Coastal Engineering 83 (2014) 49–55

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Short communication

A relationship to describe the cumulative impact of storm clusters on beach erosion

Kristen D. Splinter [a,b,*], James T. Carley [a], Aliasghar Golshani [b], Rodger Tomlinson [b]

[a] *Water Research Laboratory, School of Civil and Environmental Engineering, University of New South Wales, 110 King St. Manly Vale, NSW 2093, Australia*
[b] *Griffith Centre for Coastal Management, Griffith University, Southport, QLD 4222, Australia*

ARTICLE INFO

Article history:
Received 28 June 2013
Received in revised form 22 August 2013
Accepted 4 October 2013
Available online 25 October 2013

Keywords:
Beach erosion
Extreme storms
Storm clusters
Storm sequencing
Dune erosion
Gold Coast

ABSTRACT

Estimation of erosion volumes for adequate dry beach buffer zones is commonly estimated on the basis of a single extreme event, such as the 1 in 100 year storm. However, the cumulative impact of several smaller, closely spaced storms can lead to equal, if not more, dry beach loss, but this is often not quantified. Here we use a calibrated model for dune erosion, XBeach, to hindcast the cumulative erosion impact of a series of historical storms that impacted the Gold Coast, Queensland region in 1967. Over a 6-month period, four named cyclones (Dinah, Barbara, Elaine, and Glenda) and three East Coast Lows caused a cumulative erosion volume greater than the predicted 1 in 100 year event. Results presented here show that XBeach was capable of reproducing the measured dry beach erosion volume to within 21% and shoreline retreat to within 10%. The storms were then run in 17 different sequences to determine if sequencing influenced final modeled erosion volumes. It is shown that storm sequencing did not significantly affect the total eroded volumes. However, individual storm volumes were influenced by the antecedent state of the beach (i.e. prior cumulative erosion). Power-law relationships between cumulative energy density ($\sum E$) and eroded volume (ΔV) as well as cumulative wave power ($(\sum P)$) and eroded volume (ΔV) both explained more than 94% of the modeled dry beach erosion for the 1967 storm sequences. When the relationship was compared with observed and modeled erosion volumes for similar beaches but different storm forcing, the inclusion of pre-storm beach swash slope (β_{swash}) in the parameterization was found to increase the applicability of the power-law relationship over a broader range of conditions.

1. Introduction

While sandy coastlines are observed to be highly dynamic on timescales from days to years, the impact of storms on beaches can cause dramatic erosion over a very short time period. Storm waves determine the destructive potential of a storm, while the range in water levels (tides and surge) also influences the erosion potential, particularly on the upper beach, in the presence of spring tides and large surge. Notable examples of large erosion events include the impact of hurricanes and Nor'easters along the east coast of the USA, such as the 2013 'Super Storm Sandy', as well as tropical cyclones and East Coast Lows along the east coast of Australia, such as the 2007 'Pasha Bulker Storm'.

While typically we design for the impact of these extreme individual storms (i.e. the 1 in 100 year event, which signifies a storm that has a 1% chance of occurring every year), the cumulative impact of smaller closely-spaced storms (i.e. storm sequencing, or clusters) can far outweigh the erosion potential of a single much larger storm (Birkemeier et al., 1999; Callaghan et al., 2009; Carley and Cox, 2003; Castelle et al., 2008; Cox and Pirrello, 2001; Ferreira, 2002, 2005; Thom and Hall, 1991). Examination of almost 20 years of Duck, North Carolina data by Birkemeier et al. (1999) showed that the largest integrated wave power associated with a storm group had an average return interval of occurrence (ARI) of 20 years. However, for an individual storm of equivalent wave power, this equated to greater than a 1 in 1000 year event (i.e. 1000 year ARI). As such, it is critical for coastal engineers and managers alike to be able to predict erosion volumes for both single storms and the cumulative impact of smaller storms in order to protect the coastline and adjacent infrastructure.

This communication focuses on the sequence of storms that impacted the Gold Coast, Queensland, Australia region during the first half of 1967 and summarized in McGrath (1968) and Allen and Callaghan (1999). It is estimated that nearly 8 million cubic meters of sand was lost from the subaerial beach (above mean sea level, MSL) during this 6-month period of above average wave conditions (Delft, 1970). As a consequence, this sequence of storms is often used as the design storm for the region.

* Corresponding author at: Water Research Laboratory, School of Civil and Environmental Engineering, University of New South Wales, 110 King St. Manly Vale, NSW, 2093, Australia.
E-mail address: k.splinter@unsw.edu.au (K.D. Splinter).

0378-3839/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coastaleng.2013.10.001

The calibrated model, XBeach (Roelvink et al., 2009), is used to first predict the erosion for the 6-month period in 1967 and then assess if storm sequence may have impacted the total observed beach erosion. This communication then utilizes these results to examine more generally the relationship between cumulative storm forcing (measured as wave power or wave energy density) and total erosion volumes along a micro-tidal, exposed open coastline.

