BRINGING BACK THE SAND: BEACH RECOVERY FOLLOWING STORM EROSION

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Abstract

Sustainable beach management requires an informed knowledge of the way sandy beach coastlines change with time. An ability to articulate how and when a beach will recover a protective sand buffer without human intervention following storm erosion, is vital in planning and design of beach management strategies. This study gives a valuable insight into beach recovery on the NSW coastline. Using a decade of daily beach width observations from a coastal image station at Narrabeen-Collaroy Beach, Sydney, a total of ten major recovery periods were observed following erosion associated with high impact storms and clusters of several storms. How and when a beach recovers in width is quantitatively described in terms of rates and timescales providing rule-of-thumb estimates and typical durations. Findings show net linear rates in the range of 0.05 m/day to 0.15 m/day with typical durations spanning several months to a year. At higher resolutions (days to weeks) beach width recovery rates are variable and complex. Results demonstrate the value of field data investigation toward a better informed quantitative understanding of beach recovery that it is often lacking in coastal risk assessment and management.

Keywords: beach recovery, accretion, observation, rate, duration

Introduction

The stretches of sandy beaches along the New South Wales coastline are a valuable natural asset requiring informed management and planning as coastal populations continue to grow and expand (ABS, 2015). Nationally, beach amenity and protection has been estimated as in the value of AU$3.8-13 million per kilometre of shoreline (Blackwell, 2007). There is a growing demand for management and planning to maintain beaches as a prized recreational public space and also an important natural buffer of protection during storms for nearby coastal settlements and supporting infrastructure (Department of the Environment, 2011).

Informed coastal management requires an adequate understanding of the way beaches change with time. The dynamic movement of the coastline in response to storms is a major component of this and an important factor in defining coastal hazards and risk assessment. Beyond single storms, this involves quantifying cumulative erosion hazards over multiple storms (Wainwright et al., 2015). A key component of this is knowledge of the natural recovery response of beaches following storms during which sand makes its way back onto the beach as it progressively recovers a former condition.

However at present, temporal understanding of beach change is often limited to the short duration erosion associated with single, extreme design storm events (Shand et al., 2011). Comparably little attention is given to the way beaches recover (Kobayashi and Jung, 2012). This hinders an ability to accurately predict cumulative erosion risks associated with storm clustering (Coco et al., 2014) and future predicted climatic changes (Wong et al., 2014). Limited field observations (Ranasinghe et al., 2012) and simplistic modelling approaches (Callaghan et al., 2013) give little insight into how and why beaches recover. Failure to accurately account for this may lead to significant implications for planning and decision making (Zhang et al., 2002). Furthermore community expectations and perceptions may also lack awareness of the natural recovery of beaches following storm erosion events.

In light of these challenges, studies quantifying beach recovery through field data measurement are of significant value. A common way to do so is by measuring the return of the shoreline position (representative elevation contour) from a post-storm to a pre-storm position (e.g. Splinter et al., 2011). This enables the quantification of timescales and rates of how a beach recovers in width following storm erosion events for a given location. Such investigations from long-term (decadal) datasets of adequate resolution, covering multiple recovery periods are rare worldwide (Corbella and Stretch, 2012) and warranted in studies of the NSW coastline.

Using daily beach width observations spanning a decade, obtained from an ARGUS coastal imaging station at Narrabeen-Collaroy Beach, NSW, this study gives valuable insight into beach recovery on the NSW coastline. Investigation of multiple recovery periods explores typical durations and rule-of-thumb rates suitable for first-hand estimates of beach width recovery at the site following substantial erosion events.

Site Description

Narrabeen-Collaroy Beach is located on the microtidal, moderate to high wave-energy, south east coast of Australia (Figure 1). The 3.6 km-long, east-facing embayment is one of numerous closed sediment cells bounded by rocky headlands and reefs within the Sydney region. Tides are semi-diurnal with a mean spring range of 1.3 m and sediment is composed of medium grained ($d_{50} \approx 0.3$ to 0.4 mm) quartz sand.

