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Modeling dune response to an East Coast Low

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ABSTRACT

Coastal dunes can act as a method of soft coastal protection against inundation and direct impact of waves during storms if they are substantially large enough in volume to withstand erosion without breaching. However, the time evolution of sand dunes under direct wave impact is not well understood and many available models require site specific calibration and have had limited verification at field scales. Here we test three models of varying complexity in their ability to predict both dry beach erosion volumes and dune to a retreat for an East Coast Low storm event that occurred on the Gold Coast, Australia. The process-based model, XBeach, which models the entire profile was able to reproduce both dune toe retreat and dry beach volume, however, was sensitive to calibration parameters. The two parametric models that only modeled erosion above the initial dune toe position were capable of accurately predicting dune toe retreat, however, under-estimated dry beach erosion volumes. With no calibration, the parametric model proposed by Palmsten and Holman (2012) produced the smallest errors of dune toe retreat with mean error in final dune position of 6.6 m, or 18% of the total measured dune retreat. With minimal calibration estimated absolute error in average dune toe retreat was less than 13% of observed retreat for all three models.

1. Introduction

Coastlines and in particular sandy dune systems evolve over timescales of individual storms to decades in response to processes of wave action and wind (e.g. Morton et al., 1995; Hesp, 2002). Sandy dunes build up primarily through aeolian processes and erode due to wave action and are a well-documented source of sediment to the littoral drift system (Aubrey, 1979). Recently, coastal dune systems have also been acknowledged in their capacity to provide a natural buffer against the impacts of the sea on adjacent low-lying areas (Martinez and Psuty, 2004) provided dunes are both tall and wide enough to prevent storm surge and waves from impacting the back areas during a storm event. However, when they fail or breach, the consequences can be rapid and catastrophic. Therefore, it is of key importance to understand how resilient coastal dunes are to individual or a sequence of storm events in order to assess the vulnerability of adjacent human population and infrastructure.

Sallenger (2000) proposed a *Storm Impact Scale* for barrier islands that classified the relationship between external forcing and foreshore topography resilience into four distinct regimes: swash, collision, overwash, and inundation. External forcing was parameterized as the total water level, defined as the sum of the 2% exceedence of wave runup, tides, and non-tidal residual. The collision regime (when the total water level exceeds the toe of the dune but is below the dune crest), and the overwash/innundation regimes (when the total water level exceeds the dune crest) are of particular importance to coastal engineers, scientists, and managers when assessing the vulnerability of adjacent property. Using the 2% exceedence of wave runup parameterization of Stockdon et al. (2006, 2007) successfully used the *Storm Impact Scale* model to hindcast the potential impact of two hurricanes that made landfall on the Outer Banks, NC, USA. This methodology has since been adopted within the United States Geological Survey (USGS) to forecast storm response and alert the public prior to major storms (http://coastal.er.usgs.gov/hurricanes/) about the probability of extreme coastal change in low lying communities. Although it is assumed that erosion capacity is related to regime (with swash having the lowest erosion potential and overwash having the greatest), this approach is limited in its ability to predict possible breaching or total erosion of a dune system due to its lack of time dependence, therefore storms in a collision regime may require additional modeling to assess the true vulnerability of the adjacent coastal communities.

Vellinga (1986) used extensive lab data to derive an equation for total dune erosion based on surge, wave height, and sediment characteristics. However, no feedbacks between the changing morphology and forcing were included due to the lack of time dependence. A number of time dependent dune erosion models have also been developed. These include cross-shore sediment transport models such as EDune (Kriebel and Dean, 1985), SBeach (Larson and Kraus, 1989), CROSMOR

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(van Rijn, 2009), and XBeach (Roelvink et al., 2009) that model the evolution of the entire cross-shore profile. The cross-shore sediment transport models require knowledge of offshore wave parameters, sediment properties, nearshore bathymetry, and although they explicitly model subaqueous sediment transport, rely on parameterizations to quantify dune erosion. For instance, XBeach, invokes a user defined critical wet and dry slope to erode the upper beach profile. This volume of material is subsequently placed at the dune toe where it is mobilized and carried offshore by swash zone processes. Additionally, because of the large number of free parameters and high level of detailed physics, these models are sensitive to errors in the input variables and may require extensive calibration(and therefore data) to produce reliable results (Splinter et al., 2011a).

Alternatively, more simplified physics-based models explicitly account for dune erosion but don't account for the transport of sand seaward after it has eroded from the dune face. These include wave impact models (Overton and Fisher, 1988; Overton et al., 1994; Larson et al., 2004; Palmsten and Holman, 2012) that relate the volumetric erosion rate of a dune to the momentum flux impacting the dune, and more recently, dune instability models (Erikson et al., 2007; Palmsten and Holman, 2011) that relate dune slumping to forces acting on internal failure planes. Similar to the *Storm Impact Scale*, a key benefit of these models is their reliance solely on information such as wave runup derived from offshore wave properties and subaerial beach profiles, all of which can be easily measured or parameterized.

Along wave exposed coasts, the impacts of storms are likely to be more important in long-term coastal evolution than the impacts of sea level rise (Ruggiero, 2008; Brunel and Sabatier, 2009). Parametric models such as Larson et al. (2004) and Palmsten and Holman (2012) are favored for multi-year coastal evolution scenarios because they are less sensitive to numerical instabilities, calibration parameters and require no information about offshore bathymetry that hinder process-based models such as XBeach to be used inlong-term simulations. Recently, Ranasinghe et al. (2012) proposed a probabilistic model to predict coastal recession over multiple decades using the dune erosion model of Larson et al. (2004) and an assumed recovery rate between storms. Using 30+ years of roughly monthly survey data, Ranasinghe et al. (2012) calibrated both the erosion and recovery rates. However, the best-fit calibration coefficient in the dune erosion model was found to be an order of magnitude greater than that reported by Larson et al. (2004) for their field data set and therefore suggests a certain level of uncertainty in using these models without an appropriate calibration data set.

Although both process-based profile models and the parametric dune erosion models described above have shown potential to be used as predictive tools to estimate dune erosion and coastal vulnerability during lab experiments for individual storm events, very little work has focused on quantitative field scale comparison. Therefore, the objective of this work was to compare three models of varying complexity against field observations obtained during an East Coast Low storm off the coast of South East Queensland, Australia in May 2009 to assess their capability to accurately estimate dune erosion. From least to most complex, the models tested were: that proposed by Larson et al. (2004), herein LEH04; the expanded model with the changes described by Palmsten and Holman (2012), herein PH12; and XBeach (Roelvink et al., 2009). In the following section we summarize the study site and field conditions followed by Section 3 were we describe each of the models in more detail and the calibration procedure. Results for both the uncalibrated and calibrated models are presented in Section 4 followed by discussion in Section 5 and concluding remarks in Section 6.

2. Data

The Gold Coast, Queensland, Australia, is located along the east coast of Australia near the Queensland–New South Wales border (Fig. 1). This east-facing 35-km stretch of highly developed sandy coastline is exposed to year-round south-southeast swell, as well as infrequent tropical cyclones and East Coast Low storm events. East Coast Lows, ECLs, commonly form over the Tasman Sea and are driven by temperature gradients between air masses at sea level and the upper atmosphere (Callaghan, 1986). ECLs are usually short-lived (lasting several days) but may also intensify quite rapidly, generating gale force winds and storm surge along the coast. Shoreline variability along the Gold Coast displays an annual cyclic pattern related to changes in seasonal mean wave height (Davidson and Turner, 2009; Splinter et al., 2011b). 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 usually occurs during the milder winter and spring months. A primary dune system exists along the majority of the coast and is vegetated by low lying dune grasses and coastal bushes depending on the location. 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. Dune erosion is typically isolated to larger storm events where combined high waves and surge directly impact the primary dune system. Dune erosion may also occur during King Tide (highest spring tide of the year) events, but this is minor in comparison to storm-induced erosion. In most instances, the primary dune system covers a landward buried sea wall (elevation of roughly 5 m AHD) that acts as a last line of defense to storm induced damage to adjacent infrastructure.

As part of an ongoing coastal monitoring effort, select transects (referred to as ETA lines) are surveyed using standard survey methods. Profiles along the select transects are measured on average 1–2 times per year. This study focused on the northern end of the coast (Fig. 1) due to the proximity of the offshore wave measurement buoy and tidal gauge. Unlike the southern end of the Gold Coast, the northern Gold Coast is more exposed to wave action from all directions and does not experience large spatial gradients in longshore transport. While the southern end can experience erosional problems and the boulder wall may become exposed during large erosion events, the four northern Gold Coast sites chosen represent natural dune erosion. The four sites used were Mermaid Beach (ETA 52), Broadbeach (ETA 58), Surfers Paradise (ETA 63) and Narrowneck (ETA 67) and are shown in Fig. 1. Pre-storm surveys were completed between October and December 2008 and post-storm profiles were completed within one week of the storm impact in June 2009 prior to mechanical beach reprofiling that moved sand to reduce large and dangerous scarps.