2. Methodology

2.1. Data

2.1.1. Storm selection

Based on McGrath (1968) three named cyclones (Dinah, Elaine, and Glenda) and three East Coast Lows (ECLs) had deep-water H_s over 2 m and were used to estimate the impact of storm sequence on overall beach erosion at the Gold Coast (Table 1). Along the Gold Coast, $H_s =$ 2 m approximates the 95% exceedance value and the threshold of $H_s > 2$ m to define a storm wave is commonly used along the South-East coast of Australia (e.g. Shand et al., 2011). A storm start and finish was defined when H_s first exceeded this threshold (start) and the last successive time before H_s fell below the threshold (end).

Storm clusters are often characterized by recurring high wave events in close succession such that the beach does not have adequate time to recover significantly between events. The definition of a storm group depends on the recovery timescale of the specific beach. Typically 1 to 2 months is used as a threshold between storms to define a storm cluster (Birkemeier et al., 1999). However, along the Portugal coast, Ferreira (2005) utilized 3 weeks between storm peaks or 2 weeks between the end of one storm and the start of the next to define a storm group. Spacing between the 1967 storms ranged from a few days to just over 2 months (1). For the sequence of storms considered here, McGrath (1968) stated that for the first six months of 1967 the swell was generally heavy and that conditions conducive to beach recovery did not return until September 1967, and as such, is considered a single event (storm group).

2.1.2. Available bathymetry

Bathymetry data for the northern Gold Coast (Narrowneck) were generated from digitized profiles shown in McGrath (1968), Delft (1970), and available Gold Coast City Council surveys. Pre-storm surveys were from October 1966 and post-storm surveys were dated July 1967. It is noted that the inner surf zone/bar was not surveyed for the pre-storm survey and the gap in the data was linearly interpolated. The two most landward points from the 1967 survey were used to extend the 1966 profile backwards to allow for additional erosion.

2.1.3. Waves

No wave buoys were located in the area in 1967 such that wave statistics were taken from the global wind-wave model of the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year wave Re-Analysis with the wave height correction applied by Caires and Sterl (2005) (corrected ERA-40) for grid point coordinates (28.5°S, 154.5°E) located approximately 122 km southeast of the Gold Coast. Modeled directional wave data included spectral significant wave height (H_s), mean wave period based on the 2nd moment (T_{02}), and wave direction measured from degrees North (θ). Mean wave period was transformed to peak wave period (T_p) based on the method of Paik and Thayamballi (2007), p.107 assuming a JONSWAP ($\gamma = 3.3$) spectrum (Hasselmann et al., 1976). These were used as offshore boundary conditions in a calibrated MIKE-21 spectral wave model (Splinter et al., 2012). Modeled wave statistics (H_s, T_p, θ) in 25 m of water directly offshore of Narrowneck were extracted from the MIKE-21 spectral wave model and used as input into XBeach.

Table 1
Storm duration (denoted as hrs where $H_s > 2$ m), integrated wave energy density, E (Eq. (2)) and wave power, P (Eq. (3)).

Storm	Start date	Duration (hrs)	$\sum E$ (MJh/m^2)	$\sum P$ (MWh/m)
Dinah	28-01-1967	48	0.25	1.92
Elaine	12-03-1967	126	0.39	2.79
Glenda	31-03-1967	138	0.54	4.30
ECL1	11-06-1967	120	0.51	3.95
ECL2	21-06-1967	54	0.19	1.36
ECL3	26-06-1967	108	0.42	3.64

2.1.4. Total water levels

Total water levels can also play an important role in the erosion potential of a storm (e.g. Dean, 1991) when it lasts several tidal cycles or makes impact during spring high tides (particularly important on large tidal range beaches). These elevated water levels further expose the upper beach and dune system to direct wave impact. To include this forcing mechanism, water levels were derived from the superposition of tides and surge information detailed in McGrath (1968). Maximum surge recorded was of the order of 1 m and occurred on June 27th during ECL3. Total water levels (excluding wave setup and runup) for all six storms considered never exceeded 2 m above mean sea level (MSL). This is of the same order of magnitude as the mean spring tide range for the Gold Coast(~1.5 m) as reported by Turner et al. (2006) and as such, was not considered to be the principal driver of beach erosion during these storms. Additionally, as peak surge frequently occurred during the peak of the storm (when wave heights and periods were also at their largest), simple relationships correlating wave height to erosion may also capture some effect of total water levels.

2.2. Model

XBeach (Roelvink et al., 2009) is a process-based numerical model designed to estimate eXtreme Beach erosion under storm events. The reader is referred to Splinter and Palmsten (2012), Roelvink et al. (2009) and the XBeach user's manual (www.xbeach.org) for a complete description of the model. Model inputs included a time series of 3-hourly offshore significant wave heights (H_s), spectral peak wave period (T_p), and wave direction (θ, degrees North) as well as hourly total water elevation (tide + surge) as described above.