Deepwater waves in the region are predominantly from the south east (mean $H_s \approx 1.6$ m and $T_p \approx 10$ s) with significant wave heights exceeding 3 m for approximately 5% of the time. In the nearshore, Long Reef Point to the south, shelters the southern corner of the embayment (Collaroy) to predominant wave energy, with increasing exposure toward the north (Narrabeen). Shoreline positions used in this analysis were measured about Wetherill St, Narrabeen, located at a partially exposed region of the beach (refer Figure 1).

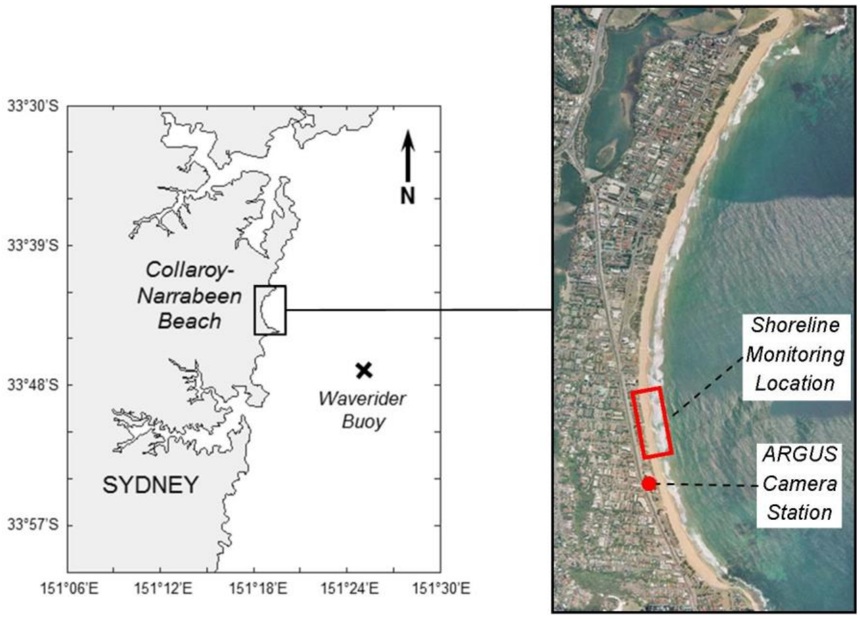

Figure 1: Study site location of Narrabeen-Collaroy Beach near Sydney on the South East Australian coastline. ARGUS image station and monitoring site near Wetherill St are illustrated.

Methodology

Beach Width Data Collection

Daily beach width data was obtained from time exposure ARGUS camera images collected over a ten-year period from mid-2004 to the end of 2014. Shoreline positions were identified from these images using the *Pixel Intensity Clustering* technique (Aarninkhof et al., 2003) combined with a simple elevation model accounting for tide and run-up effects (Harley et al., 2011b). Daily shoreline positions are based on the cross-shore position of the 0.7 m AHD contour (approx. MHW) derived from multiple hourly shoreline positions collected over a single tidal cycle (Harley et al., 2011b). Beach width for each alongshore position was defined as the horizontal distance from this shoreline position to a fixed reference point in the backshore. This was then averaged over a 400 m alongshore section of the beach near Wetherill St, South Narrabeen (Figure 1) to remove alongshore variability due to localised rips and beach cusps.

Wave data and Storm Classification

Deepwater wave data was acquired hourly from the Sydney waverider buoy located 11 km offshore from the site in 80 m water depth. Individual storm events were classified using a peak-over-threshold technique with a commonly-used significant wave height threshold for the region of 3 m (approx. 95^{th} percentile) (You and Lord, 2005, Harley et al., 2009, Shand et al., 2010). A minimum duration of 12 hours (one tidal cycle) was applied to remove short duration events from the analysis.

Cumulative storm energy (MJh/m^2) for each storm event was calculated using a technique (Mendoza and Jiménez, 2006) that incorporates both magnitude and duration,

$$Storm\ Energy = \frac{1}{16}\rho g \Delta t \sum_{i=1}^{N} H_i^{\ 2} \tag{1}$$

where ρ is the density of ocean water (1025 kg/m^3), g is the gravitational acceleration (9.8 m/s^2), Δt dataset resolution (hourly), and H_i the deepwater significant wave height at a given hour i for the total hours in the storm event N. This technique has successfully been applied to estimate erosion of beach width at the study site (Harley et al., 2009).

