MULTI-SCALE MORPHODYNAMIC ASSESSMENT OF AN EMBAYED LOW ENERGY ESTUARINE BEACH, SHOAL BAY, PORT STEPHENS, NSW.

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Shoal Bay is an embayed estuarine beach in the tide dominated estuary of Port Stephens on a wave dominated coast. It has been undergoing erosion for the past 40 years with the cross-shore extent associated with a well developed flood-tide delta (FTD). Morphodynamics of FTDs are poorly understood, despite their ubiquitous nature on wave dominated coastlines. This paper presents a multi-scale detailed study on the morphodynamics of Shoal Bay beach and associated estuarine morphologies. Our study included short term summer and winter intensive surveys (hydrodynamics and morphology), over one year of beach surveys to analyse seasonal beach behaviour and long-term evolution using ArcGIS on four decades of aerial photographs. It is expected that the results from this study will be relevant for the future management of the study area.

Westward trending sediment pathways were found at all three time-scales with short-term studies indicating that measured currents have the capability of transporting sediment alongshore towards the west. This corresponded with accumulation of sediment in the western end of the beach at all scales, with high energy events triggering considerable beach change causing erosion. Significant erosion and shoreline recession was found in the long- and medium- term morphological analysis. Additional information regarding the ARC Port Stephens project can be found at:

http://www.geosci.usyd.edu.au/research/re_portstephens.shtml.

Introduction

The morphodynamics of low-energy beaches have been broadly overlooked in the coastal literature with few process-based assessments in such environments (Eliot *et al.* 2006; Hegge *et al.* 1996; Travers 2007). As a result, predictive and descriptive morphodynamic models and equations derived from wave dominated environments often inaccurately interpret the dynamics of low-energy beaches. While some morphodynamic studies of low-energy beaches exist (i.e. Hegge *et al.* 1996; Jackson 1995; Jackson and Nordstrom 1992; Nordstrom 1980; Nordstrom *et al.* 2003; Sanderson *et al.* 2000; Travers 2007; Vila-Concejo *et al.* 2009a) limited knowledge regarding hydrodynamic forcing and sediment exchanges with other morphologies exacerbates the uncertainties inherently present when attempting to manage these coastal systems (Vila-Concejo *et al.* 2009a).

The definition of low-energy beaches is a the subject of discussion with geological setting, wave height and dominant hydrodynamic forcing mechanisms having all been used to define the low-energy environment (Jackson *et al.* 2002). Terms fetch-limited, sheltered and wave attenuated are often used interchangeably when describing low-energy beaches, however they are referring to differing hydrodynamic forcing mechanisms. Jackson *et al.* (2002) suggested four criteria to define low-energy beaches as (1) minimal non-storm significant wave heights (<0.25 m); (2) significant wave heights due to strong onshore winds low (<0.50 m); (3) beach face widths narrow (<20 m); and, (4) relict morphologies occur inherited from high energy events. Most of the shoreline within the Port Stephens falls within the low-energy classification of Jackson *et al.* (2002), yet process-based assessments (Ainley 2007; Pezzimenti 2008; Vila-Concejo *et al.* 2009a; Vila-Concejo *et al.* 2009b) and studies on historic evolution (Cholinski 2004; DPWS 1999; 2000 ; Frolich 2007; PWD 1985; 1987; Thom *et al.* 1992; Vila-Concejo *et al.* 2007b) have indicated a highly dynamic environment antithetic to the low-energy definition (Vila-Concejo *et al.* 2009a; Vila-Concejo *et al.* 2009b).

Low Energy Setting

The majority of low-energy beaches are within protected environments such as bays, sounds, estuaries, embayments, lakes or lagoons and in lee of islands, reefs or submarine ridges (Jackson *et al.* 2002). As a result, the morphodynamics of such beaches are inherently connected to the evolution and fluctuations of their geological setting. On the energetic, micro-tidal, wave-dominated coast of Southeast Australia well developed flood-tide deltas occur; their evolution is connected to the long term morphodynamics of the associated shorelines (Cowell *et al.* 1995). In order to gain insight into the long term shoreline change and the processes driving such change, an integrated multi-scale approach is necessary (Smith and Zarillo 1990).

Study Site

Port Stephens estuary is a ria-like drowned river valley located approximately 230 km north of Sydney (Figure 1). It is a tidally dominated estuary on a wave dominated coast, with wave processes typically a significant hydrodynamic forcing mechanism in the lower estuarine environment of such estuaries (Dalrymple *et al.* 1992; Roy *et al.* 2001). A well developed flood-tide delta is found within the lower estuary typical of a wave dominated environment with ebb-tide deltas unable to form as a result of waves reworking the sediment as they propagate into the estuary (Dalrymple *et al.* 1992; Hayes 1980; Vila-Concejo *et al.* 2007a). Tides are semidiurnal with a diurnal inequality resulting in generally two high and low tides per day. Maximum tidal range is 2.0 m with mean tidal ranges of 1.6 m and 1.3 m for spring and neap tides respectively (Short 1985). Spring tidal prism at the entrance of Port Stephens is 165×10^6 m^3 with maximum tidal currents exceeding 1 ms^{-1}. Tidal attenuation is minimal due to the wide mouth of the estuary (1.24 km) (Vila-Concejo *et al.* 2007a). The wave regime of the Southeast Australian coast is a classified as moderate with mean significant wave heights (H_s) of 1.5 m with an associated period of 8 s (Short and Trenaman 1992). Persistent swell with significant wave heights of 1-2 m are the modal conditions (where modal conditions occur greater than 50% of the time) with rare periods of low waves (<1 m, 10%) and a substantial amount of high-energy waves (2-3 m, 21%; 3-5m, 5%). Waves from the NE dominate during summer, with E-SE waves occurring throughout the rest of the year (Short and Trenaman 1992). Winds are strongly influenced by daily breeze patterns with strong E-SE winds (<30 km/h) occurring in the afternoon between Spring and Autumn and strong westerlies occurring throughout winter (<30km/h) (BOM 2009).