For the results presented here, XBeach (version 18) was run in profile mode and calibrated using the Narrowneck pre- and post-storm surveys from the May 2009 East Coast Low as detailed in Splinter and Palmsten (2012). Good model agreement between the observed dry beach erosion and modeled erosion for the May 2009 ECL was found using default values except γ_{ua} (best-fit = 0.15), which defines the influence of short wave skewness and asymmetry on sediment transport, and wave dissipation (best-fit = Roelvink (1993), Eq. 2). Observed shoreline retreat was 28 m and was modeled to within 1 m. Observed dry beach erosion volume (measured above 0 m AHD (Australian Height Datum) and roughly equal to MSL) was 66 m^3/m and was over-estimated by 11 m^3/m (17%). Detailed sensitivity analysis to both errors in the pre-storm profile and model free parameters is presented in Splinter et al. (2011) and Splinter and Palmsten (2012).

2.3. Assumptions and simplifications

Several simplifications have been made in order to run the 1967 storm sequence. First, the model was run in profile mode (no alongshore gradients in transport) and this was assumed as an acceptable simplification given that the focus here is on the modeled dune erosion (a cross-shore process) and limited survey data was available. Longshore transport is of order 500,000 m^3/year (e.g. Patterson, 2007; Splinter et al., 2012), however, alongshore gradients in longshore transport are not the dominant mode of shoreline variability at the seasonal to annual scale (Davidson and Turner, 2009; Davidson et al., 2013). Second, the model was restarted for each new storm. As detailed above, it was assumed that negligible recovery occurred between the closely spaced storms such that the final bathymetry from the preceding storm was used as the initial bathymetry for the subsequent storm. Additionally, XBeach has already been shown to be relatively insensitive to small errors in the offshore bathymetry. For example, Splinter et al. (2011) showed that the observed dry beach erosion for the May 2009 storm was within the 95% confidence intervals of estimated erosion volumes when all available offshore profiles for Narrowneck were used as input for XBeach with the pre-storm upper beach profile. As there were no available inter-storm profile data available and the focus here is on the erosion of the upper beach profile, the assumption of no recovery was considered reasonable. The impact of starting the model for each storm appropriately limits the growth of infragravity energy in the model.

3. Results

The destructive forcing of a storm can be assessed by considering the storm duration (N), integrated wave energy density ($\sum E$), and wave power ($\sum P$). Integrated wave energy density is defined as:

$$\sum E = \int_0^N \frac{1}{8}\rho g H_{rms}^2 \Delta t. \tag{1}$$

Assuming a Rayleigh distribution of waves, H_{rms} can be substituted by $H_s/\sqrt{2}$ (Dean and Dalrymple, 1991) and Eq. (1) becomes:

$$\sum E = \int_0^N \frac{1}{16}\rho g H_s^2 \Delta t. \tag{2}$$

Similarly, wave power is defined as $P = EC_g$, where C_g is the group velocity and for deep-water can be written as:

$$\sum P = \int_0^N \frac{\rho g^2}{64\pi} H_s^2 T_p \Delta t \tag{3}$$

where ρ is the density of sea water, g is gravitational acceleration, H_s is the deepwater significant wave height, T_p is the peak wave period, Δt is the time step of measurements, and N is the total duration of the storm. Cyclone Glenda was the longest duration storm and had the largest integrated energy/power, while the second ECL (ECL2) was the shortest and had the smallest integrated energy/power (Table 1).

3.1. 1967 Storm cluster

XBeach was first run to match the observed sequence of six storms and subsequently ran in seventeen representative combinations to examine the influence of storm sequence on cumulative eroded dry beach volumes and shoreline retreat. Representative combinations included running in the reverse order, and from high–low (and vice versa) storm energy. Each storm started and ended a sequence at least once.

Two metrics were used to determine model skill. First, whether the model was able to reproduce the observed change in shoreline (Δx_{MSL}), measured as the cross-shore (horizontal) displacement of the MSL contours (0 m AHD) between the initial survey (subscript i) and the final (subscript f):

$$\Delta x_{MSL} = x_{MSL,f} - x_{MSL,i}. \tag{4}$$

The second metric examined the model ability to reproduce the correct amount of eroded dry beach volume (ΔV). Dry beach volume was calculated as the cross-shore integration of the profile elevation (z) above MSL:

$$\Delta V = \int_0^{x_{MSL,f}} z dx - \int_0^{x_{MSL,i}} z dx. \tag{5}$$

The observed shoreline retreat for the 1967 storms was 41 m and the observed change in volume was $-103\,m^3/m$. Modeled shoreline retreat for the original storm sequence over the 6-month period was underestimated by 4 m (10%) and eroded volume above MSL by 22 m^3/m (21%). Fig. 1 shows the XBeach results for the upper beach for the original sequence of the six storms.

Analysis of the eighteen different storm sequences (1 observed and 17 synthetic) found that erosion volume for a given storm was both proportional to the integrated wave energy density (Eq. (2)) or wave power (Eq. (3)) from the individual storm as well as the cumulative energy density (or power) from previous storms (Figs. 2 and 3). As shown in Figs. 2 and 3 cumulative erosion volumes based on the original observed sequence of storms (solid circles) are not differentiable (lies within the bands of variability) from the remaining 17 permutations (open circles). This indicates that the beach follows a general equilibrium approach based on the prevailing wave conditions.