In 1987 a non-directional wave buoy was installed offshore of Narrowneck (ETA 67) in 18 m of water. The buoy is operated in conjunction with Gold Coast City Council and the Queensland Department of Environment and Resource Management (DERM) and was upgraded to include direction in 2007. The buoy provides statistical measurements of significant wave height, H_s (m), maximum wave height, H_{max} (m), peak wave period, T_p (s), and peak wave direction, θ_p (°N) at 30 minute intervals. Water levels are recorded every 10 min and include both tides and surge. The tide gauge is operated by Maritime Safety Queensland and is situated within the Gold Coast Seaway located at the northern end of the Gold Coast.

In May 2009, an ECL 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 second largest significant wave height (H_s = 6.1 m) and fourth largest maximum wave height (H_{max} = 10.6 m) since monitoring began. Wave periods peaked at ~14 s and wave direction was ~90° N (directly onshore). Maximum recorded surge was 0.5 m and the highest recorded water level (surge + tides) was 1.2 m AHD and exceeded the highest astronomical tide. Conditions for the event are summarized in Fig. 2.

3. Models

3.1. LEH04 and PH12

3.1.1. Model description

The models of Larson et al. (2004), LEH04, and Palmsten and Holman (2012), PH12, are both derived from the same principles, and therefore, will be described together here. LEH04 extended the work of Overton and Fisher (1988), Overton et al. (1994), whereby the volume of eroded sand per unit width alongshore, ΔV (m^3/m), was modeled as:

$$\Delta V = 4C_s(R - z_b)^2 \frac{t}{T}, \tag{1}$$

where C_s is a calibration coefficient that parameterizes the physics of the interaction between hydrodynamics and sediment and depends on the ratio between the deep water root mean square wave height, $H_{0,rms}$ (m), and median grain diameter, d_{50} (mm), R (m) is the parameterized runup, z_b (m) is the elevation of the dune toe, t (s) is the duration of exposure, and T (s) is the wave period. LEH04 define C_s as:

$$C_s = \frac{1}{2}\frac{C_E}{C_u^2}\frac{\rho}{\rho_s}\frac{1}{1-p}, \tag{2}$$

where C_E is an empirical coefficient used to describe the relationship between weight of eroded sediment and the estimated swash force (see LEH04 Eq. (1)), C_u is an empirical coefficient used to describe the relationship between bore speed and bore height (see LEH04 Eq. (6)), ρ (kg/m^3) is the density of water, ρ_s (kg/m^3) is the density of the sediment, and p is the sediment porosity. LEH04 parameterize runup as:

$$R_{LEH} = 0.158\sqrt{H_{o,rms}L_o}, \tag{3}$$

based on a best fit comparison of measured runup and deep water wave height, $H_{o,rms}$ (m), and wavelength, L_o (m), for a series of large wave flume experiments. They noted that this formulation may not actually represent a physical runup, but rather the impact that wave runup has on dune erosion. However, Palmsten and Holman (2012) found that substituting the mean beach slope for the laboratory experiments of LEH04 ($tan\beta = 0.16$) into the parameterization for R_2 (Stockdon et al., 2006) yielded $R_{LEH} \sim R_2$ and thus R_2 was an equivalent and more transferable measure of runup across a range of beach slopes and could also explain the wide range of calibration coefficients (C_s) reported in LEH04 for the various field and lab data sets.

Palmsten and Holman (2012) compared the formulation of LEH04 against observations from a lab experiment. They observed the best agreement between measured and modeled runup during the swash regime when $R = R_{16}$ (representing the 16% exceedence level) and $tan\beta$ was measured as the mean beach slope $\pm$ 1 standard deviation (1σ) of the swash, $tan\beta_{\sigma s}$, or as the mean slope between the still water level, SWL, and the dune toe prior to the collision regime, $tan\beta_m$. $R_{n\sigma}$ was defined as:

$$R_{n\sigma} = 1.1\left\{0.35\tan\beta(H_oL_o)^{1/2} + \frac{\left[H_oL_o\left(0.563\tan\beta^2 + 0.004\right)\right]^{1/2}}{2}\frac{n}{2}\right\}, \tag{4}$$

where H_o (m) is the deep water significant wave height and n = [1,2] is the number of standard deviations about the mean water level (the 16% and 2% exceedence level, respectively). The first term inside the bracket represents the contribution of setup or the mean water level, $\langle\eta\rangle$, to swash, while the second term represents the standard deviation of swash, σ_s, about the mean water level.

The dry beach face (above the still water level) was small during the experiment and most of the active dune erosion occurred during the collision regime (Sallenger, 2000). During the collision regime, Palmsten and Holman (2012) found that R_{16} under-estimated runup and suggested a multiplication factor, K_d, could be included to improve results. For the wave conditions tested, K_d was between 1.1 and 1.2 when $tan\beta_m$ was used.

In both LEH04 and PH12, to estimate the time-dependent position of the dune toe, z_b, in Eq. (1), it was assumed that the dune retreated along some trajectory, $tan\beta_t$, such that:

$$z_b(t) = \tan\beta_t(t)x(t) + z_b(0), \tag{5}$$

where x is the cross-shore axis. The lab experiments of Larson et al. (2004) and Erikson et al. (2007) found $tan\beta_t = tan\beta(0)$, such that the dune retreated along the pre-storm beach slope, whereas Palmsten and Holman (2012) found $tan\beta_t = 0.54tan\beta(0)$, indicating the dune receded along a trajectory at roughly half the initial beach slope. This suggests that considerable uncertainty exists in applying such a model in predictive mode. Due to the complexity of measuring active dune erosion in the field, few observations of dune toe retreat exist.

Lastly, Palmsten and Holman (2012) compared the parameterization of total number of collisions, t/T (Eq. (1)), against their lab data and found this term significantly over-estimated the amount of exposure. They proposed an improved parameterization, N_c, to estimate the number of collisions based on an assumed Gaussian distribution of runup:

$$N_c = \left[\sum p\left(z_R + z_{tide} + z_{surge} > z_b, \langle\eta\rangle, \sigma_s\right)\right]\frac{t}{T}, \tag{6}$$

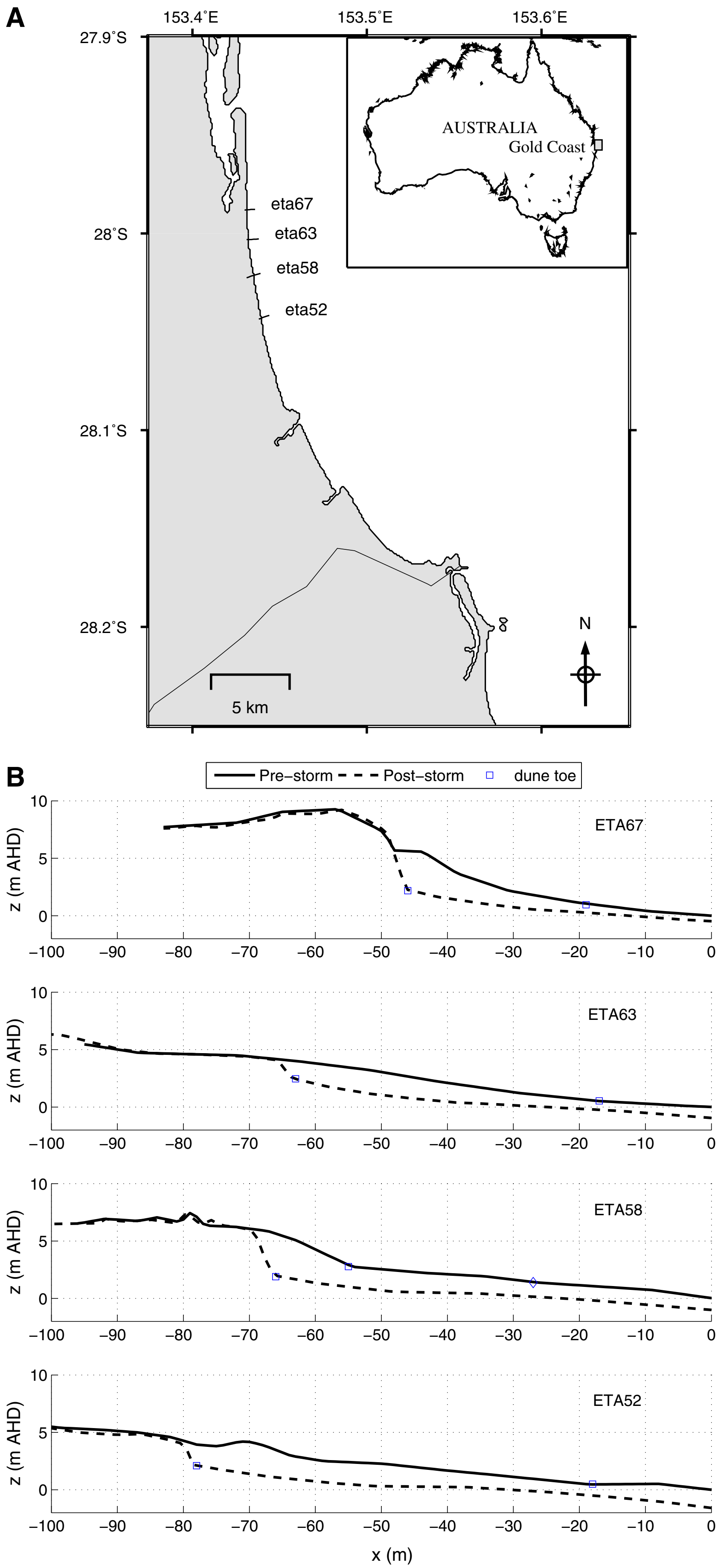
where z_{tide} and z_{surge} were the measured or modeled tide and surge elevations. Substituting Eqs. ((4)–(6)) based on parameterized forcing from offshore wave measurements for R_{16}, the initial beach profile and $tan\beta_t = 0.54tan\beta(0)$ into Eq. (1), and setting $C_s = 1.34 \times 10^{-3}$ (based on eqn. 37, LEH04), Palmsten and Holman (2012) were able to explain 49% of the observed variance in dune volume change during a 12 hour period of active dune erosion. The model reproduced 93% of the measured dune toe retreat, only slightly under-estimating it by 0.36 m (out of the 5.04 m that actually occurred) indicating the simple model had the potential to be used to predict dune retreat with reasonable accuracy.