Morphological Evolution: Flood-tide delta and associated shoreline changes

According to Frolich (2007), the flood-tide delta complex has been accumulating sediment over the last four decades, both in the major shoal formations as well as some of the smaller morphologies including the sand ridges and ebb shoal located close to Shoal Bay. Accretion has also occurred in two other locations, at Winda Woppa spit and Yacaaba sandwave (Cholinski 2004; Vila-Concejo *et al.* 2007a; 2009b). Conversely, the Port Stephens shorelines of Shoal Bay, Jimmy's Beach, Nelson Bay have been undergoing erosion for the past 40 years (DPWS 1999; 2000 ; Frolich 2007; PWD 1979; 1985; 1987; Vila-Concejo *et al.* 2007b).

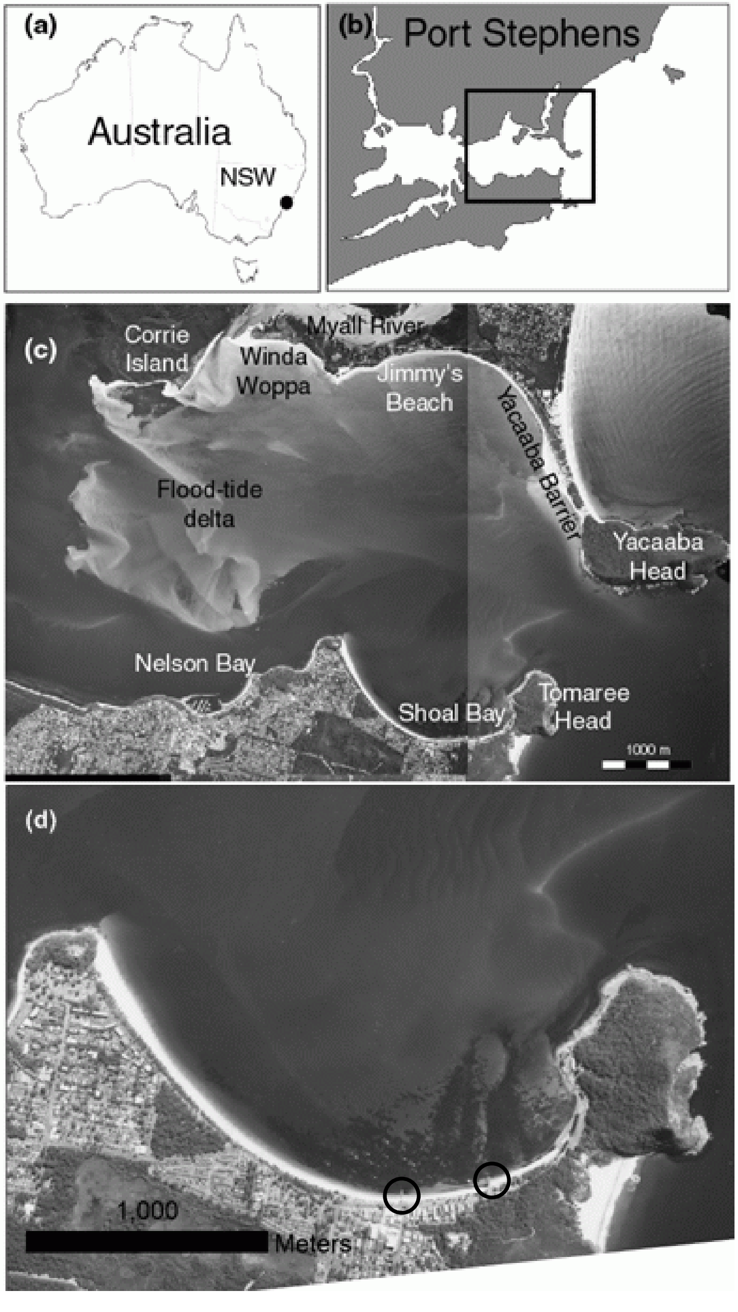

Figure 1. (a) Location of Port Stephens, NSW, Australia; (b) Map showing the entire estuary; (c) aerial photo of the lower estuarine environment (April 2006) showing the main morphological features; (d) Study site of Shoal Bay is located on the southern shoreline immediately west of Tomaree Head, jetty in the centre of the beach and boat ramp to the west highlighted by black circles.

Shoal Bay is the most easterly and energetic beach on the southern shoreline of Port Stephens (Figure 1). It is a 2.5 km long embayed, swash aligned, low-energy estuarine beach (Frolich 2007; Short 2007). Existing records of sand nourishment extend back to 1986, with almost all nourishment occurring in the areas immediately east and west of the jetty. The first major nourishment in 1986 used 25,000 m^3 of sand placed approximately extending from the boat ramp to 500 metres west of the Jetty (Watson 1997). Extensive shoreline management then occurred during the 1990s with some of the erosion problems correlated with the development the boat ramp in the west and drainage outlets and associated rock wall constructed in 1991 underneath the public jetty. Minor nourishment was undertaken throughout 1994 before a major nourishment of 33,000 m^3 of sediment was deposited on the beach from the boat ramp to 700 metres west of the Jetty in September 1994. By 1996 further nourishment was needed periodically until at least 1999 with approximately 50,000 m^3 of sand deposited between April 1994 and November 1999. The rock wall protecting the drainage outlet underneath the jetty was removed in 2000 with no major nourishment projects occurring since then. However, emergency nourishment and sand relocation from the west has occurred periodically since 2000.

Methods

Beach Sections

Analysis of morphological change in Shoal Bay was conducted through the use of beach sections (Figure 2). Results of shoreline displacement, width and volume were compartmentalised and averaged into 6 sections to represent the mean value for that section. This was done for both the long- and medium-term morphological analysis.