Net Erosion Period Classification

Net erosion periods were first identified in the beach width dataset as dates bounded by individual storm events or storm clusters (see storm definition above) that resulted in a substantial net reduction in beach width of greater than 20m. The demarcation of these erosion periods was necessary to identify subsequent recovery periods.

Recovery Definition and Quantification

In order to quantify beach width recovery duration and rates, beach width recovery is defined as the return of beach width immediately following a net erosion period (as defined above) to the width as it was immediately prior to the onset of this erosion (see Figure 2).

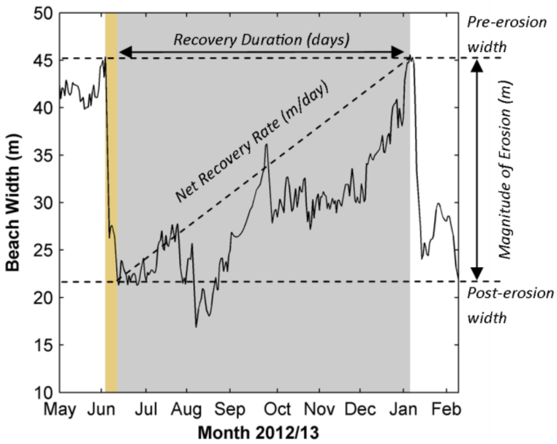

Figure 2: Illustration depicting erosion period (yellow) and subsequent recovery period (grey) in beach width with duration and net recovery rate.

The duration (days) as well as a net linear rate (m/day) for each recovery period was subsequently calculated as,

$$Duration = Date_{Post\,Recovery} - Date_{Post\,Erosion} \tag{2}$$

$$Net\ Recovery\ Rate = \frac{W_{Pre\,Erosion} - W_{Post\,Erosion}}{Recovery\ Duration} \quad (3)$$

where *W* denotes beach width (m).

On a high energy coastline such as this site, it is inevitable that beach width recovery (as defined in Eq.3) is interrupted to some degree by storm events of a smaller magnitude and return interval. These smaller events have the effect of prolonging beach recovery, but are included in the analysis in order to provide more realistic values of beach width recovery.

Following on from this linear analysis, beach width recovery rates were explored in greater detail for each recovery period by first smoothing the raw data using a 15-day (i.e. fortnightly) moving average (to remove higher-order noise) and then calculating daily rates of beach width change during the recovery period.

Results

Raw daily beach width observations from mid-2004 to the end of 2014 are plotted in Figure 3a. The beach width fluctuated significantly within a range of 62 m about a mean of 24 m. In total 10 recovery periods were identified following erosion periods in the dataset. The identified cycles of erosion and subsequent recovery capture a large degree of this variability with magnitudes of erosion (and, by definition, recovery) in the range of 20 to 32 m per period. These cycles are seen to occur about a notably narrower beach (mean 16 m) during the first five years shifting to a wider beach (mean 31 m) over the later five years. This is associated with the anticlockwise rotation of embayed NSW beaches during transitions from El Nino to La Nina wave climates respectively (Ranasinghe et al., 2004a).

The storm wave energy associated with individual events for the same monitoring period is shown in Figure 3b. The mean cumulative storm energy per year was 3.2 MJh/m^2 (s.d. = 0.9 MJh/m^2). Interestingly, cumulative storm energy during recovery periods (mean 1.7 MJh/m^2) was often comparable if not greater than storm energy during erosion periods (mean 1.5 MJh/m^2). However spacing between storm events for recovery periods was on average 46 days (s.d. = 14 days) whereas for erosion periods associated with storm clusters this was 13 days (s.d. = 6 days). Calm conditions during which recovery occurs were better described by a greater spacing between storms rather than the absence of these events which is rare in a high wave energy setting such as the NSW coastline.