In the present work erosion volumes for LEH04 were calculated using Eqs. (1) and (3). The LEH04 formulation does not include any time dependency for water level variability due to storm surge and tides. For PH12 erosion volumes were calculated using Eqs. (1), (4) for R_2, and (6). For both models the dune toe was assumed to retreat along the trajectory defined by Eq. (5) and the slope of the dune trajectory was assumed to be the initial beach slope ($tan\beta_t = tan\beta(0)$) in agreement with LEH04. Implications of this assumption are discussed in Section 5.2. Due to model discretization (grid size) predicted eroded volumes/retreat were integrated in time until they met or exceeded the volume of sand available to be eroded for a given cross-shore grid cell.

3.1.2. Calibration

Both the models are run in uncalibrated (default parameters) and calibrated mode. For the LEH04 uncalibrated test, $C_s = 1.7 \times 10^{-4}$ was used based on the mean value found for the field based storm erosion data set of Birkemeier et al. (1988) discussed in LEH04. For PH12,

Fig. 1. (left) Location of Gold Coast, Qld, Australia with transects used in study indicated. (right) Pre and post-storm surveys for each of the transects. All transects have been set so pre-storm shoreline is at $x = 0$ m. Pre and post-storm dune toe locations are marked by squares (ETA 58a — diamond symbol).


A
153.4˚E
153.5˚E
153.6˚E
27.9˚S
28˚S
28.1˚S
28.2˚S
AUSTRALIA
Gold Coast
eta67
eta63
eta58
eta52
5 km
N
B
Pre−storm
Post−storm
dune toe
ETA67
ETA63
ETA58
ETA52
z (m AHD)
x (m)

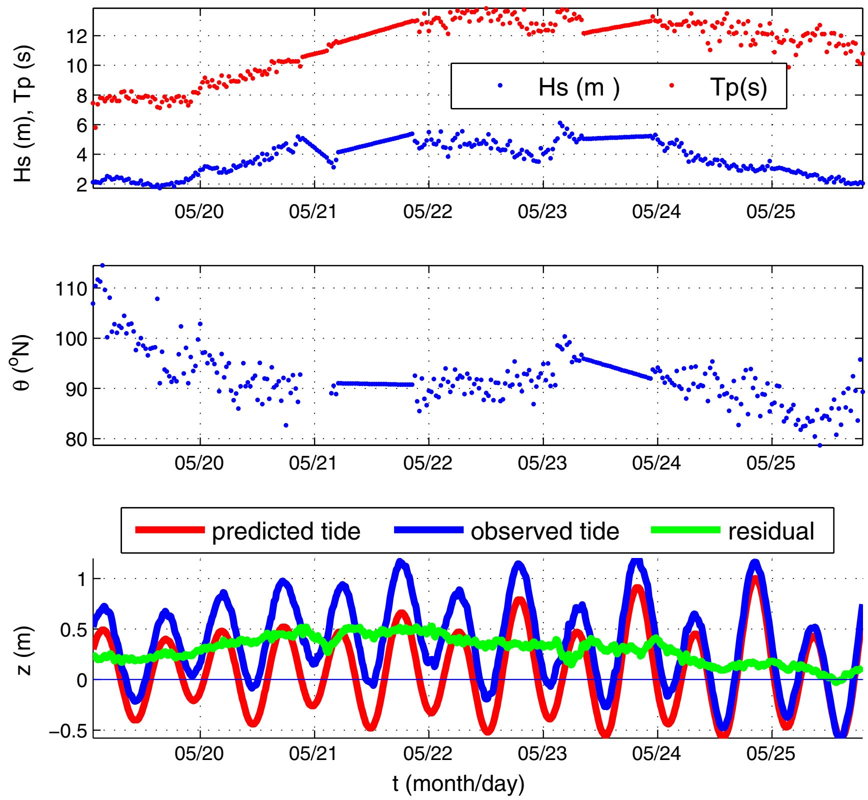


Fig. 2. Summary of May 2009 ECL measured statistics. (top) Wave height and wave period; (middle) wave direction; (bottom) water levels.

which explicitly accounted for beach slope, tide and surge, we used $C_s=1.4\times10^{-3}$ based on the best-fit of lab data from LEH04. Calibrations were done using profile ETA 67 because of its proximity to the wave buoy, thus limiting errors due to spatial variation in waves. For LEH04 and PH12 calibration was based on the goodness of fit to modeled dune toe retreat, rather than erosion volumes since the model formulation assumed a slope of dune toe retreat (trajectory) and sand eroded from below this trajectory was not included.

For the calibrated model tests we also considered two other versions of the PH12 model: using R_{LEH} and R_{16} with measured tides, surge and number of wave impacts (N_c). Calibration coefficients for all variations of the LEH04 and PH12models are summarized in Table 1. For the LEH04 model, best fit was found when $C_s=4\times10^{-5}$, an order of magnitude lower than the best fit value for the field data set used in Larson et al. (2004) and two orders of magnitude lower than Ranasinghe et al. (2012). However, Larson et al. (2004) note that their R parameter is a best fit to data; therefore, R_{LEH} is not site specific since it does not account for beach slope. By comparison, the PH12 model uses the formulation of Stockdon et al. (2006) for runup, which accounts for varying beach slope and for the calibration data set R_2~$0.46R_{LEH}$ for the ETA 67 profile. As a result, best-fit values for the PH12 model were 2–3 orders of magnitude larger: $C_s=2.5\times10^{-3}$ and $C_s=7.0\times10^{-2}$ for R_2 and R_{16}, respectively.

3.2. XBeach

3.2.1. Model description

XBeach (Roelvink et al., 2009) is a process-based numerical model designed to estimate extreme beach erosion under storm events. The model solves the depth-averaged nonlinear shallow water equations using a wave action balance formulation:

$$\frac{\partial A}{\partial t}+\frac{\partial c_x A}{\partial x}+\frac{\partial c_y A}{\partial y}+\frac{\partial c_\theta A}{\partial \theta}=-\frac{D}{\sigma}, \tag{7}$$

where t,x,y,θ represent the temporal, spatial and directional dependencies, c (m/s) is the wave celerity, and the wave action, A (Ns/m),

$$A(x,y,\theta,t)=\frac{S_w(x,y,\theta,t)}{\sigma(x,y,t)}, \tag{8}$$

is the ratio of wave energy in each directional bin, S_w (N/m), and σ (Hz), the intrinsic wave frequency as determined by linear dispersion. The wave dissipation, D (N/m/s), is modeled using the formulation of Roelvink (1993, eq. 2) for non-stationary waves (model parameter: *break* = 1):

$$D=2\alpha f_{rep}E_w Q_b \tag{9}$$

or Roelvink (1993, eq. 3) (model parameter: *break* = 3):

$$D=2\alpha f_{rep}E_w Q_b\frac{H_{rms}}{h}, \tag{10}$$

where α is a coefficient of O(1), f_{rep} (Hz) is the representative intrinsic frequency, E_w (N/m) is the total wave energy summed over all directional bins, and Q_b is the fraction of breaking:

$$Q_b=min\left[1-e^{-\left(\frac{H_{rms}}{\gamma h}\right)^n},1\right], \tag{11}$$

where H_{rms} (m) is the local rms wave height, h (m) is the local water depth and n,γ are free parameters in the model. Default values for n (10) and γ (0.55) are based on calibration using Roelvink (1993, eq. 2) and describe the transition between no breaking ($Q_b=0$) and full breaking ($Q_b=1$) and the ratio of wave height to depth at breaking, respectively. The model includes the transfer of momentum due to breaking waves through a similar roller energy balance formulation.