Long Term

Aerial Photography

Aerial photographs of Shoal Bay covered the period of 1963 and 2006; photos from 1963, 1977, 19986, 1991, 1994, 1996, 1999, 2001 and 2006 were available for this study. Analysis of shoreline change was conducted on 50 transects using the Digital Shoreline Analysis System (Thieler *et al.* 2009). Displacement values were normalised using the method presented in Short and Trembanis (2004) to allow easy comparison of shoreline change between each section by removing trends within time series data sets. Shoreline displacement for each section (*Vi(t)*) was normalised by the average displacement for that section (*Vi*) divided by the square root of the variance in width (Eq. 1).

$$Vi(t) = \frac{Vi(t) - Vi}{\sqrt{\sigma i}} \qquad \text{Eq.1}$$

The error associated with shoreline analysis was derived by using the average slope of the beach ($\tan\beta = 0.12$), where a 1 m variation in water level results in a cross-shore shoreline displacement of 8.3 m, resulting in an error of ±7 m when taking into consideration the mean amplitude of spring tides (0.8 m). A similar result was obtained by Vila-Concejo *et al.* (2007b).

Forcing Mechanisms

Historical storm (significant wave height (H_s) > 3 m) data were obtained from DECCW through the Manly Hydraulics Laboratory (MHL) for the Crowdy Head wave rider buoy, 115 km north of the study site. Data included date, direction, significant wave height and the duration of the storm. This allowed for a calculation of total wave power for the storm by assessing offshore wave power through time for the duration of the storm as calculated by Vila-Concejo (2009b) Offshore wave height was calculated using standard linear wave theory.

Over 60 years of wind data were obtained from the Bureau of Meteorology (BOM) weather station at the Williamtown RAAF base located 32 km southwest of Port Stephens. Average wind speed throughout the day was used to assess the occurrence of wind conditions that may affect the morphology of Shoal Bay shoreline. Previous studies conducted by Frolich (2007) and observations during this study concluded that only winds above 10 ms^{-1} have the potential to affect the nearshore hydrodynamics of the lower estuarine environment of Port Stephens.

Medium Term

Beach Surveys

Beach surveys were conducted using a state-of-the-art Trimble R8 RTK-GNSS (Real Time Kinematic Global Navigation Satellite System) from May 2008 to May 2009 (Table). 23 profiles were taken approximately every 100-200 metres during each survey (Figure 2) with linear volume and width derived from the dune scarp (origin of survey) to the 0 m Australian Height Datum (AHD) line, where AHD is approximately equal to Mean Sea Level (MSL). Results were averaged for each beach section and volume calculated by multiplying two-dimensional linear volume with the alongshore length of the section. Width and volume were normalised using Equation 1.

Forcing Mechanisms

Offshore wave data from March 2008 to June 2009 was obtained from MHL for the Crowdy Head wave rider buoy which includes hourly wave statistics of significant wave height and period. Storm events could then be classified into their relevant categories as high frequency (> 3 m), moderate ($3.5<H_s<5$ m), severe ($5< H_s< 6$ m) and category X (> 6 m) (NSWG 1990; Watson *et al.* 2007).

Short Term

Hydrodynamic Deployments

Two intensive field campaigns in winter (22nd-24th July) and summer (13-14th and 16-17th December) were undertaken in 2008. The intensive campaigns included measurement of nearshore hydrodynamics over approximately one tidal cycle using current meters (Acoustic Doppler Velocimeters (ADVs)) and pressure transducers (PTs).

There were two deployment locations in the nearshore zone, SB1 in the east and SB3 sampling in the west (Figure 2). The PTs were measuring continuously at 10 Hz and currents were measured in 15 minute runs every half an hour. Deployments were made so that the PTs were never under more than 1 m of water to avoid wave attenuation with depth.

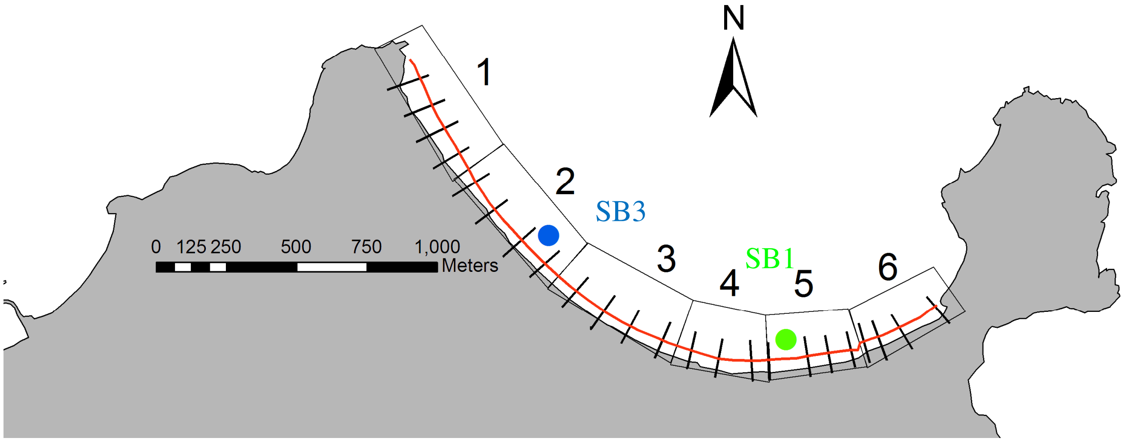

Figure 2. Beach sections and 23 cross-shore profiles used for analysis of beach change with the 2006 shoreline in red. Jetty located between sections 4 and 5 with boat ramp located between 5 and 6. Green dot and Blue dot represent hydrodynamic deployment stations of SB1 and SB3 respectively.