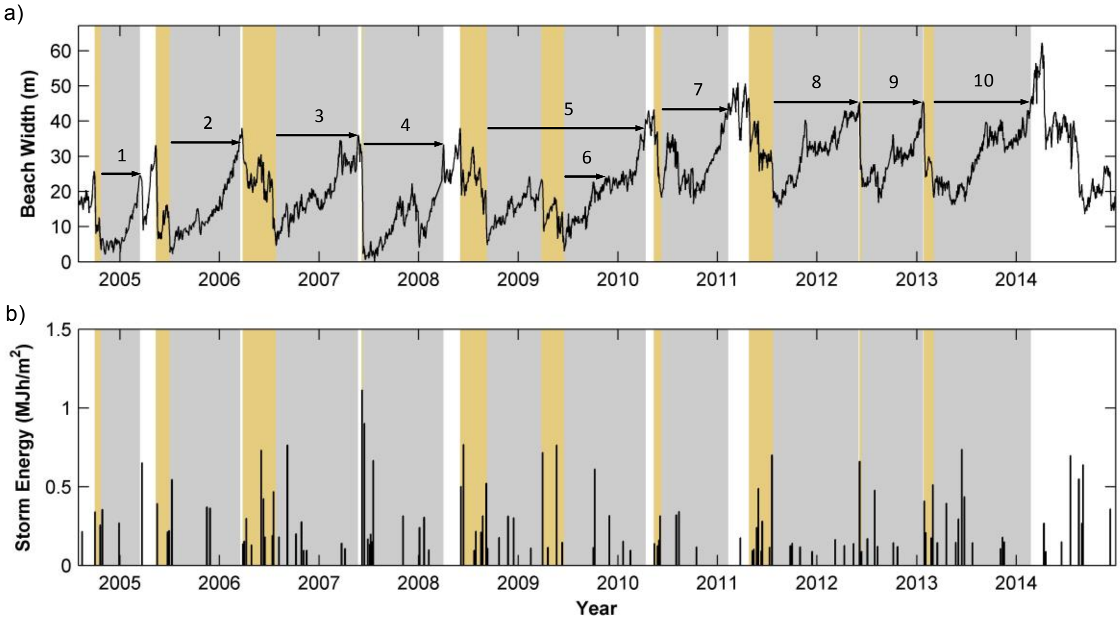

Figure 3: a) Time-series of daily beach width alongshore averaged about Wetherill St, South Narrabeen. Classified erosion periods (yellow) and recovery periods (grey and labelled) are shaded. b) Time-series of individual storm event energy during monitoring period.

A notable annual reoccurrence of beach width erosion and recovery cycles is evident in the data. This annual cycle is illustrated in Figure 4a showing the mean beach width for each month of the calendar year over the 10 year dataset. Beach width tended to reach a maximum in April (mid-autumn) and was at a minimum in September (early spring). The most significant erosion occurred entering winter from May to June and recovery during late summer from January to March. 2013 was a notable exception to this trend during which the cycle occurred earlier in the year in the summer months with the tracking of tropical cyclone Oswald.

Day-to-day rates of beach width change over the entire dataset are plotted in Figure 4b. At the daily resolution, recovery rates (i.e., positive daily rates of beach width) accounted for 57% of observations. The tails in this distribution are associated with less

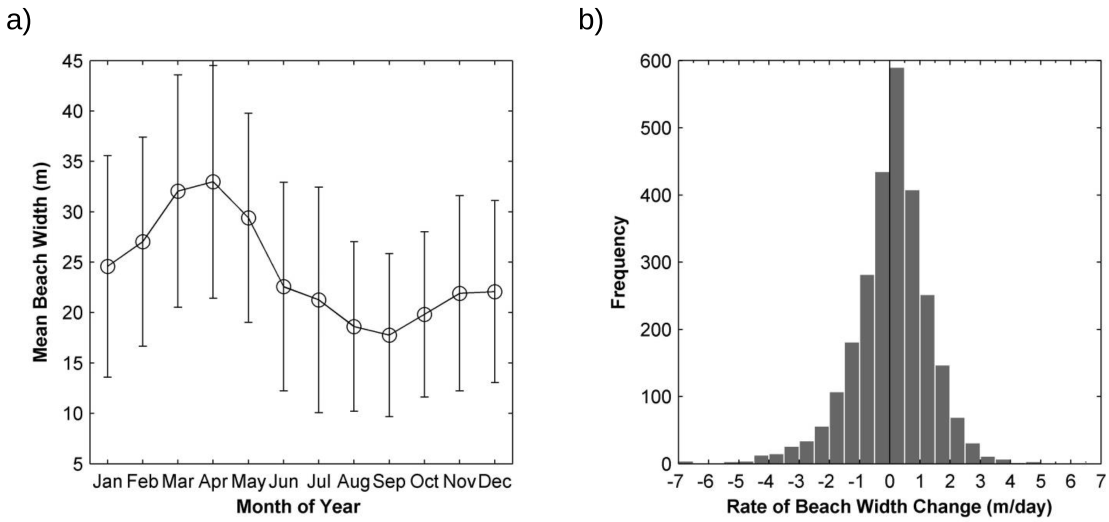

Figure 4: a) Mean monthly beach width over the 10 year dataset. Error bars correspond to standard deviations. A distinct annual signal is evident. b) Frequency histogram of daily rate of beach width change over a 10 year monitoring period