Table 1
Calibration coefficient for the original LEH04 model and PH12 parameterizations for R and t/T.

Model	R	t/T	C_s
LEH04	R_{LEH}	t/T	4.0×10^{-5}
PH12	R_{LEH} + tides + surge	N_c using R_2	1.1×10^{-4}
	R_2 + tides + surge	N_c using R_2	2.5×10^{-3}
	R_{16} + tides + surge	N_c using R_{16}	7.0×10^{-2}

The model uses the Generalized Lagrangian Mean (GLM) formulation to represent the depth-averaged undertow and its effect on bed shear stresses and sediment transport. In the subaqueous environment, sediment transport is modeled using the depth-averaged advection diffusion formulation of Galapatti (1983):

$$\frac{\partial hC}{\partial t}+\frac{\partial hCu_{av}}{\partial x}+\frac{\partial hCv_{av}}{\partial y}+\frac{\partial}{\partial x}\left[\mathrm{D}_h h\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[\mathrm{D}_h h\frac{\partial C}{\partial y}\right]=\frac{hC_{eq}-hC}{\mathrm{T}_s}, \quad (12)$$

where C is the depth averaged sediment concentration varying on the infragravity time scale, u_{av}, v_{av} (m/s) are the cross-shore and alongshore velocity including the effects of short wave skewness and asymmetry, D_h is the horizontal diffusion factor, C_{eq} is the equilibrium suspended sediment transport concentration, and T_s (s) is the adaptation time-scale for the entrainment of sediment. u_{av}, v_{av} (m/s) have recently been implemented into XBeach (version 18 and above) and are defined as

$$u_{av}=V_w cos\theta_m+u_e,$$
$$v_{av}=V_w sin\theta_m+v_e, \quad (13)$$

where θ_m is the mean wave direction and the velocity amplitude, V_w, is modeled to include the effects of short wave skewness, S_k, and asymmetry, A_s:

$$V_w=\gamma_{ua}u_{rms}(s_k-A_s), \quad (14)$$

and γ_{ua} (model free parameter: *facua*) determines the influence of short wave properties on sediment transport and u_{rms} is the near bed root mean square velocity. Higher values of γ_{ua} induce more onshore directed transport, while a value of 0 dictates that all sediment transport is offshore directed.

Bed updating uses the continuity equation, where gradients in sediment transport result in changes in bed elevation. The upper beach profile is updated via an avalanching criteria in the bed updating scheme, whereby the user defines a critical stable slope for both the wet (*wetslp*) and dry (*dryslp*) grid cells. Profile updating, z_p, is then dictated by:

$$\delta z_p=min\left(\left(\left|\frac{\partial z_p}{\partial x}\right|-m_{cr}\right)\Delta x, 0.05\Delta t\right), \frac{\partial z_p}{\partial x}>0,$$
$$\delta z_p=max\left(-\left(\left|\frac{\partial z_p}{\partial x}\right|-m_{cr}\right)\Delta x, -0.05\Delta t\right), \frac{\partial z_p}{\partial x}<0. \quad (15)$$

where m_{cr} is the critical slope as defined by *wetslp* and *dryslp*, Δx and Δt are the cross-shore grid spacing and time step, respectively. The reader is referred to Roelvink et al. (2009) or the XBeach users manual (www.xbeach.org) for a full description of the model.

For the present study, XBeach is run in profile mode (three alongshore grid cells, dy = 5 m) at the four sites for the duration of the storm. Grid spacing in the cross-shore is variable, with a minimum grid spacing in the upper beach profile of 1 m. Offshore forcing is based on an assumed Jonswap spectrum and updated every 30 min in the model. Water levels are updated every 10 min to account for tidal changes. To decrease modeling time, the morphological factor for updating bed elevations is set to 10 and the maximum Courant number is set to 0.9.

3.2.2. Calibration

Model calibration is based on profile ETA 67 and minimizing model–data root mean square (rms) error for the upper beach ($z>0$ m AHD) profile. The emphasis was on requiring as little deviation from the default parameter values where possible. Asno wave transformation data was available, we used default wave dissipation values and varied the dissipation formulation (Roelvink, 1993, Eqs. (2) or (3)). Calibration focused on adjusting *hmin* (threshold depth for concentration and return flow, default = 0.01 m), *eps* (threshold depth for drying and flooding, 0.1 m), *hswitch* (water depth at interface of *wetslp* and *dryslp*, 0.1 m), *wetslp* (critical avalanching slope under water, 0.3), *dryslp* (critical avalanching slope above water, 1), and γ_{ua} (influence of short wave skewness and asymmetry on sediment transport, 0). Good model agreement was found using these default values except γ_{ua} (best-fit = 0.15) and wave dissipation (best-fit = Roelvink (1993, eq. 2)). Sensitivity of results to model free parameters is further discussed in Section 5.4.

4. Results

4.1. Observed erosion

While all cross-shore transects included in this study were located within a 6.5 km region, dune morphology and storm response varied widely with erosion volumes increasing towards the south. The observations described in this subsection are summarized in Table 2. Observations are presented from the most northerly transect and moving southward. The most northerly transect, ETA 67, was composed of a two-tiered dune with a crest height of 9.25 m AHD and an initial dune toe of 0.95 m AHD. The beach width (BW) in front of the dune was 17 m, resulting in a foreshore beach volume (measured between the shoreline and dune toe) of 8.08 m^3/m. The dune retreated 28 m during the ECL, removing the entire volume (66 m^3/m) of the first tier of the dune and creating a steep (slope = 0.21, height = 8.3 m) dune scarp. Approximately 80% of the total (above AHD = 0 m) eroded volume occurred above the initial dune toe elevation. The trajectory of the dune base was upward and was 81% of the pre-storm beach slope. The elevation of the dune crest was unaffected by the storm. The shoreline retreated 13 m and final beach width was 32 m. Based on the initial dune toe elevation, the estimated percent duration of the storm where the dune was in a collision regime ($R_2+\bar{\eta}+tide>z_b(0)$) was 90% and in the swash regime 10%. However, accounting for the dune

Table 2
Dune statistics for Gold Coast data used here. BW = beach width measured from shoreline to z_b, z_b = elevation of dune base, z_c = dune crest elevation.$tan\beta_{dune}$ is the pre-storm slope of the dune measured between z_b and z_c. The dune retreat trajectory is measured as $tan\beta_t=tan\beta_{fac}tan\beta(0)$, where $tan\beta$ is measured from the shoreline (z = 0 m) to the base of the dune. For ETA 58 two choices of dune toe elevation are considered.

	ETA 67	ETA 63	ETA 58a	ETA 58b	ETA 52	PH12 lab
BW(0) (m)	18	17	54	26	18	0.71
$z_b(0)$ (m)	0.95	0.53	2.77	1.38	0.49	0.12
z_c (m)	9.25	5.45	7.32	7.32	6.18	1.04
$tan\ \beta_{dune}$	0.21	0.06	0.18	0.11	0.06	0.61
z_b(final) (m)	2.18	2.46	1.89	1.89	2.10	0.74
$tan\ \beta(0)$	0.05	0.03	0.05	0.05	0.03	0.17
β_{fac}	0.81	1.31	−1.50	0.24	1.01	0.54
$tan\ \beta$(final)	0.07	0.06	0.04	0.04	0.04	0.14

recession (and assuming a dune retreat trajectory equal to the initial beach slope), the dune was in the collision regime only 18% of the time, indicating dune erosion was episodic and swash zone processes were actively moving sand in the lower beach face.

South of ETA 67, the initial dune profile at ETA 63 was more gradually sloping (0.06) without a steep dune face. The dune crest was at 5.45 m AHD, less than half the height of ETA 67. Initial beach width was the same (17 m) as ETA 67. However, the initial dune toe was substantially lower (0.53 m AHD) and below the Mean High Water Springs (MHWS) elevation = 0. 65 m AHD. Although erosion volumes were similar to ETA 67 (74 m^3/m), retreat of the dune toe was almost double (46 m). Similar to ETA 67, 82% of the eroded volume was above the initial dune toe elevation. The trajectory of the dune toe was 31% greater than the initial beach slope and beach slope steepened compared to pre-storm data. The shoreline retreated 25 m and final beach width was 38 m. Based on the initial dune toe elevation, the estimated percent time of storm where the dune was in the collision regime was 100%, with periods of time where the mean water level alone could have reached the dune toe. Accounting for the dune recession (and assuming the trajectory given in Table 2) the duration of the collision regime was reduced to 27%.