Sediment Entrainment

To determine the ability of the surveyed currents to entrain sediment wave orbital velocity as well as Shields' parameter equations were used. Currents were measured at less than 20 cm from the bed and they were carefully oriented such as one axis was perpendicular to the incoming waves; thus it can be assumed that the oscillatory measurements that were taken in the across-shore direction correspond to the waves orbital velocities that cause sediment entrainment. Peak near bed orbital velocity (U_w, ms^{-1}) and its associated frequency (F) (H_z) were used in Equations 2, 3 and 4 to determine the orbital velocity (A) (ms^{-1}, Eq. 2), relative roughness (r, Eq. 3) and wave friction factor (f_w, Eq. 4);

$$A = \frac{U_W F}{2\pi} \qquad \text{Eq. 2}$$

$$r = \frac{A}{k_s} \qquad \text{Eq. 3}$$

$$f_w = 0.237 r^{-0.52} \qquad \text{Eq. 4}$$

where, k_s is Nikuradse roughness length ($2.5 \times D_{50}$) and D_{50} is the mean grain size.

Critical shear stress (τ_{cr}, Eq. 7) and velocity amplitude (U_{cr}, Eq. 8) (ms^{-1}) were then determined using Equations 5, 6, 7 and 8;

$$D* = D50\left[\frac{g(s-1)}{(u^2)^{\frac{1}{3}}}\right] \qquad \text{Eq. 5}$$

$$\theta cr = \left[\frac{0.30}{1+1.2D*}\right] + 0.055[1-\exp(-0.02D*)] \qquad \text{Eq. 6}$$

$$\tau_{cr} = \vartheta_{cr} g(\rho-\rho_s)D_{50} \qquad \text{Eq. 7}$$

$$U_{cr} = \sqrt{\frac{2\tau_{cr}}{\rho f_w}} \qquad \text{Eq. 8}$$

where ρ is water density (1027 kg/m^3), ρ_s is the sediment density (2650 kg/m^3), s is ratio of sediment to water density (ρ_s/ρ), g is the gravitational acceleration (9.8 ms^{-2}) and u is the kinematic viscosity of water ($1.1\times10^{-6}\ m^2s^{-1}$).

Currents exceeding the velocity amplitude were deemed capable of entraining sediment. The percentage of entrainment (*E*) was computed using Eq.9 and represents how often the` surveyed nearshore currents have the theoretical capability to entrain sediment from the bed.

$$E = \left(\frac{C_f}{C}\right) \times 100 \qquad \text{Eq. 9}$$

where, *Cf* is the duration for which the sampled nearshore currents were above U_{cr}; and C is the total duration of the deployment.

Residuals: Current and Percentage of Entrainment

Residual current velocities were averaged over the 15 minute runs to determine the dominant direction of the longshore current velocity. Direction of net residual flow in the alongshore direction was determined by a non-dimensional residual scaling factor R_f (Eq. 10) modified from Austin *et al.* (2009)

$$R_f - (d_w \times v_w) - (d_e \times v_e) \qquad \text{Eq. 10}$$

where, d_w and d_e are the duration of currents in the west and east directions respectively and v_w and v_e the longshore velocity towards the west and east.

A similar approach was taken in determining the direction of current flow producing the most entrainment (Eq. 11). E_f was derived by using the nearshore current residuals towards the east and the west and their associated values of *E* where

$$E_f = (d_w \times E_w) - (d_e \times E_e) \qquad \text{Eq. 11}$$

E_w corresponds to the average values of E associated with westward residual currents and E_e with eastwards. Values obtained from residual scaling factors only suggest dominant direction of current and entrainment and are therefore useful as a comparative tool but with no real value attached to the subsequent results. Larger values do not necessarily suggest stronger hydrodynamic forcing but dominance in either the east or west direction.

Results

Long term

Overall, shoreline recession occurred for the last 43 years at a rate of 0.52 myr^{-1} and caused some 22 m of retreat (Figure 3). The most extensive recession happened in sections 1-2 and 5-6, with smaller amounts of shoreline erosion found in the central sections of the beach (3-4). The majority of the recession from 1963 to 2006 took place between 1963 and 1977, with further erosion occurring between 1994-96 (Figure 3). Erosion also occurred between 2001-2006 where sections 1-3 eroded and sections 4-6 accreted (Figure 4). Erosion and accretion events experienced in opposing areas of the beach generate beach rotation. This rotation between east and west is most apparent between sections 2-3 and section 4 where rotation over decadal scales is observed. The only significant period of accretion occurred during 1996-99 with section 4 eroding while the rest of the beach accretes. A similar result was obtained between 1986 and 1991 where section 4 eroded while all other sections remained relatively stable. Periods 1977-86 and 1999-2001 also showed relative little change in shoreline position.

Forcing Mechanisms

Historic storm data shows clustering of storms between 1985 and 1991, just before a period of little storm activity that extends to the mid 1990s. Storm events increase again in 1995, 1999 and 2002 however when compared to the late 1980s the period from 1991 to 2006 has been relatively calm (Figure 5).

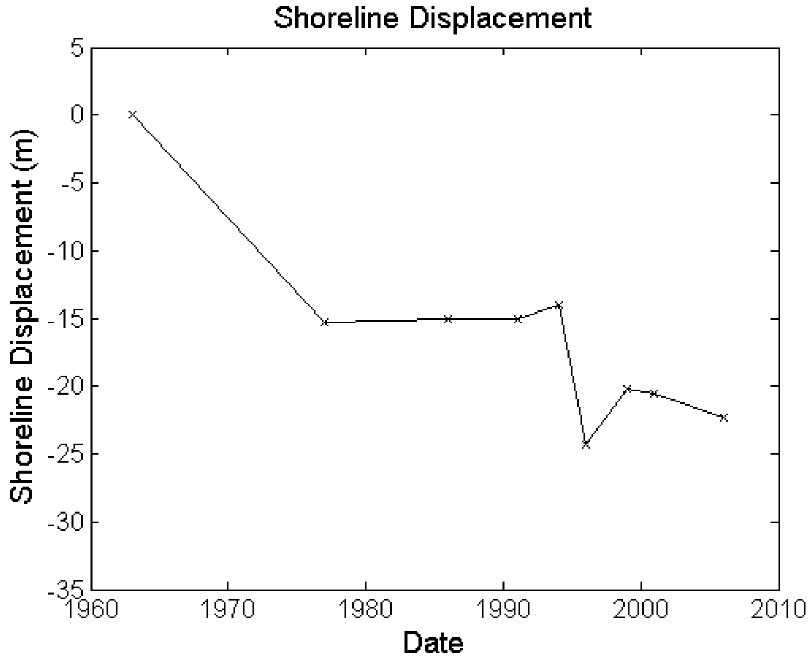

Figure 3. Time series of shoreline displacement from 1963 to 2006.