A power-law relationship (Eq. (6)) has been suggested by others to reasonably represent the relationship between eroded beach width and integrated storm energy (Harley et al., 2009) as well as eroded beach volume and storm return period (Ferreira, 2005). The power law used here follows the form:

$$\Delta V\left(m^3/m\right) = a\sum F^b, \tag{6}$$

where a and b are free model coefficients and F (Eqs. (2) and (3)) is the generic forcing term that represents either wave energy density, E (MJh/m^2), as examined in Harley et al. (2009) or wave power, P (MWh/m), as used in Birkemeier et al. (1999). The power-law relationship explained over 94% of the modeled dry beach erosion variance for the 1967 storm sequences (Table 2). Results of the best-fit coefficients and 95% confidence intervals are presented in Table 2 along with goodness of fit based on correlation-squared (R^2) statistics.

3.2. Generic application

To determine if the relationship described in Eq. (6) showed generic applicability beyond the specific cluster of storms in 1967, and how the cumulative impact of storms related to notable single storm events, additional erosion volumes from a number of storms were plotted in Figs. 2 and 3. These include observations from the Northern Gold Coast at two sites: Narrowneck and Surfers Paradise, for three successive storms in 1988 and East Coast Lowsin 1996 and 2009 as detailed in Carley et al. (1999) and Splinter and Palmsten (2012). Additional XBeach model results using a temporally-averaged beach profile for Surfers Paradise for design storms with ARIs of 1, 2, 5, 10, 20, 50 and 100 years are also included (Carley et al., 1998). For these field cases, buoy data in 17 m of water located directly offshore of Narrowneck was used. The wave statistics include significant wave height using the zero-upcrossing method (H_s), spectral peak period (T_p), and wave direction (θ, degrees North). As is observed in Figs. 2 (top) and 3 (top), Eq. (6) based on the 1967 data shows good agreement ($R^2 = 0.75$) with the new observations and modeled erosion with the exception of one outlier storm in 1988 and the predicted erosion volumes for the ARI events. The use of integrated wave power or wave energy density did not alter model skill (Table 2), suggesting that the small variations in wave period ($\Delta T_p < 5$ s) between the storms did not significantly influence upper beach erosion (Carley et al., 1998).

To understand why the modeled ARI storms under-predicted erosion for a given forcing compared to the 1967 storms (Eq. (6)), the influence of: (1) nearshore beach slope ($\beta_{nearshore}$, measured between

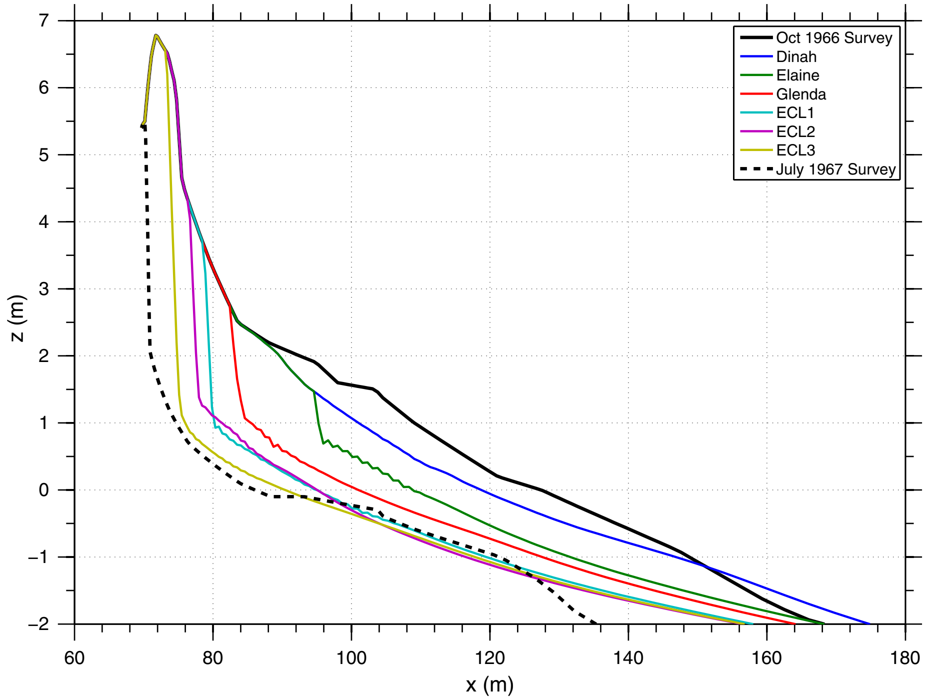

Fig. 1. Successive modeled erosion cuts for northern Gold Coast (Narrowneck) during the original sequence of storms in 1967 with pre- and post-storm surveys. Shoreline retreat was modeled to within 10% and erosion volume (above MSL) to within 21%. The vertical elevation (z) is measured relative to Australian Height Datum (AHD), where AHD = 0 is roughly mean sea level.