frequent higher magnitude rates of beach width change. As expected due to rapid storm erosion events, the tails are slightly negatively skewed with a maximum erosion rate of -12.6 m/day. However interestingly, though not as common, recovery rates of up to 6.4 m/day were also observed perhaps associated with rapid bar welding events. Modal rates on the other hand are slightly positively skewed toward gradual recovery rates in the range of 0 to 0.5 m/day. It is perhaps the influence of high impact storm erosion rates and modal gradual recovery rates that respectively characterise net erosion and recovery periods identified in the dataset.

Periods of net erosion and subsequent recovery are summarised in Table 1. Spanning the decade of monitoring at this site, approximately 14% of daily beach width observations were classified during net erosion periods in comparison to 75% for recovery periods with 11% unclassified. Unclassified data occurred after a beach had fully recovered prior to the following erosion period and also at the end of the monitoring where a complete erosion and recovery cycle was not observed. The temporal dominance of the more progressive net recovery periods in beach width dynamics is evident.

The average duration for beach width to complete recovery was approximately 9 months and slightly influenced by the magnitude of net erosion occurring prior. Following smaller magnitude erosion (20 to 25 m) recovery tended to take shorter (5 to 7 months) and after larger magnitude erosion (25 to 30 m) recovery took longer (8 to 12 months). Erosion periods were in most cases sufficiently spaced such that recovery had completed before the next erosion period commenced.

A notable exception to this was the recovery following erosion in 2008, with a longer duration of 19 months in Table 1 and illustrated in Figure 3a. In 2008 the magnitude of erosion was relatively high (32 m) and the erosion period extended later in the year into early spring. By the beginning of the following erosion period seven months later, the beach width had only partially recovered (63%) and complete recovery did not occur until April 2010. For this recovery period both the magnitude of erosion and spacing of subsequent erosion periods were found to result in a longer beach width recovery duration.

Net rates of beach width recovery are also listed in Table 1 for each recovery period. These were observed in the range of 0.06 to 0.14 m/day, with a mean value for all ten

Table 1: Identified net erosion periods and subsequent beach width recovery including duration, net rate, the maximum rate and its occurrence expressed as a percentage of the recovery duration.

Recovery Period #	Prior Net Erosion Period	Recovery Duration (days)	Net Recovery Rate (m/day)	Maximum Recovery Rate *	
				Value (m/day)	Time of Occurrence
1	30 Sep to 23 Oct 2004	142	0.14	0.50	93%
2	12 May to 3 Jul 2005	257	0.12	0.38	96%
3	27 Mar to 27 Jul 2006	300	0.10	0.57	75%
4	6 Jun to 11 Jun 2007	294	0.10	0.35	83%
5	1 Jun to 8 Sep 2008	581	0.06	0.47	95%
6	27 Mar to 18 Jun 2009	150	0.14	0.43	62%
7	13 May to 10 Jun 2010	244	0.10	0.68	4%
8	26 Apr to 24 Jul 2011	313	0.08	0.56	34%
9	5 Jun to 14 Jun 2012	223	0.10	0.42	96%
10	26 Jan to 4 Mar 2013	355	0.07	0.44	97%
Mean	-	286 (s.d. = 124)	0.10 (s.d. = 0.03)	0.48 (s.d. = 0.10)	-

**based on 15 day (fortnightly) moving average* periods of 0.1 m/day. Slower net rates were attributed to longer recovery periods. This net rate however is relatively consistent and provides a useful approximation of beach width recovery following erosion of greater than 20 m after a storm and storm cluster at this site.