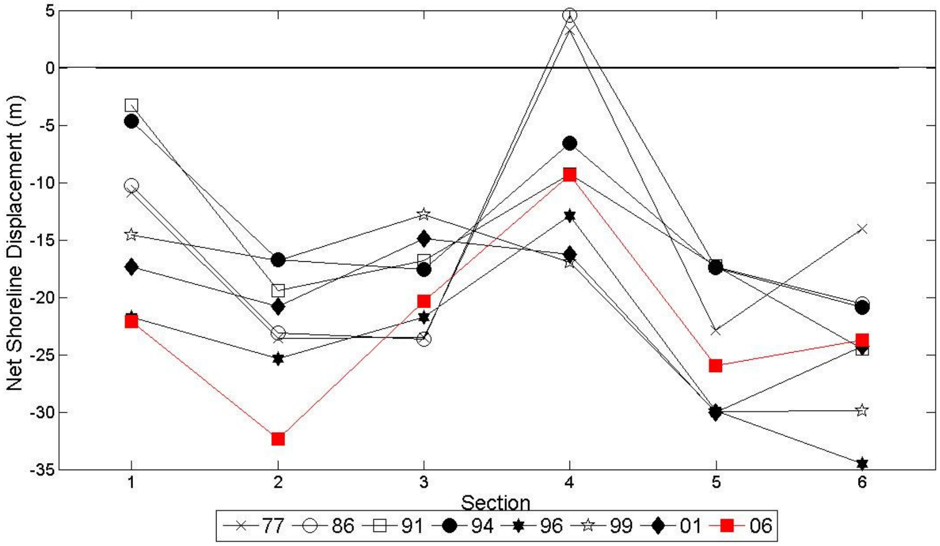

Figure 4. Net shoreline displacement from the 1963 shoreline in the aerial photographs for each beach section. The red plot is the 2006 shoreline.

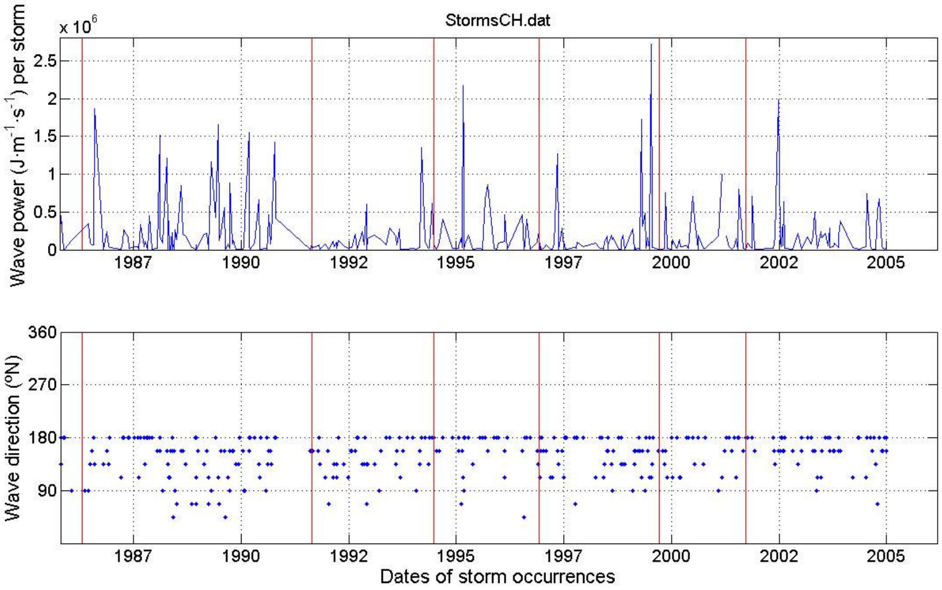

Figure 5. Historical storm data from the Crowdy Head wave rider buoy with wave power for each storm in the top panel and direction in the bottom panel. Red lines indicate dates of aerial photographs.

Medium Term

Shoal Bay lost approximately 10,000 m^3 of sediment between May 2008 and May 2009 (Figure 7 a and b). This erosive trend correlates with an average reduction of width of almost 1 m along the beach (Figure 7 b and d). The majority of the sediment was lost between March and May 2009. Almost half (4500 m^3) of this sediment was eroded from section 1; however section 4 incurred the most significant sediment rate of annual loss.

Rates of recession are most significant in sections 3-5 with section 1 and 2 accreting during the study period and section 6 remaining relatively stable. However, substantial erosion between March and May 2009 resulted in a slight loss of volume in sections 1 and 2 between May 2008 and May 2009. Sections 4-5 underwent general trends in erosion over the study period with section 3 eroding during summer but showing accretion during winter. Similarly, sections 4 and 5 showed similar patterns of erosion and accretion with the exception of March/May 2009 where erosion occurred while section 3 accreted. Section 6 incurred a slight trend in accretion over one year of surveys.

Rotation between sections 1-2 and 3-5 occurred with erosion in sections 3-5 corresponding with accretion in section 1-2, with the most significant erosion/accretion differential occurring between October and December 2008.