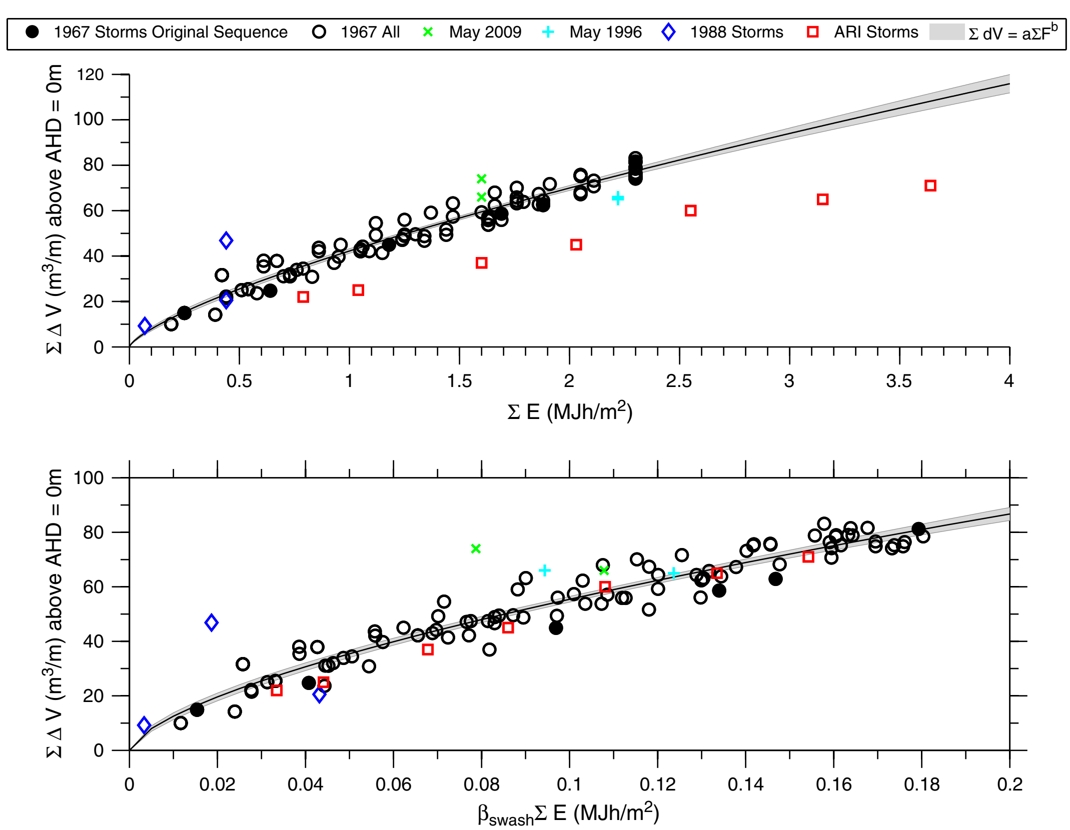

Fig. 2. (Top) Relationship between modeled and observed erosion volumes compared to cumulative wave energy density ($\sum E$). (Bottom) Relationship accounting for swash excursion beach slope estimated between MSL (0 m AHD) and +2 m AHD contour. Swash beach slopes ranged from 0.0424 to 0.1071. The inclusion of the swash beach slope improved overall model squared-correlation to 0.89 (Table 2). For both figures, 1967 and ARI storms are modeled erosion whereas May 2009, May 1996 and 1988 are observed erosion. Best-fit model prediction (with 95% CI, gray band) is based on the modeled erosion volumes for the 18 sequences of the 1967 storms. Model coefficients are summarized in Table 2.