Rates of beach width recovery periods however showed a significant degree of non-linearity. This is illustrated in Figures 6a and 6b showing smoothed beach width data and corresponding rates of change respectively for recovery period 9 (Table 1), commencing in 2012. The recovery period began with a distinct lag in beach width response lasting nearly a month. Rates then began to increase but were soon interrupted by two storm events in late July and early August. Following these storms, rates rapidly increased reaching up to 0.3 m/day and persisted for over a month. A sharp increase in beach width is noted in Figure 6a during this phase. In October, recovery was again interrupted by a storm event and followed by a two month phase of little beach widening. Entering the summer months, rates then began to rise and another sharp increase in beach width is observed in the progression of recovery in Figure 6a with rates reaching a maximum of 0.4 m/day as the recovery period neared completion.

Maximum rates from smoothed data for each recovery period are shown in Table 1 along with when these occurred as a percentage of the recovery duration. Maximum rates on average of 0.5 m/day were observed and these generally occurred during the later stages of recovery. This is perhaps related to the temporal reworking of sand from the outer nearshore to the inner nearshore and then causing a subsequent increase in sediment feed to the foreshore, driving an increase in beach width toward the end of the recovery period.

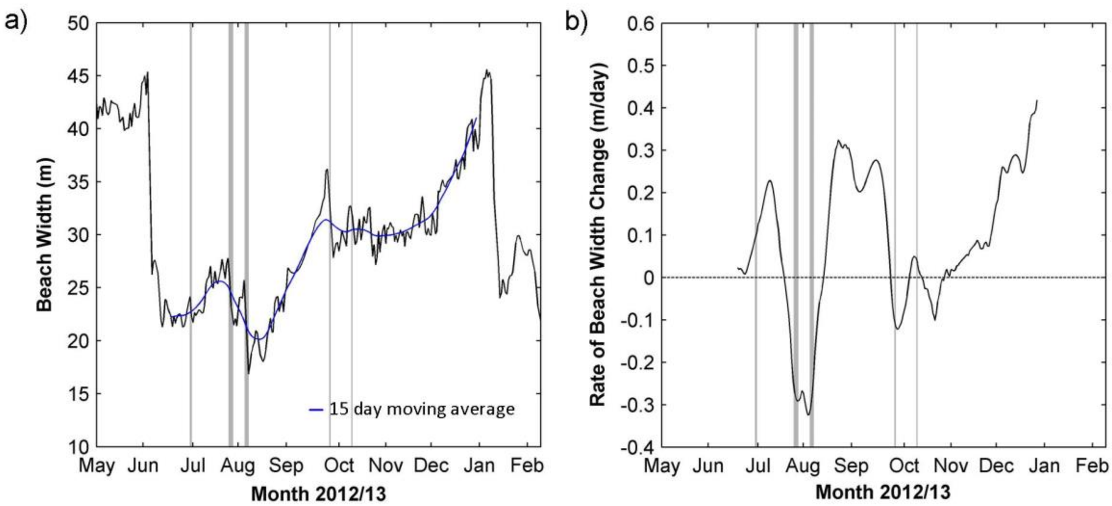

Figure 4: a) Beach width recovery commencing in 2012 with both raw and smoothed data. b) Corresponding rate of beach width change of smoothed data. Storm events are shaded in grey. The non-linearity of rates during recovery periods are evident.

Discussion

The findings of this study demonstrate an ability to distinguish and quantify beach width recovery, as defined by the cross-shore movement of the shoreline to a pre-storm(s) position, for a range of time-scales using long-term (decadal) high resolution (daily) beach width data. Recovery periods are distinguished by a net return of beach width following substantial erosion (greater than 20 m) associated with a storm or storm cluster. Rather than the absence of storm energy, which is rare on the high wave energy NSW coastline, recovery periods are particularly characterised by longer spacing between storms at this site. As such, the annual reoccurrence of erosion and recovery cycles was found to follow seasonal variations in regional storm activity (Shand et al., 2010). This also supports findings from a study of beach rotation at this site that showed a strong annual signal dominated by cross-shore sediment transport due to storms (Harley et al., 2011a).