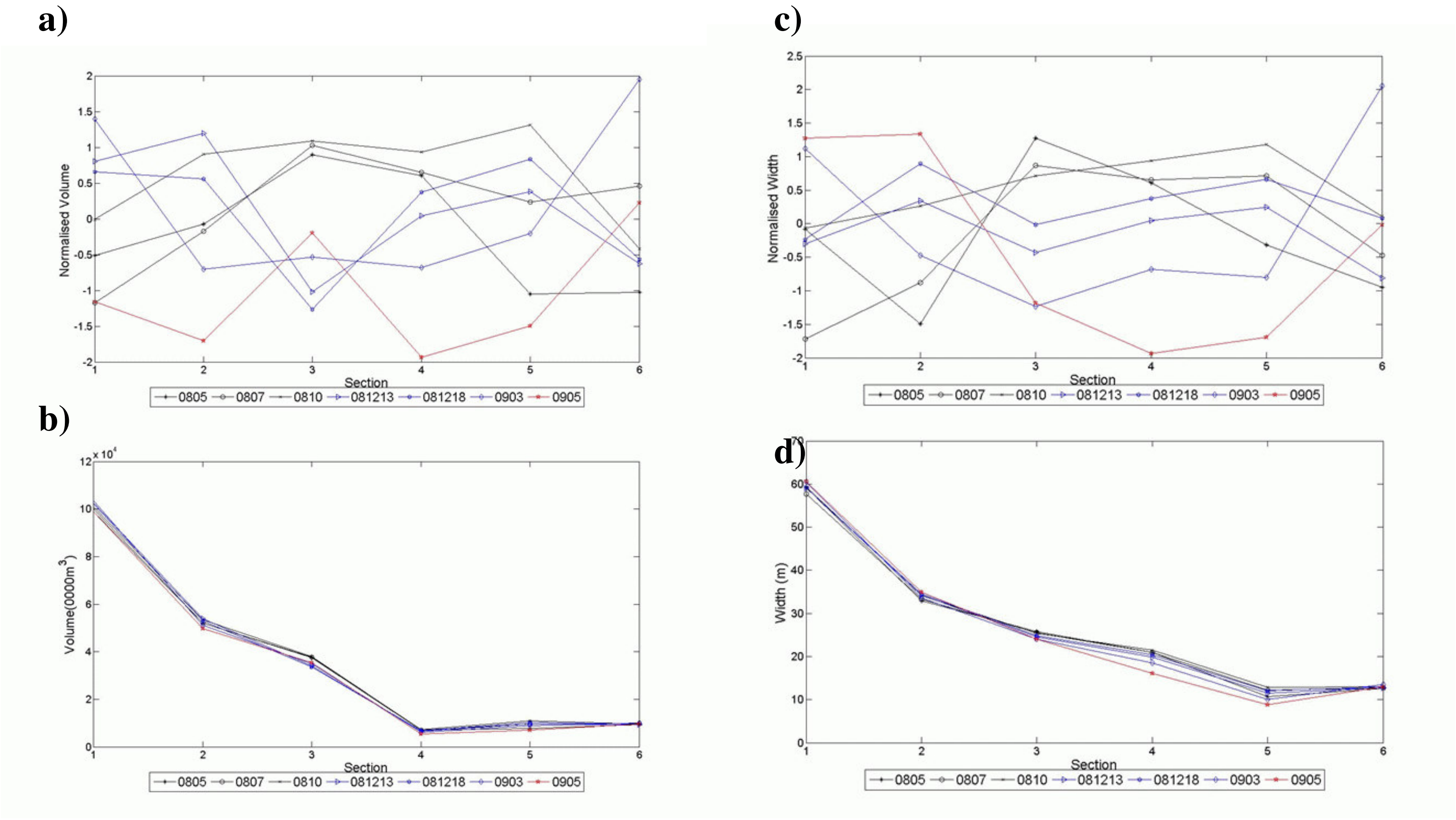

Figure 7. Beach change in each section derived from one year of RTK-GNSS surveys with summer conditions in blue and winter in black with the with red the last survey in May 2009 after a severe storm event. Graphs represent; a) normalised width indicating rotation between summer and winter surveys; b) total beach width; c) normalised volume; d) total volume.

Analysis of the of hourly wave data from the Crowdy Head wave rider buoy indicates that a number of storm events occurred during the study period. One severe storm as well as a category X storm (extreme storm) occurred between March to May 2009 (Figure 7). Moderate storms occurred between May and October 2008 with high-frequency low-energy storms dispersed throughout the rest of the wave record.

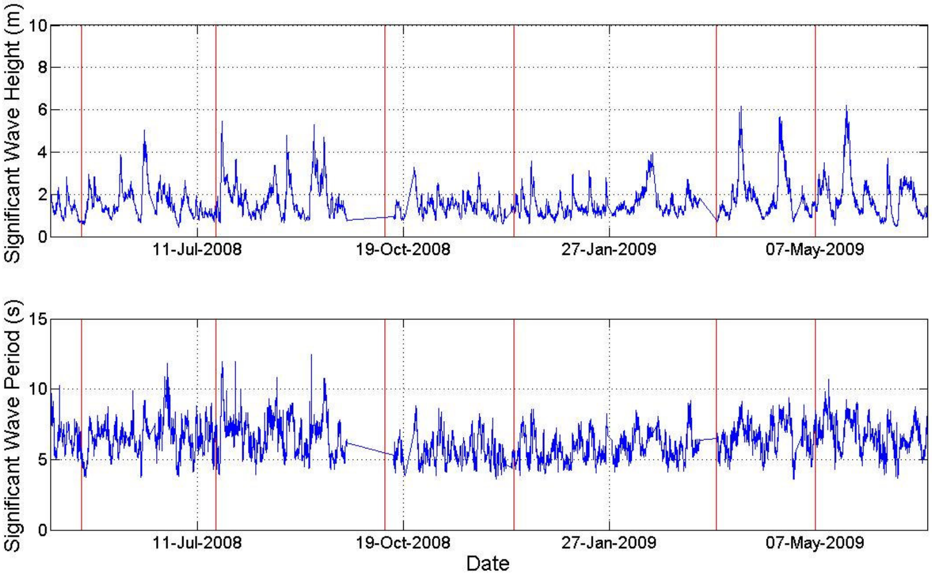

Figure 7. Offshore wave data from the Crowdy Head wave rider buoy with significant wave height in the top panel and significant wave period in the bottom. Red lines indicate dates of beach surveys