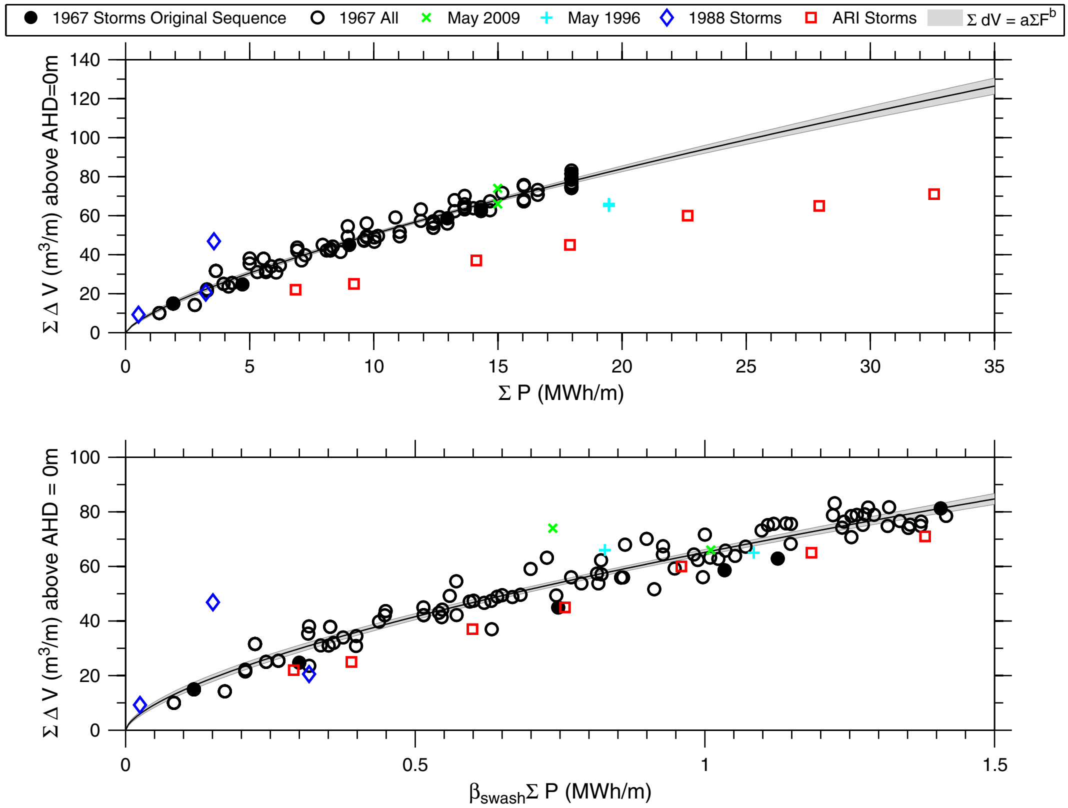

Fig. 3. (Top) Relationship between modeled and observed erosion volumes compared to cumulative wave power ($\sum P$). (Bottom) Relationship accounting for swash excursion beach slope estimated between MSL (0 m AHD) and +2 m AHD contour. Swash beach slopes ranged from 0.0424 to 0.1071. The inclusion of the swash beach slope improved overall model squared-correlation to 0.89 (Table 2). For both figures, 1967 and ARI storms are modeled erosion whereas May 2009, May 1996 and 1988 are observed erosion. Best-fit model prediction (with 95% CI, gray band) is based on the modeled erosion volumes for the 18 sequences of the 1967 storms. Model coefficients and statistics are summarized in Table 2.

MSL (0 m AHD) and −15 m AHD); (2) swash beach slope (β_{swash}, measured between the 0 m AHD and +2 m AHD contour); and (3) maximum dune height (z_{max}) were examined (see Fig. 4). These three parameters were chosen as they influence: (1) surf-zone dissipation and the cross-shore location of wave breaking; (2) wave run-up (e.g. Stockdon et al., 2006), which is a key component in dune erosion potential (e.g. Sallenger, 2000; Stockdon et al., 2007) along with the elevation of the dune top with respect to MSL (3) which acts as a proxy for the level of erosion that might be experienced (Sallenger, 2000), as well as the volume of sand available to replace eroded sand at the base of the dune. An example of how each term was estimated is shown for the pre-storm profile used in the 1967 storm sequence (Fig. 4). While there was approximately 70 different measurements made for the 1967 storm sequence, Table 3 summarizes the pre-storm characteristics used at each of the sites based on available survey data.

Table 2
Coefficients (± 95% confidence intervals) for empirical relationship between forcing and estimated erosion volumes based on the 1967 storms (circles in Figs. 2 and 3). Units of Energy Density = MJh/m^2 and Power = MWh/m. R^2(1967) is the squared-correlation of the model versus the observed 1967 erosion volumes and R^2(All) is for all data considered.

Model F	a	b	R^2(1967)	R^2(All)
$\sum E$	42.24 ± 1.02	0.73 ± 0.04	0.96	0.75
$\beta_{swash}\sum E$	245.29 ± 21.37	0.65 ± 0.04	0.94	0.88
$\sum P$	9.42 ± 0.77	0.73 ± 0.03	0.97	0.75
$\beta_{swash}\sum P$	65.14 ± 1.05	0.65 ± 0.04	0.95	0.89

When the influence of pre-storm beach swash slope, β_{swash} ($0.0424 \le \beta_{swash} \le 0.1071$) for each of the events was included in Eq. (6) as

$$\Delta V' = \beta_{swash} a \sum F^b, \tag{7}$$

overall model skill was significantly improved (R^2 ~ 0.9). As shown in Figs. 2 (bottom) and 3 (bottom), the individual ARI storms now lie within the variability of the 1967 storm sequences. This suggests that pre-storm beach swash slope (β_{swash}) is an important parameter in estimating dune erosion potential for an individual storm.

4. Conclusion

Estimating the impact of storm clusters on beaches has long been a concern for coastal engineers with very little data available to develop relationships between cumulative wave forcing and total beach erosion. Here the historical storm sequence experienced along the Gold Coast in the first six months of 1967 was used to model and develop a relationship between the impact of storm clusters and overall dry beach erosion. XBeach was capable of reproducing the observed dry beach erosion to within 21% based on the original sequence of storms. Analysis of erosion volumes based on 18 permutations of this storm sequence indicates that modeled erosion for a particular storm is both a function of the storm itself (here measured by the integrated wave energy density or wave power for a specific storm) as well as the antecedent beach state (here measured by the cumulative wave energy density or wave power that has impacted the beach in the recent past). Additionally, it was observed that storm sequencing did not significantly impact the total erosion volumes for the entire storm cluster.