The initial profile of ETA 58 was also low sloping like ETA 63, however, ETA 58 included a steep swash slope with an elevated berm and a flattening of the beach face around 0.75 m AHD. Similar berms existed at ETA 67 (below AHD = 0 m) and ETA 52. For completeness we present results based on the dune toe chosen at maximum curvature ($z_b(0) = 2.77$ m AHD, ETA 58a) and a local maximum at $z_b(0) = 1.38$ m, ETA 58b, closer to dune toe elevations recorded at the other sites. This lower toe contains only a small amount of sand above the average beach slope, therefore predicted erosion volumes using LEH04 and PH12 will be quite similar for both choices. The initial dune had a relatively steep scarp (slopes = 0.18 and 0.11 for ETA 58a and b, respectively). The dune crest was at 6 m, and was unaffected by the storm. Initial beach widths were significantly wider than at other sites (54 m and 26 m, respectively) with foreshore beach slopes of 0.05 and 0.03. The total erosion volume above 0 m AHD was 109 m^3/m, of which only 24% was above the initial dune toe elevation for the choice of $z_b(0) = 2.77$ m, and 56% for the choice of $z_b(0) = 1.38$ m. This indicates considerable erosion occurred in the swash regime at this site. Based on initial dune toe locations, the collision regime was reached 0% of the time for ETA 58a, whereas for the lower dune toe choice, ETA 58b, runup exceeded the dune toe 76% of the time. ETA 58a was the only profile where the dune toe eroded downwards.

The most southerly profile, ETA 52, was morphologically most similar to ETA 63, with a gradually sloping dune face (0.06) and a dune crest of 6.18 m. Beach width was 18 m, similar to the widths of ETA 67 and ETA 63. The dune retreated along a trajectory that was approximately equal to the initial beach slope. Also like ETA 63, the initial dune toe was low (0.49 m) and the total elevation change between toe and crest was 5.69 m. ETA 52 experienced the largest dune toe retreat (59 m) and the greatest volume of eroded sediment (114 m^3/m). However, similar to ETA 58, ETA 52 had a distinct swash slope, followed by a steeper berm and dune. In contrast to ETA 58, a high-tide terrace was present at ETA 52 that showed a distinct change in slope between the terrace and the much steeper berm/dune, therefore the lower of the two toe choices was used here. Similar to ETA 58, a secondary change in beach slope occurred around 2.8 m AHD, marking the toe of a more established dune. Similar to ETA 67 and 63, 83% of the measured erosion occurred above the specified dune toe elevation and 100% of the storm was considered to be in the collision regime based on initial dune toe elevation. During the storm the secondary dune was eroded, resulting in a steep dune scarp, steep upper beach, a similar high-tide terrace and steep swash slope. Pre and post storm dune toe locations are shown on Fig. 1.

4.2. Dune toe retreat

Results of the uncalibrated models are summarized in Table 3. At all profiles the LEH04 formulation over predicted dune toe retreat, Δx, by 6–31 m (15–67%), while PH12 under estimated dune retreat by 4–11 m (7–73%). The least agreement in terms of predicted dune toe elevation, Δz_b, was found at ETA 58a where the observed post-storm dune toe had retreated and lowered compared to the pre-storm survey and violates the current model assumption that the dune toe retreats upwards along the trajectory of the pre-storm beach slope. XBeach significantly over-estimated dune retreat at all sites. Using default parameters, XBeach eroded the entire dry beach volume and continued to erode and lower the profile below AHD = 0 m. Dune toe retreat was over-estimated by 30–40 m (5–273%) and was limited only by the shoreward extent of the model. At all sites, Δz_b was negative using XBeach.

Calibration of LEH04, PH12 and XBeach significantly reduced the errors in modeled dune toe retreat (Table 4). At ETA 67 (calibration profile) dune toe retreat (Δx) was modeled within 1 m (cross-shore grid resolution). Examples of the modeled dune erosion and dune toe retreat with time (both in the horizontal and vertical) are given in Figs. 3 and 4. For ETA 63 and ETA 52 errors in Δx for LEH04 were reduced to 1 and 5 m (2 and 8%), respectively. The three versions of PH12 had errors between 0 and 7 m (0–11%), while XBeach underestimated total dune toe treat by 3–5 m (7–8%) and the modeled dune toe retreat trajectory was slightly flatter than observed. The largest errors were still at ETA 58 where errors in Δx were between −11 m (100%) and +4 m (36%).

4.3. Erosion volumes

Erosion volumes were calculated based on volumes above AHD = 0 m. However, it is worth noting that XBeach is capable of eroding the entire profile while LEH04 and PH12 only erode landward of the initial dune toe and above the initial beach slope along the assumed dune toe retreat trajectory (Eq. (5)). Thus for the same dune toe retreat, erosion volumes for LEH04 and PH12 will be less than observed and those predicted by XBeach if erosion occurred below the pre-storm dune toe as was the case at ETA 58 and 52.

Estimated erosion volumes with respective model default parameters were over estimated for LEH04 (7–50%) and XBeach (182–485%) simulations and under estimated for PH12 (51–70%). The exception

Table 3
Summary of dune retreat (Δx(m)) relative to the initial dune toe position and change in dune toe elevation (Δz_b (m)) using the uncalibrated models. Parentheses represent % difference.

Method	ETA 67		ETA 63		ETA 58a		ETA 58b		ETA 52	
	Δx (m)	Δz_b (m)	Δx (m)	Δz_b (m)	Δx (m)	Δz_b (m)	Δx (m)	Δz_b (m)	Δx (m)	Δz_b (m)
Observed	28	1.24	46	1.93	11	−0.88	39	0.51	59	1.61
LEH04	38(36)	2.11(70)	77(67)	2.42(25)	18(64)	0.92(−205)	45(15)	2.70(429)	8 (42)	2.27(41)
PH12	26(−7)	1.45(17)	42(−9)	1.32(−32)	3(−73)	0.15(−117)	31(−21)	1.64(222)	48(−19)	1.29(−20)
XBeach	64(129)	−1.26(−202)	77(67)	−3.38(−275)	41(273)	−3.92(−555)	69(77)	−2.57(−604)	99(68)	−0.67(−142)

Table 4
Summary of dune retreat (Δx(m)) relative to the initial dune toe position and change in dune toe elevation (Δz_b (m)) using the different calibrated models. Calibration coefficients for C_s are based on calibration to ETA 67 (Table 1). Parentheses represent % difference.

Method	ETA 67		ETA 63		ETA 58a		ETA 58b		ETA 52	
	Δx (m)	Δz_b (m)	Δx (m)	Δz_b (m)	Δx (m)	Δz_b (m)	Δx (m)	Δz_b (m)	Δx (m)	Δz_b (m)
Observed	28	1.24	46	1.93	11	−0.88	39	0.51	59	1.61
LEH04	28(0)	1.47(19)	47(2)	1.47(−31)	15(36)	0.77(−188)	31(−21)	2.12(316)	54(−8)	1.46(−9)
PH12 R_{LEH}	28(0)	1.47(19)	47(2)	1.47(−31)	7(−36)	0.36(−141)	35(−10)	1.86(265)	54(−8)	1.46(−9)
PH12 R_{16}	28(0)	1.47(19)	48(4)	1.50(−22)	0(−100)	0(−100)	31(−21)	1.64(222)	54(−8)	1.46(−9)
PH12 R_2	28(0)	1.47(19)	46(0)	1.44(−25)	1(−91)	0.05(−106)	32(−18)	1.70(233)	52(−12)	1.4(−12)
XBeach	28(0)	1.05(−15)	43(−7)	1.14(−25)	5(−55)	−1.23(40)	33(−15)	−0.1(−120)	54(−8)	1.44(−11)

was for ETA 58 where the dune eroded both back and for ETA 58a down. In this case both PH12 (99-100%) and LEH04 (72–76%) under estimated erosion due to the model assumption that the dune toe retreated upwards along the pre-storm beach slope while XBeach over-estimated erosion by 198%. Default parameters for XBeach resulted in large erosion volume estimates. The entire dune and upper beach were eroded back to the most landward grid point and then the profile continued to lower. Results are summarized in Table 5.

Model calibration significantly improved model results (Table 6). Observations showed the entire profile at each of the sites evolved and lowered during the May 2009 storm. As expected, modeled erosion volumes for the PH12 and LEH04 models were significantly under predicted compared to observations (35–100% and 38–93%, respectively). However, XBeach successfully modeled the erosion of the entire upper beach profile, resulting in volume change errors of 11–30% over the 161.5 h modeled (see Fig. 5 and Table 6).

