slopes measured at ETA 52 – 63 and this may account for some of the overall under-estimation at profiles 52 and 58 (Table 2) if a steeper slope had indeed been present in the true pre-storm profile.

Table 4. Summary of pre-storm beach slopes measured between 0 and +2 m contour.

Site	Pre-storm survey β_f
ETA 52	0.041
ETA 58	0.049
ETA 63	0.052
ETA 67	0.070

6.3 Considering 2D bathymetry effects

This section of the coast is relatively straight and we would not expect strong alongshore gradients in transport to occur. However, comparison of pre and post-storm surveys show that ETA 52 and ETA 58 lost considerable amounts of sand (ΔV_{total} = -254 m^3/m and -184 m^3/m, respectively) compared to ETA 67 (ΔV_{total} = -1 m^3/m). Both ETA 52 and 58 were surveyed in October 2008 and had a more terraced nearshore and mildly defined bars compared to the December surveys at ETA 63 and 67 that had a defined bar crest z ~ -2 m. Visual comparison of CoastalCOMs cameras for ETA 67 and 63 in May 2009 (Figure 5) show on offshore breaker zone when pre-storm waves were of order 1 m, suggesting that there was a bar z ~ -2 m depth and another breaking zone at the shore, similar to that found in the December 2008 surveys. No camera data are available for the ETA 52 - 58 to determine what the pre-storm bathymetry looked like, but it can be inferred from the far-field view (right hand side, Figure 5) that a similar bar system was present to the south as well. Therefore, it is unlikely 2D effects had a large impact during this storm and that the majority of the error in predicted erosion volumes for ETA 52 – 58 can be attributed to errors in the pre-storm nearshore and inter-tidal bathymetry.

Figure 5. CoastalCOMs image of the Northern Beaches, covering ETA 67 and 63. The breaking patterns reveal a relatively longshore uniform offshore bar and a low-tide terrace system with minimal 2D breaking patterns. Image taken May 13, 2009. Image courtesy of Gold Coast City Council (GCCC) and CoastalCOMs.

7. Conclusions

Ninety-seven profiles were used to test the sensitivity of modelled dune erosion to errors in nearshore bathymetry and to determine a range of possible erosion volumes for an ECL storm impacting the Gold Coast, Qld, Australia. The model required minimal calibration to reasonably hindcast the observed erosion. Accounting for possible errors in the nearshore bathymetry, the range of predicted erosion volumes and shoreline retreat showed the model was not overly sensitive to small errors in nearshore bathymetry. Using the range of predicted erosion volumes, it was shown that profiles with milder slopes and low-tide terraces/nearshore bars resulted in less dune erosion, while steeper and/or unbarred profiles resulted in more erosion. Using the maximum depth profile resulted in the largest amount of predicted erosion and is considered a very conservative estimate.

8. Acknowledgements

This work was funded as part of the Queensland Smart State Fund and Griffith University Future Coastlines Project. Survey data was provided by GCCC. The waverider is operated in partnership between GCCC and Department of Environment and Resource Management (DERM). Water levels were provided by Maritime Safety Queensland.

9. References

[1] Davidson, M.A., Turner, I. L. (2009) A behavioral template beach profile model for predicting seasonal to interannual shoreline evolution. *Journal of Geophysical Research*, Vol. 114, p. F01020.

[2] Galapatti, R. (1983) *A depth integrated model for suspended transport.*, in *Communications on Hydraulics*. Department of Civil Engineering, Delft University of Technology.

[3] Harley, M.D., et al. (2009) An empirical model of beach response to storms – SE Australia. in *Coasts and Ports*. Wellington, NZ: Engineers Australia.

[4] Kriebel, D.L. and Dean, R.G. (1985) Numerical simulation of time-dependent beach and dune erosion. *Coastal Engineering*, No. 9, p. 221-245.

[5] Larson, M. and Kraus, N.C. (1989) *SBEACH: Numerical model for simulating storm-induced beach change; Report 1, Empirical foundation and model development*. Coastal Engineering Research Center: U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. USA.

[6] Plant, N.G., et al. (2009) The effect of bathymetric filtering on nearshore process model results. *Coastal Engineering*, Vol. 56, p. 484-493.

[7] Reniers, A., Thornton, E.B., and Roelvink, J.A. (2004) Morphodynamic modeling of an embayed beach under wave-group forcing. *Journal of Geophysical Research*, Vol. 109, p. C01030.

[8] Roelvink, D., et al. (2009) Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering*, Vol. 56, p. 1133-1152.

[9] Roelvink, J.A. (1993) Dissipation in random wave groups incident on a beach. *Coastal Engineering*, Vol. 19, p. 127-150.

[10] Ruessink, B.G., et al. (2007) Modeling cross-shore sandbar behavior on the timescale of weeks. *Journal of Geophysical Research*, Vol. 112, p. F03010.

[11] Sallenger, A.H., Jr. (2000) Storm impact scale for barrier islands. *Journal of Coastal Research*, Vol. 16, No. 3, p. 890-895.

[12] Senechal, N., et al. (2011) Wave runup during extreme storm conditions. *Journal of Geophysical Research*, Vol. 116, No. C07032.

[13] Splinter, K.D., Palmsten, M. L, Holman, R. A., Tomlinson, R. B. (2011) Comparison of measured and modeled run-up and resulting dune erosion during a lab experiment. in *Coastal Sediments*. Miami, FL, USA: World Scientific. p. 782-795.

[14] Stockdon, H.F., Holman, R. A., Howd, P. A. , Sallenger Jr., A. H. (2006) Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, Vol. 53, p. 573-588.

[15] Stockdon, H.F., Sallenger Jr., A. H., Holman, R. A., Howd, P. A. (2007) A simple model for the spatially-variable coastal response to hurricanes. *Marine Geology*, Vol. 238, p. 1-20.

[16] van Enckevort, I.M.J., et al. (2004) Observations of nearshore crescentic sandbars. *Journal of Geophysical Research*, Vol. 109, p. C6.

[17] Wright, L.D. and Short, A.D. (1984) Morphodynamic variability of surf zones and beaches: A synthesis. *Marine Geology*, Vol. 56, p. 93-118.