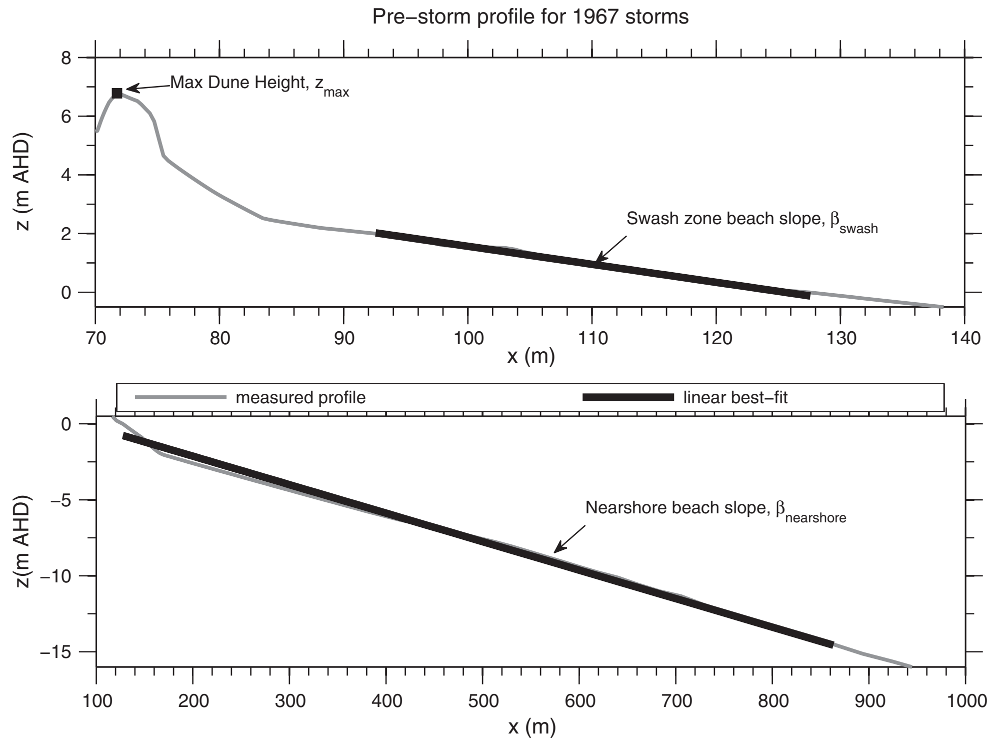

Fig. 4. Example of estimated beach parameters used to examine inter-site variability. (Top) Estimation of max dune height (z_{max}) and swash zone beach slope (β_{swash}) based on a linear best-fit of the profile measured between 0 m and +2 mAHD. (Bottom) Estimation of nearshore beach slope ($\beta_{nearshore}$) measured between 0 m and −15 m AHD.

From these results, a simple power-law relationship between storm forcing (measured as either cumulative wave energy density or wave power within a storm cluster) versus eroded dry beach volume was derived (R^2>0.94). When the relationship was compared with observed and modeled erosion volumes for individual events at similar beaches with different storm forcing, and varying pre-storm bathymetry, the inclusion of pre-storm beach swash slope (β_{swash}) was found to increase the applicability of the derived relationship between eroded volume and forcing over a broader range of conditions for both individual events and storm clusters (R^2~0.90). The derived relationship between cumulative wave energy density (or power) and cumulative beach erosion shows excellent predictive skill on an exposed coastline with varying beach slope and can be used as a first pass assessment of beach vulnerability to a particular storm event (or storm cluster) in micro-tidal environments where storm surge is not the driving factor in dune erosion.

Table 3
Pre-storm measurements of parameters explored during the generic application of model. z_{max} is the maximum dune height, β_{swash} is the beach slope measured using linear regression between 0 m and +2 m AHD, $\beta_{nearshore}$ is the beach slope measured using linear regression between 0 m and −15 m AHD.

Site and storm ID	z_{max} (m)	β_{swash}	$\beta_{nearshore}$
Narrowneck 1967	6.78	0.0614	0.0188
Narrowneck 2009	9.26	0.0674	0.0208
Surfers Paradise 2009	5.45	0.0492	0.0209
Narrowneck 1996	7.52	0.0557	0.0214
Surfers Paradise 1996	5.46	0.0425	0.0209
Surfers Paradise June 1988	3.02	0.0981	0.0199
Surfers Paradise Sept. 1988	2.98	0.0479	0.0199
Surfers Paradise Nov. 1988	3.01	0.0424	0.0203
Surfers Paradise ARI	5.37	0.0424	0.0202

Acknowledgments

This work was funded under the Future Coastlines Projects in partnership with Griffith University and Queensland Smart State. Beach profiles and wave data were provided by Gold Coast City Council and European Centre for Medium-Range Weather Forecasts, respectively. The authors wish to thank I.L. Turner and D. Basco for their review comments.