Cumulative erosion volumes (normalized by the total predicted erosion volume for each model) throughout the storm are shown in Fig. 6. Modeled erosion with time was more variable for XBeach than LEH04 and PH12. Since the LEH04 model did not explicitly include a time variation for the water levels, the erosion rate was fairly constant throughout the storm (correlation between dV/dt and $tide = 0.25$ (0.27 neglecting ETA 58)). Alternatively, PH12 and XBeach included both the tides and surge over the duration of the storm. Using N_c as the parameterization for t/T resulted in dune erosion that varied with the tidal signal and was likely a better representation of the true time dependent erosion of the dune. Erosion occurred during almost every high tide using the PH12 formulation, with similar results using R_{LEH} and R_2 parameterizations (mean correlation between dV/dt and $tide$ for PH12 with $R_2 = 0.56$ (0.67 neglecting ETA 58)). In contrast, erosion was slightly more episodic, but still maintained a tidal signal when R_{16} was used (mean correlation $= 0.29$ (0.42 neglecting ETA 58)).

5. Discussion

5.1. Estimation of initial dune toe position in field data

The choice of initial dune toe position, as well as the dune toe trajectory (the slope at which the dune erodes) in the PH12 and LEH04 models will dictate the effectiveness of these models at reproducing the correct erosion/dune toe retreat. Isolating the dune toe can be difficult and somewhat user sensitive in field data when no obvious change in slope is present. In the field examples presented here, the pre-storm profiles had a generally steep concave shape between the shoreline and the crest (Fig. 3). The dune toe was chosen based on maximum change in slope between a user-defined area (between 0 m and 4 m AHD). At the profiles where large upper beach berms (with and without distinct changes in slope) were present (ETA 58 and 52), there was a potential for more than one toe to be considered and higher initial dune toe elevations didn't necessarily indicate the dune was more resilient to erosion. For instance, using the lower toe location for ETA 58, the toe eroded back and up (instead of back and down as in the instance of ETA 58a) and better agreement between models and observations were found.

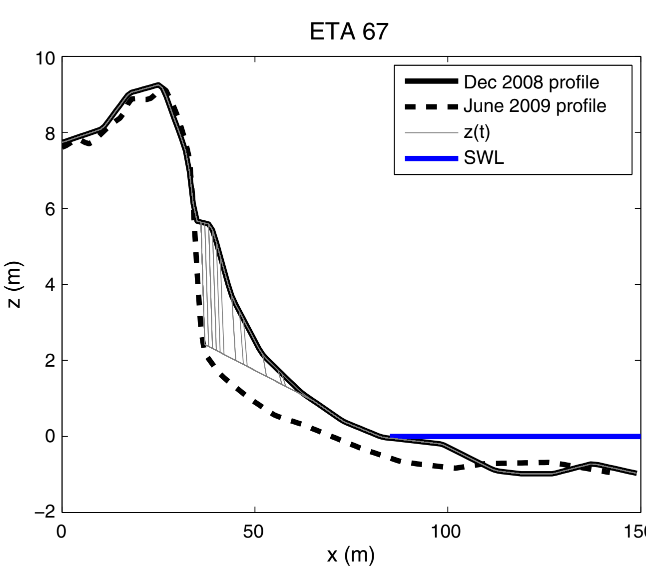


Fig. 3. Dune evolution for ETA 67 using R_2 and N_c in PH12 model.

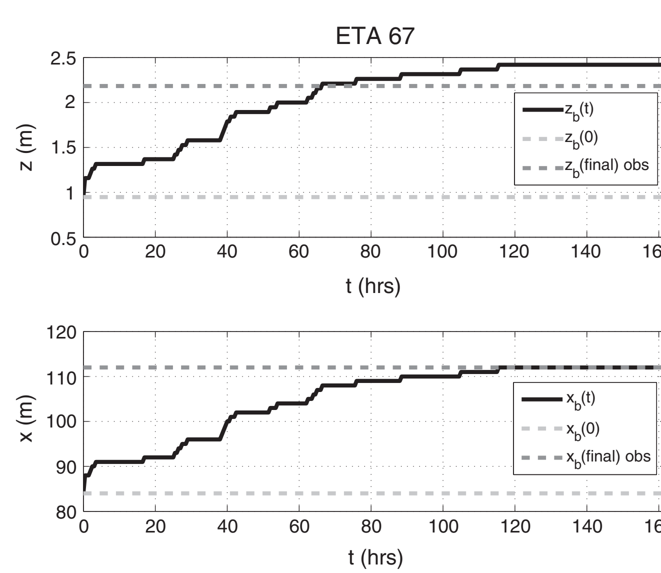


Fig. 4. Modeled dune retreat from ETA 67 using R_2 and N_c in PH12 model.

Table 5
Summary of eroded volumes (m^3/m) using the different uncalibrated models. Note a positive change in volume is erosion. Volume calculations are based on area above z = 0 m AHD. The models of LEH04 and PH12 do not erode below the dune toe, so erosion volumes are expected to be under-estimated if the profile lowered during the event. *Default runs for XBeach eroded to the landward grid point of the domain, thus erosion volumes are limited to volume of sand in pre-storm profile above AHD = 0 m. Parentheses represent % difference.

Method	ETA 67	ETA 63	ETA 58a	ETA 58b	ETA 52
Observed	66	74	109	109	114
LEH04	84(27)	11(50)	31(−72)	26(−76)	122(7)
PH12	25(−62)	36(−51)	1(−99)	0.4(−100)	34(−70)
XBeach*	386(485)	250(238)	325(198)	325(198)	321(182)

Similarly, the choice of dune toe at ETA 52 was at a distinct change in slope just above the swash zone at the base of the steeper berm and not at a second change in slope at the base of a more established dune above 2 m AHD. Comparison of pre and post-storm profiles for both ETA 58 and 52 show that significant erosion occurred in the upper beach/berm area as it eroded back towards the dune. Although no direct measurements were made during this storm, other mild storms at this location have shown that these beach berms will erode and scarp similar to a dune when under direct wave attack and thus if models such as LEH04 and PH12 are to be used at locations where large berms are present seaward of much higher, well established dunes, the lowest 'toe' is expected to give the most accurate results. Using the higher elevation of the pre-storm dune toe inhibited erosion of ETA 58 for LEH04 and PH12 in this case since water levels rarely reached the dune toe to cause erosion.

Post-storm surveys show the upper beach profile was lowered substantially and this cannot be accounted for in the models of LEH04 and PH12, yet has a large consequence to predicting runup and dune exposure to waves as highlighted at ETA 58. Despite these limitations, the simplified model of PH12 provided the most reliable estimate of dune toe retreat (% error between 7 and 73%) for the field data before calibration. With the exception of profile ETA 58, estimates using PH12 and LEH04 were between 0 and 12% of observed dune toe retreat when the model was calibrated to ETA 67 (including profile ETA 58, percent errors increased considerably for both models: PH12 (0–100%) and LEH04 (2–36%)). In the absence of offshore bathymetry needed to run XBeach, these results suggest both the uncalibrated model of PH12 and the calibrated models of PH12 and LEH04 could be useful as a first order estimate of coastal vulnerability to dune breaching as they provided reasonable estimates of dune toe retreat.

5.2. Estimation of the slope of dune retreat (dune trajectory, $tan\beta_t$)

In the results presented above, the dune toe trajectory was assumed to equal the initial beach slope and agrees with previous work of Larson et al. (2004) and Erikson et al. (2007). Palmsten and Holman (2012) observed in their experiments of dune retreat with over-topping and significant collisions that the dune retreated at half the initial beach slope. This variation suggests other parameters such as dune height (a proxy for the amount of sand available to feed the beach face as it erodes) as well as mean water level with respect to the dune toe may dictate how a dune retreats and warrants further investigation. For the field data set presented here, the dune crest was considerably higher than the total estimated runup and a large volume of sand was available to feed the upper beach. For ETA 67, 63, and 52, the mean $tan\beta_{fac} = 1.04$, thus the assumption that $tan\beta_t = tan\beta(0)$ seems reasonable based on this field data. A summary of observations from the field data used here is given in Table 2.