Typical beach width recovery durations were generally in the order of several months to a year, and found to be prolonged following higher magnitudes of erosion, insufficient spacing of subsequent erosion periods and increased amount of storm energy during the recovery period. The findings from this study are in contrast to recovery following the extreme erosion that occurred in 1974 at this site and others in the region, after which at Moruya Beach, NSW (240km south of Narrabeen-Collaroy Beach), recovery was found to take several years to complete (Thom and Hall, 1991).

Beach width at this site recovered at a net rate of 0.05 to 0.15 m/day during these periods. This gives a simple rule-of-thumb to estimate the time for the beach at Narrabeen-Collaroy to recover in width following storm erosion in the order of 20 m. For example given a 30m erosion event one could estimate the beach to recover in width in approximately 300 days. Interestingly, comparable rates of shoreline recovery are noted in the literature at other high energy sandy beaches. On the Gold Coast, QLD shoreline (MSL contour) recovery rates of 0.3 to 0.7 m/week (or 0.04 to 0.1 m/day) were found over a 12 month post-storm monitoring period. In Durban, South Africa a 37 year dataset found an average lower swash contour recovery of 39 m/year (or 0.1 m/day) (Corbella and Stretch, 2012).

Additionally at Narrabeen-Collaroy, comparisons with three dimensional topographic surveys from an RTK-GPS equipped All-Terrain-Vehicle have shown that changes in beach width (ΔW) observed from coastal images are well-correlated (R^2 = 0.96-98) with changes in volume above MSL (ΔV) (Harley, 2009). At the alongshore section about Wetherill St this relationship (R^2 = 0.96) is given by,

$$\Delta V = 2.5 \Delta W \tag{4}$$

Therefore net linear rates of beach width recovery from this study may also provide a first-pass estimate of volume recovery at the site with rates from Equation 4 corresponding to 0.13 to 0.38 m^3/m/day. These values are similar to rates in the range of 0.12 to 0.42 m^3/m/day during phases of recovery observed at Moruya Beach, NSW, following the extreme erosion events of 1974 (Thom and Hall, 1991). Further investigation into the alongshore and inter-site variability of recovery on sandy beaches along the NSW coastline with different environmental settings is the subject of current research.

At higher temporal resolutions, the progression of beach width recovery deviated from net linear rates. Rates from smoothed (fortnightly) data ranged from zero during phases of negligible beach recovery to 0.5 m/day during extended phases of beach widening. Maximum rates of beach width recovery were found to generally occur as recovery neared completion (83-97% in the recovery cycle). This observation is in complete contrast to the common exponential decay fit applied to recovery periods (Callaghan et al., 2013, Wainwright et al., 2015), where beach recovery rates are assumed to be greatest immediately following a storm. Phases of rapid recovery observed in this study are believed to be associated with major bar welding events following the progressive reworking of storm deposited sediment from the outer nearshore to the inner nearshore. Extended high resolution monitoring of sandbar morphodynamics would be of great value to further correlate recovery rates with wave forcing parameters.

A particular limitation of this study is the spatial extent captured by a single contour in the foreshore using the beach width or shoreline approach. More holistically, the process of recovery also includes the movement of sand within the nearshore and backshore regions of the beach. In comparison to timescales of several months observed in this study, other studies have reported nearshore recovery following storms to modal beach states over a matter of days (Ranasinghe et al., 2012, Ranasinghe et al., 2004b). On the other hand, aeolian driven backshore and dune recovery has been found to occur over decades (McLean and Shen, 2006). Such considerations are important when interpreting reports of beach recovery timescales and rates.

Conclusion

A decade of daily beach width observations obtained from ARGUS coastal images at Narrabeen-Collaroy Beach, NSW have been used to distinguish and quantify beach width recovery following significant erosion (greater than 20m in beach width) associated with isolated storms and storm clusters. Recovery periods were defined as the return of beach width following erosion to a pre-storm(s) width. These periods were characterised by a net rate of beach width recovery of 0.05 to 0.15 m/day and on average took several months to a year to complete. This quantitative knowledge provides a simple first hand estimate of beach width recovery at the site for storms and storm clusters resulting in erosion of greater than 20 m. At higher resolutions (days) rates of beach width recovery are much more complex, ranging from minimal to magnitudes comparable to that of erosion. Prolonged phases (weeks) of moderate recovery rates (up to 0.5m/day) are often present in the progression of recovery, believed to be associated with major bar welding events, and generally occur toward the end of the recovery period.

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