References

Allen, M., Callaghan, J., 1999. Extreme wave conditions for the South Queensland coastal region. Report.EPA Queensland.
Birkemeier, W.A., Nicholls, R.J., Lee, G., 1999. Storms, storm groups and nearshore morphologic change. In: Kraus, N.C., McDougal, W. (Eds.), Coastal Sediments '99, ASCE. ASCE, pp. 1109–1122.
Caires, S., Sterl, A., 2005. A new nonparametric method to correct model data: application to significant wave height from the ERA-40 re-analysis. J. Atmos. Ocean. Technol. 22, 443–459.
Callaghan, D.P., Ranasinghe, R., Short, A.D., 2009. Quantifying the storm erosion hazard for coastal planning. Coast. Eng. 56, 90–93.
Carley, J.T., Cox, R.J., 2003. A methodology for utilising time-dependent beach erosion models for design events. Proc 16th Australasian Coastal and Ocean Engineering Conference, Engineers, Auckland, NZ.
Carley, J.T., Couriel, E.D., Cox, D.R., 1998. Numerical modelling sand nourishment profiles/quantities and beach erosion due to storms and sea level rise. WRL Technical Report 98/04. Water Research Laboratory, UNSW, 110 King St. Manly Vale, NSW 2093.
Carley, J.T., Turner, I.L., Couriel, E.D., Jackson, L.A., McGrath, J.E., 1999. The practical application of four commercially available numerical beach morphology models on a high energy coastline. Proceedings of the Australian Coastal and Ocean Engineering Conference, Perth, AU, pp. 101–106.
Castelle, B., Le Corre, Y., Tomlinson, R., 2008. Can the Gold Coast beaches withstand extreme events. Geo-Mar. Lett. 28, 23–30.
Cox, J.C., Pirrello, M.A., 2001. Applying joint probabilities and cumulative effects to estimate storm-induced erosion and shoreline recession. Shore Beach 69, 5–7.
Davidson, M.A., Turner, I.L., 2009. A behavioral template beach profile model for predicting seasonal to interannual shoreline evolution. J. Geophys. Res. 114, F01020.
Davidson, M.A., Splinter, K.D., Turner, I.L., 2013. A simple equilibrium model for predicting shoreline change. Coast. Eng. 73, 191–202.

Dean, R., 1991. Equilibrium beach profiles: characteristics and applications. J. Coast. Res. 7, 53–84.
Dean, R.G., Dalrymple, R.A., 1991. Water Wave Mechanics for Engineers and Scientists, volume 2. World Scientific Publishing Co.
Delft, 1970. Gold Coast, Queensland, Australia — coastal erosion and related problems. Technical Report R257. Delft Hydraulics Laboratory.
Ferreira, O., 2002. Prediction of the impact of storm groups and their importance in coastal evolution. Proceedings of the International Conference on Coastal Engineering, ASCE, pp. 2725–2730.
Ferreira, O., 2005. Storm groups versus extreme single storms: predicted erosion and management consequences. J. Coast. Res. SI 42, 221–227.
Harley, M.D., Turner, I.L., Short, A.D., Ranasinghe, R., 2009. An empirical model of beach response to storms — SE Australia. Coasts and Ports 2009: In a Dynamic Environment, Engineers Australia, pp. 600–606.
Hasselmann, K., Ross, B., Muller, P., Sell, W., 1976. A parametric wave prediction model. J. Phys. Oceanogr. 6, 200–228.
McGrath, B.L., 1968. Erosion of Gold Coast beaches. J. Inst. Eng. Aust. 40, 155–166.
Paik, J.K., Thayamballi, A.K., 2007. Ship-shaped Offshore Installations: Design, Building, and Operation. Cambridge University Press.
Patterson, D., 2007. Sand transport and shoreline evolution, Northern Gold Coast, Australia, in: proceedings of the 9th International Coastal Symposium. J. Coast. Res. SI 50, 147–151.
Roelvink, J.A., 1993. Dissipation in random wave groups incident on a beach. Coast. Eng. 19, 127–150.
Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., Lescinski, J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coast. Eng. 56, 1133–1152.
Sallenger, A.H.J., 2000. Storm impact scale for barrier islands. J. Coast. Res. 16, 890–895.
Shand, T.D., Goodwin, I.D., Mole, M.A., Carley, J.T., Browning, S., Coghlan, I.R., Harley, M.D., Peirson, W.L., 2011. NSW coastal inundation hazard study: coastal storms and extreme waves. Technical Report 2010/16. Water Research Laboratory, The University of New South Wales.
Splinter, K.D., Palmsten, M.L., 2012. Modeling dune response to an East Coast Low. Mar. Geol. 329–331, 46–57.
Splinter, K.D., Strauss, D., Tomlinson, R.B., 2011. Can we reliably estimate dune erosion without knowing pre-storm bathymetry? In: Stul, T. (Ed.), Coasts and Ports 2011, Engineers Australia.
Splinter, K.D., Davidson, M.A., Golshani, A., Tomlinson, R.B., 2012. Climate controls on longshore sediment transport. Cont. Shelf Res. 48, 146–156.
Stockdon, H.F., Holman, R.A., Howd, P.A., Sallenger, A., 2006. Empirical parameterization of setup, swash and runup. Coast. Eng. 53, 573–588.
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. Mar. Geol. 238, 1–20.
Thom, B.G., Hall, W., 1991. Behaviour of beach profiles during accretion and erosion dominated periods. Earth Surf. Proc. Land. 16, 113–127.
Turner, I.L., Aarninkhoff, S.G.J., Holman, R.A., 2006. Coastal imaging application and research in Australia. J. Coast. Res. 22, 37–48.