In contrast to this field data, runup exceeded or covered the dune face for most of the lab experiment reported in Palmsten and Holman (2012) and the height of the dune face was significantly lower resulting in less sand available to feed the upper beach (see Table 2). The beach and dune configuration considered by Palmsten and Holman (2012) was also significantly steeper than the field data due to scaling effects in the wave tank. A second likely laboratory effect in Palmsten and Holman (2012) was the step wise increase in the water level representing storm surge, rather than the continuously varying tide and surge level observed in the field. When the water level was increased, Palmsten and Holman (2012) reported an initial flattening of the beach, followed by steepening as sediment input from the dune decreased, possibly as the foreshore adjusted to a new equilibrium. For the field sites, locations with steeper pre-storm beach slopes retreated with a $\beta_{fac} < 1$ and the milder sloping beaches had a $\beta_{fac} > 1$. However, three of the four sites had very similar retreat slopes ($0.03 < tan\beta_t < 0.04$). In general, higher initial dunes toe $z_b(0)$ were also correlated with smaller β_{fac} as swash zone processes were expected to erode the foreshore below the base of the dune.

5.3. Choice of R_2 versus R_{16}

Palmsten and Holman (2012) tested both R_2 and R_{16} for their lab data used in PH12. With smaller beach faces and shorter dune crest height relative to total runup levels, they found R_{16} to be slightly better correlated with dune volume change than R_2, partly because measured R_2 was truncated when it exceeded the dune crest. Initial dune toe position prior to the onset of the storm was only 0.12 m above the still water level (SWL) and the dune was under considerable impact during the experiments. Both R_2 and R_{16} can be used in the field data cases presented here with the various calibration coefficients. R_{16} results in more episodic erosion (mean correlation with tide = 0.29), while R_2 modulates closely with the tides and surge (mean correlation = 0.56). R_2 produced lower average error in dune toe retreat than R_{16}, suggesting that when conditions fall in the collision regime R_2 is a better predictor of erosion at field scale.

5.4. XBeach model sensitivity

Sensitivity of XBeach results was investigated using the calibration profile, ETA 67. This was done in 2 parts: testing the sensitivity to uncertainty in offshore bathymetry (a frequent occurrence since pre-storm bathymetry is rarely available immediately before the storm); and to uncertainty in best-fit parameter values. To test the sensitivity of modeled dune erosion to uncertainty in offshore bathymetry, the model was run using the same pre-storm upper beach (z > 0 m AHD) profile and substituting in other available offshore bathymetry for this site. In total 27 profiles, including a maximum and minimum envelope, as well as a mean profile were used. Using measured data (Fig. 7, 95% CI), the model was not overly sensitive to variations in offshore bathymetry. The range of predicted erosion volumes was 59 m^3/m (−11% error) to 123 m^3/m (+87%). More terraced profiles resulted in less dune erosion, while profiles with steeper nearshore slopes and offshore bars resulted in slightly more erosion. The profile derived from using the maximum

Table 6
Summary of eroded volumes (m^3/m) using the different calibrated models. Calibration coefficients for C_s are based on calibration to ETA 67 (Table 1). Note a positive change in volume is erosion. Volume calculations are based on area above z = 0 m AHD. The models of LEH04 and PH12 do not erode below the dune toe, so erosion volumes are expected to be under-estimated if the profile lowered during the event. Parentheses represent % difference.

Method	ETA 67	ETA 63	ETA 58a	ETA 58b	ETA 52
Observed	66	74	109	109	114
LEH04	31(−53)	46(−38)	9(−92)	8(−93)	47(−59)
PH12 R_{LEH}	31(−53)	46(−38)	6(−94)	4(−96)	47(−59)
PH12 R_{16}	31(−53)	48(−35)	0(−100)	0.4(−100)	47(−59)
PH12 R_2	31(−53)	44(−41)	1(−99)	1(−99) 42(−63)	
XBeach	77(17)	82(11)	87(−20)	87(−20)	80(−30)

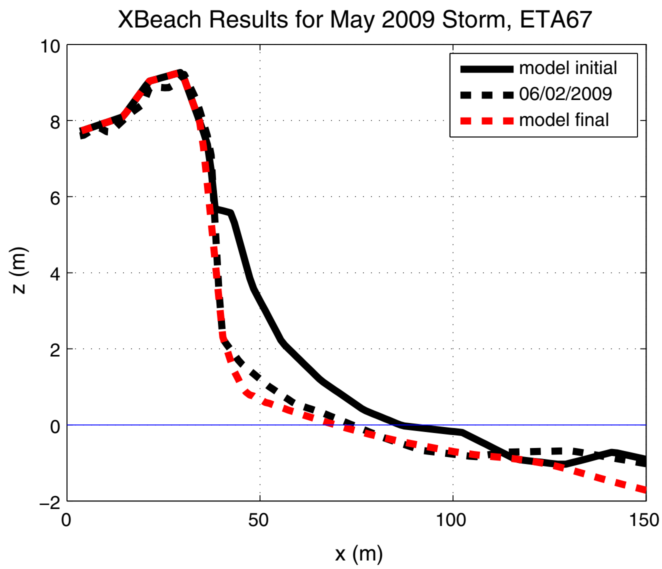


Fig. 5. ETA 67 XBeach calibrated result.

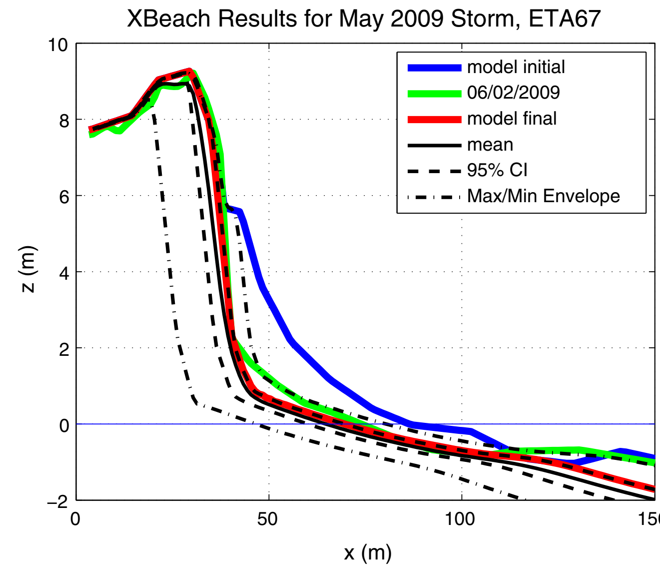


Fig. 7. ETA 67 XBeach: sensitivity to offshore bathymetry.

depth of all measured profiles (essentially an un-barred, steeper profile) resulted in the most upper beach erosion of $\Delta V = 213$ m^3/m or 223% (Fig. 7, lower bound dash-dot line), while the profile derived from the minimum depth of all measured profiles (i.e. a highly terraced/barred system) resulted in the least erosion ($\Delta V = 45$ m^3/m, −32%).The shallowest profile effectively dissipated more energy offshore and reduced runup and offshore directed erosion. At a field site where considerable two-dimensionality of the nearshore is expected with large flat terraces and deeper rip channels, it is often observed that locations where rip heads are directly offshore are co-located with areas of higher upper beach/dune erosion. This envelope of predicted erosion based on a range of bathymetries is therefore a good assessment of the possible range of erosion due to large alongshore variability in the nearshore bathymetry.

Erosion volumes were far more sensitive to changes in model free parameters than they were to variations in offshore bathymetry. Sensitivity testing of model free parameters were done by using best-fit values and then twice and half that value. Using the default values, XBeach significantly over-estimated upper beach erosion volume for profile ETA 67

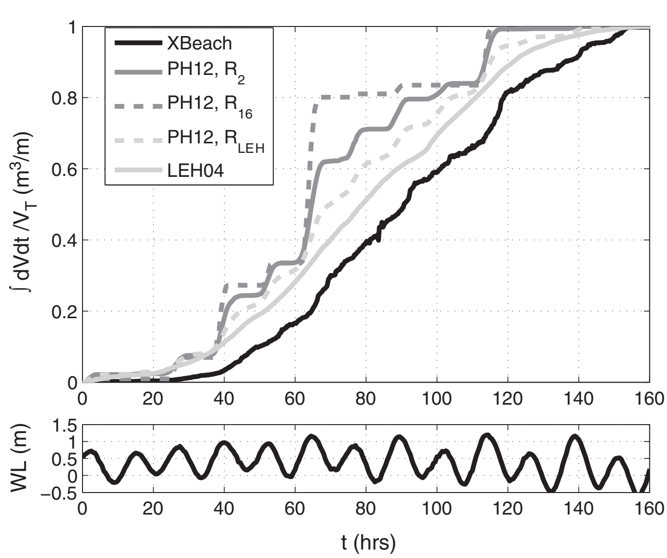


Fig. 6. Comparison of (top) modeled cumulative dune erosion using the various parameterizations listed in Table 1 and (bottom) measured water levels (tide + surge). All erosion volumes have been normalized by total erosion predicted (V_T).