Short Term: Hydrodynamic Measurements

Summer conditions were calm with large tidal range of approximately 2 m during each day of deployments (the 14th of December incurring tides of 2.1m, larger than the theoretical maximum on the NSW coast). These tidal ranges were associated with larger longshore current velocities than winter. Westerly winds greater than 10 ms^{-1} also occurred on the 13th and 14th. Currents in winter were measured under neap tide conditions (approximately 1 m tidal range) and they were smaller than in summer.

Currents were stronger during summer than winter with residual scaling results (R_f) averaged over the entire summer and winter producing westward trends in nearshore flows, with the exception of SB1 during winter which shows no distinguishable trend (Table 1). E_f values show sediment was entrained and transported towards the west with the exception of SB1 during summer which showed sediment transport towards the east. However, compared to SB3 entrainment at SB1 was minimal.

Table 1. Average statistics of the hydrodynamic forcing mechanisms, sediment entrainment and residual scaling factors over summer and winter hydrodynamic surveys. Positive values in the R_f and E_f results indicate a westwards trending residual and negative eastwards.

		Wave				Residuals	
Field Campaign	Station	Hs (m)	Tz (sec)	Wind Speed (m/s)	Ucr Exceedence (%)	*Rf*	*Ef*
Summer	SB1	0.16	8.62	5.86	6.0	0.27	-0.57
	SB3	0.36	8.26		60.0	0.74	2.78
Winter	SB1	0.31	11.07	4.20	5.00	-0.02	0.29
	SB3	0.56	9.98		70.00	0.49	1.42

Discussion

Multi-scale Morphodynamic Analysis

Both entrainment and current residuals suggest sediment is transported towards the west under modal conditions. The most active area of longshore sediment transport is in the central/western area of the beach indicated by large entrainment values at SB3 as well as large amounts of erosion in sections 3-4 over the year of surveys. This is also correlated with parallel recession of the cross-shore profiles indicative of longshore dominating processes (Nordstrom and Jackson 1992). Over longer time scales, sediment transport to the west in sections 5 and 6 is also indicated by the sediment build up on the east of the boat ramp and periods of erosion in section 5 associated with accretion in the western sections. Frolich (2007) assumed the driving hydrodynamic force inciting westwards transport of sediment was swell waves, however conflicting or inconclusive studies over the governing morphodynamic processes in other shorelines within the estuary (e.g. PWD 1985; 1987; Vila-Concejo *et al.* 2009a; Vila-Concejo *et al.* 2009b; Watson 2000) suggest that it is not necessarily this simple.

Smaller longshore currents during winter are associated with neap tides and more energetic wave conditions. This is a result smaller tidal forcing at neap tides as well as incident waves being more shore normal during surveys with larger wave periods allowing for greater refraction of swell waves around Tomaree Head. Similarly, the stronger longshore currents surveyed during summer are a result of a larger tidal ranges and larger angle of incidence associated with smaller wave periods and decreased refraction (Komar 1998). Both summer and winter deployments incur dominant westwards trending residual currents. However, strong westerly winds above 10 ms^{-1} influenced the nearshore residual current direction during December 14th with easterly trending residuals dominating throughout the day at SB3. However, winds of 10 ms^{-1} rarely occur in Port Stephens with only 2% of average daily wind speeds greater than 10 ms^{-1} overly the last 60 years which is not regular enough to significantly affect the morphodynamics of Shoal Bay.

Similarly, highly energetic winds were not observed to effect sediment entrainment with E related to significant wave height. However, this relationship is not clear with H_s of 0.36 m associated with 60% entrainment percentages at SB3 during summer and a H_s of 0.31 m incurring an E value of only 5% at SB1 during winter. This may be due to the inclusion of wind waves generated by locally generated winds in the nearshore H_s and T_z calculations. Shorter wave periods with larger wave heights were found at SB3 when compared to SB1, which is antithetic to standard wave theory. The small wave heights and periods of wind waves that have been observed to affect the hydrodynamic forcing at SB3 may have reduced the T_z and H_z calculated at SB3. Taking this into consideration the wave climate at SB3 may incur longer wave periods and larger H_s values then what is portrayed in the results, ultimately confounding the relationship between E and H_s at SB3.

Nonetheless the dominant hydrodynamic forcing mechanisms are waves that work in conjunction with tidal forces producing longshore westward sediment transport under modal conditions. No other forces occur with the strength or frequency required to incite change of the beach morphology in the long term. Similarly, waves are the only force that appears to be capable of entraining sediment that is subsequently transported alongshore.

Modal sediment transport towards the west is supported by beach survey results with general trends of accretion in the west and erosion in the east occurring during lower energy summer conditions. In some instances during winter, specifically between sections 2 and 3, these trends are reversed with accretion in the central/eastern areas of the beach and erosion in the west. Beach rotation is usually the result of changing seasonal swell wave direction however this process cannot occur in estuarine beaches since swell is always propagated through the entrance and thus arrives from the same direction. Westerly winds are unlikely to incite such rotation since wind speeds required to influence the nearshore hydrodynamics rarely occur. Rotation in Shoal Bay is therefore a function of differences in cross-shore processes with accretion in the east correlated with higher energy winter swell that may produce onshore hydrodynamic forcing in the protected environment in lee of Tomaree head, while waves that have undergone less attenuation erode the west. Indeed, significant wave heights at SB1 during winter are similar to the wave heights found at SB3 during summer which is associated with accretion. Dail *et al.* (2000) and Nordstrom (1980) observed similar results in protected environments where similar wave conditions caused erosion and accretion simultaneously in different areas of the beach.