by 485%. XBeach explicitly models the processes of waves and sediment transport below the mean water level and dune erosion is controlled by a critical avalanching term (Eq. (14)). Sediment transport is only calculated for grid cells that are ‘wet’ and have a user defined minimum water depth (*hmin*). Therefore, foreshore and dune erosion in the swash and collision regime (Sallenger, 2000) is based on the model's ability to accurately predict total water levels (runup + tide + surge). As water levels reach the much steeper dune, the critical slope threshold is exceeded and the dune avalanches and sand is placed at the dune toe to be moved by the next wave impact. Two parameterizations in XBeach exerted the most control on dune erosion: wave dissipation and wave skewness, yet both parameterizations dictate how sediment is transported and the profile evolves below the mean water level and not how the dune itself erodes. Model results were most sensitive to the choice of wave dissipation models (Roelvink, 1993, Eqs. (2) and (3)). The default model in XBeach (break = 3: (Roelvink, 1993, Eq. (3)) resulted in 120% error in eroded volume. The use of a slightly modified version of the default model (break = 1: (Roelvink, 1993, Eq. (2)) reduced error in eroded volume to 17%. The difference being dissipation proportional to H^2/h (Eq. (9)) rather than H^3/h (Eq. (10)). Roelvink (1993, eq. 2) is based on the assumption that wave height is the same order as water depth or Òpenetration depthÓ (Stive and Dingemans, 1984). Practically, this results in less intense dissipation of waves in the nearshore region when default values for n and γ are used in the percent breaking equation (Eq. (11)) and broader offshore sandbars develop, which will in turn, dissipate more wave energy offshore. Had the model been recalibrated for n and γ when using Roelvink (1993, eq. 3) similar results may have been achieved but this highlights the compounding sensitivity possible in XBeach.

The second most sensitive parameterization for modeling dune erosion in XBeach is the relative influence of wave skewness (γ_{ua}) on sediment transport. Error related to choice of γ_{ua} ranged from −72 to 112%. The choice of γ_{ua} (Eq. (14)) dictates the relative influence of onshore versus offshore wave driven sediment transport. In storm situations, it is assumed that sediment transport is predominantly driven by infragravity waves, is alongshore uniform, and is entirely offshore directed. Sand is mobilized by breaking waves and is carried offshore by strong undertow. Transport is in phase with the long wave component of the near-bed wave velocity ($\gamma_{ua} = 0$). These results in sediment being removed from the nearshore and the vertical flattening of sandbars, and in turn, waves dissipating closer to shore and increased runup. For values of $\gamma_{ua} > 0$, the effects of short wave skewness and asymmetry are included. Both short wave skewness and asymmetry have been shown to move sediment onshore under calm conditions (e.g. Gallagher et al., 1998; Hoefel and Elgar, 2003) and under the current formulation, $\gamma_{ua}=1$ would indicate that all sediment transport is onshore directed. This would result in steep swash zone berms and bars that would effectively dissipate more wave energy. By calibrating the model for $\gamma_{ua}>0$, we optimize for a balance of onshore versus offshore directed processes and sediment transport in the nearshore for storms. Offshore bars are maintained to a certain degree, allowing for offshore dissipation of wave energy and limiting runup. In contrast to wave dissipation and wave skewness, the model was generally insensitive to changes in the minimum depth of where sediment transport was calculated (*hmin*). For values of *hmin* ranging between 0.1 m and 0.001 m, the variability in erosion volume was 11–17%). The depth of wetting and drying (*eps*) ranging between 0.2 m and 0.05 m resulted in eroded volume differences of −9–35%. When variation in the critical slope on the wet and dry beach (*wetslp* or *dryslp*) were considered erosion volume varied by 17%. Sensitivity results are summarized in Table 7. These results suggest site specific calibration is likely necessary in order to ensure accurate estimates of erosion for future storm scenarios.

5.5. Applicability of models to dune erosion scenarios

This study applied three models to the same section of coastline. The different levels of calibration needed and accuracy of the results indicate that each model has a unique niche for dune modeling. To explore the benefits of the different models, one can consider two different modeling scenarios. In the first scenario, the objective is to forecast dune erosion and retreat over a long stretch of coastline prior to the arrival of a storm similar to the approach of Stockdon et al. (2007). In the second scenario, the physical processes controlling a well-documented erosion event are investigated and volume of sand eroded from the dune is the quantity of interest.

PH12 would be a likely candidate for estimating dune retreat in the first scenario because it requires little to no calibration and is computationally inexpensive. Given offshore wave predictions and an initial beach slope and dune profile along with an assumption made for the dune toe trajectory, dune retreat distance (Δx) could be made in a matter of seconds. With this information, possible locations of dune breaching and subsequent flooding may occur could also be given to local authorities to better plan for evacuation and the likelihood of property damage. Based on results presented here, the models of LEH04 and PH12 work best when erosion is expected to be predominantly within the ‘collision’ regime (Sallenger, 2000) and waves are actively impacting the dune. Where initial dune toe elevations are significantly higher than MHW and water levels are expected to be predominantly in the ‘swash’ regime (Sallenger, 2000), the proportion of dune erosion versus total subaerial beach erosion is diminished and these parametric dune erosion models are no longer valid. In these situations estimates of dune retreat are often under-estimated and additional estimates of ‘swash’ regime erosion are needed to determine the time evolution of erosion.

In contrast to the first scenario, the second scenario assumes that a significant amount of information about boundary conditions is known, that the model is properly calibrated to the site, and that there is no time requirement for producing results, so that computational expense is not a limiting factor. Our results suggest that XBeach would be the optimum model for this scenario. In addition, where erosion is expected to be dominated by ‘swash’ or ‘overwash’ regimes (Sallenger, 2000) and no parameterized model exists, then a model that is capable of resolving these processes, such as XBeach, is preferred.

Table 7
Sensitivity of eroded volumes (m^3/m) in XBeach to different model parameters. Volume calculations are based on area above z = 0 m AHD. Observed erosion for ETA 67 was $\Delta V=66$ m^3/m. Best-fit values *break* = 1, *hswitch* = 0.1 m, *hmin* = 0.01 m, *eps* = 0.1 m, *facua* = 0.15. rmse = root mean square error between the measured and modeled final profiles above z = 0 m AHD.

Parameter	ΔV (m^3/m)	rmse (m)
Default	386	6.13
Best-fit	77	0.39
break = 3	145	2.04
hswitch = 0.05 m	77	0.38
hswitch = 0.2 m	77	0.38
hmin = 0.005 m	77	0.39
hmin = 0.02 m	73	0.31
eps = 0.05 m	89	0.68
eps = 0.2 m	60	0.52
facua = 0.075	140	1.95
facua = 0.3	19	1.07

6. Conclusions

In this paper we tested and compared three dune erosion models of varying complexity. The first was a simple parametric model that only requires information about the initial dune toe position and offshore wave parameters (Larson et al., 2004) and includes no influence of tides and surge. The second model was an expansion of LEH04 that explicitly includes runup, *R*, tides and surge via the number of collisions of waves impacting dunes (Palmsten and Holman, 2012). The third was the process-based model, XBeach (Roelvink et al., 2009), which explicitly models wave transformation, dissipation and resulting sediment transport across the entire profile but as a result also requires nearshore bathymetry as an additional input. With no calibration, PH12 produced the smallest errors of dune toe retreat for all three models, with mean error in final dune position of 6.6 m, or 18% of the average observed total dune retreat. With minimal calibration all 3 models provided reliable estimates of dune toe retreat for a storm event on the Gold Coast, Queensland, Australia. Estimated error in average dune toe retreat for the four sites tested was within 13% of observed retreat (average absolute error: XBeach = 11%, LEH04 = 10%, PH12 = 13%). Excluding ETA 58 where a significant portion of the erosion was below the initial dune toe, absolute errors drop to: 7%, 5%, and 6% for the three models.

XBeach and LEH04 formulation predicted relatively continuous erosion, while PH12 was more tidally modulated. XBeach was the only model capable of predicting the lowering of profiles and erosion of the beach face due to the nature of LEH04 and PH12 which only model erosion above the pre-storm dune toe. Despite this, similar results were achieved by all models in terms of dune retreat. The sensitivity of the process-based model to tuning parameters was somewhat concerning and suggests site specific calibration may be needed. Alternatively, the formulation of PH12 performed well using default values found from lab data in Larson et al. (2004) and best-fit calibrations were only slightly greater for the field site tested here. Thus replacing R_{LEH} with R_2 and using a probability distribution for predicted collisions (N_c) provided a more robust model that can be applied at different sites without the need for calibration, making it more attractive than models requiring significant field site specific tuning such as LEH04 and XBeach. Regardless of its simpler form, the model of PH12 with R_2 and assuming a dune retreat trajectory equivalent to the pre-storm beach slope provides a reasonable estimate of dune retreat and a viable alternative to the more complex models when offshore field data is not available. Additionally, the simplicity of the model makes it attractive for large scale application to determine coastal vulnerability along coastlines prior to the onset of storms if pre-storm upper beach data (ex. from lidar) is available.

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