During high-energy events offshore forcing mechanisms dominate the entire embayment with the severe storms between March and May 2009 resulting in erosion in almost all sections of the beach and a loss of 10,000 m^3 of sediment. Complete beach recovery after similar events in low energy environments such as Shoal Bay only occurs after extended fair weather conditions if at all, with modal conditions unable to transport sediment back onshore (Costas *et al.* 2005; Nordstrom 1980; Owens 1977). The western sections (1 and 2) are most affected by storm events with over half of the 10,000m^3 of erosion occurring between March and May 2009 lost from these sections. These sections are most exposed to ocean swell and therefore are greatly affected by high-energy ocean swell events with sediment lost to the beach.

Shoreline recession was most pronounced in sections 3 and 4 over a year of beach surveys with profiles in these areas undergoing parallel retreat which is often associated with beach change dominated by longshore transport (Nordstrom and Jackson 1992). Large amounts of recession do not correlate with rates of shoreline displacement in the aerial photography, with sections 3 to 4 showing the smallest amount of recession over 43 years. Such a result can be attributed to the effects of beach nourishment and shoreline management which were most intense in these areas of the beach since at least 1986. In spite of this, average rates of recession in both scales across the entire beach are within 1 myr^{-1} with approximately 0.5 myr^{-1} associated with the aerial photo analysis and 1 myr^{-1} from the beach surveys. Thus, according to Jimenez et al. (1997), the short-term results seem to support the aerial photo analysis. However, short term assessment often results with much larger trends when compared to longer term analysis, with small scale fluctuations (such as storms) inherently effecting the results derived from short term analysis (Cowell 2002; 2004; Smith and Zarillo 1990).

Long-term trends of recession at the engineering scale suggest the shoreline is attempting to revert to a static or dynamic equilibrium plan form as a result of changes to the littoral sediment budget. Historic storm effects on the beach are inconclusive with only slight correlation with the erosion between 1994-96 and storms during 1995. Aerial photographs are unlikely to show the effects of storms unless they were taken immediately after a storm event. The large time steps between the aerial photography therefore limit the ability to confer the effects of historic storms on the long term shoreline evolution.

The extensive erosion that occurs throughout the 1990s is potentially exacerbated by shoreline engineering with the rock wall and drainage line under the jetty being constructed in 1991. Subsequent nourishment in sections 3-5 seem to have been ultimately transported and accumulated in the western sections (1-3). However when major nourishment projects ceased in the 2000s erosion occurred in these sections (1-3) from 2001-06. During this time, accretion occurs in sections 4 and 5 between 2001 and 2006 potentially associated with the removal of the rock wall and groin underneath the public jetty as well as small emergency nourishment that has been observed to occur periodically. Shoreline engineering of 1991 may have affected the sediment budgets of Shoal Bay - highlighted by the erosion in section 4 immediately west of the jetty during 86-91 and 96-99 – however it has been associated with long term trends of recession and while exacerbating the erosion effects is unlikely to be the sole cause of shoreline recession.

Long Term Shoreline Evolution and Change

Small scale fluctuations of rotation and seasonal erosion/accretion are part of a long term trend of shoreline recession which is correlated with Frolich's (2007) apparent accumulation of sediment in the flood tide delta. Recruitment of sediment into the flood-tide delta has the potential to affect the sediment pathways and morphodynamics of Shoal Bay and adheres to the very definition of Port Stephens as "estuary with a youthful maturity" (Cowell *et al.* 1995; Roy *et al.* 2001). However, the theory of accumulation of sediment within an estuary during the Holocene still stand does not necessarily correspond to continuous accretion in the flood-tide delta; according to Thom et al. (1992) the FTD was undergoing erosion in 1927. Reworking of sediment within the estuary is continually occurring with changes in the flood-tide delta linked to shoreline evolution. Indeed such large changes to the shoreline and FTD complex may be associated with fluctuations inherent in estuarine evolution occurring at much larger geological scales. Such events are difficult to predict and to successfully mitigate its potential effects. However, analysis of such processes is beyond the scope of any morphodynamic study.

Conclusion

Westwards transport of sediment occurs at all three scales with nourishment in the east observed to accumulate at the west in the aerial photos. Modal conditions are shown to transport sediment towards the west driven predominantly by wave forcing which is in turn observed in the morphological analysis with erosion in the east and accretion in the west. Evolution over short and long term also incurs rotation suggesting that replenishment of sediment occurs in the cross-shore direction during moderate winter swell from the flood-tide delta in the east as the west erodes, with the converse process in the summer a result of longshore transport under modal conditions. As a result, shoreline stability of Shoal Bay is connected to the transport of sediment from the flood-tide delta to the shoreline. In spite of this, overall erosion has occurred for the last 4 decades. This suggests that the FTD does not supply sufficient sediment to the shoreline, with high energy events eroding the beach most significantly in the west without adequate replenishment.

The expediency of the multi-scale approach is in its ability to derive longer term systemic trends that are removed from superfluous small scale fluctuations. Indeed analysis of aerial photography is an important first step before launching quantitative morphodynamic assessments particularly with the advent of cheap and accurate GIS (Bowman *et al.* 2009; Thieler and Danforth 1994). However, to ultimately derive the effects of the FTD on the Shoal Bay shoreline quantitative assessment of its evolution must occur in conjunction with shoreline analysis. While establishing the trends and processes interacting on an estuarine shoreline can be deduced by methods presented in this study, to accurately confer the processes driving systemic shoreline change and the sediment pathways within the Shoal Bay embayment quantitative assessment of linked morphologies must also occur. Such assessments are ongoing within the Port Stephens estuary with modelling of hydrodynamic conditions and sediment pathways to occur in the future.

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