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'Low energy' sandy beaches in marine and estuarine environments: a review

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Abstract

This review was undertaken to identify locations where low energy beaches may occur and their diagnostic forms and process controls, including waves, tides and water levels. Examples are drawn from the sheltered coastline of Western Australia near Perth and fetch-limited estuarine environments on the northeast coast of the United States. We suggest that the term low energy be used in locations where: (1) non-storm significant wave heights are minimal (e.g. < 0.25 m); (2) significant wave heights during strong onshore winds are low (e.g. < 0.50 m); (3) beachface widths are narrow (e.g. < 20 m in microtidal environments); and (4) morphologic features include those inherited from higher energy events. Micro-topographic features can persist in the swash zone of low energy beaches under non-storm wave conditions. There is little evidence of cyclic cross-shore sediment exchange. Bars, excepting transverse forms, located seaward of low still-water level do not appear to be part of the sediment exchange system with the foreshore. Developing a better definition of the term low energy requires understanding the occurrence and duration of morphological characteristics and the type, magnitude and frequency of hydrodynamic controls that are responsible for these characteristics. Efforts also should be directed toward: (1) discriminating between processes generated within basins (in true fetch-limited environments) and processes generated outside basins (that affect sheltered environments); (2) identifying the relative contributions of tide- and surge-related water level fluctuations on low energy beach shape; and (3) estimating thresholds for beach change.

Keywords: Low energy sand beach; Storm wave; Estuarine environment

1. Introduction

The term 'low energy' often serves as a major component of coastal classification systems (Tanner, 1960; Davies, 1964; Davis and Hayes, 1984). There is great variety in the application of this term in regard to wave height and degree of sheltering from waves generated in adjacent larger water bodies. As a result, the term is ambiguous.

Tanner (1960) defines low energy as "breaking wave heights < 0.10 m". Davis and Hayes (1984) use the term to describe environments such as the Gulf of Mexico where mean annual wave heights are 0.30 m. Davies (1964) describes low energy by relative energy and comparative location and includes "beaches in

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partially enclosed seas that are sheltered from swell'' and ''where wave action is minimal compared with exposed coasts''. The term low energy has been applied to beaches in environments ranging from narrow, shallow lagoons, where onshore winds of 13.0 m s^{-1} can generate significant wave heights < 0.10 m on the foreshore (Nordstrom et al., 1996), to beaches in the lee of reefs, where the significant breaker height is up to 1.0 m (Hegge et al., 1996). Some authors describe low energy environments by focusing on beach characteristics while omitting discussion of wave heights or periods (Ragan and Smosna, 1987; Barusseau et al., 1994), leaving the definition of low energy vague. The terms 'sheltered' or 'fetch-limited' have been used instead of the term 'low energy', but the ways that these terms are used often imply that they are considered synonyms.

The inconsistent use of the term 'low energy' to describe beaches with different geographic settings and relative energy regimes begs the question: what is a low energy beach? The purpose of this paper is to address this question and provide a framework within which low energy beaches could be considered. Specific objectives are to: (1) identify the geographic locations where low energy beaches may occur; (2) review published studies of process regimes and morphologic characteristics on beaches these authors defined as low energy; (3) identify the conditions under which diagnostic low energy forms occur; and (4) relate these conditions to process controls, including wave, tide and water level characteristics. Most of our detailed discussion is confined to sandy beaches that are formed and maintained by wave action and located in marine and estuarine environments, with examples drawn from the sheltered coastline of Western Australia near Perth and fetch-limited estuarine environments on the northeast coastline of the United States. These sites were selected because they represent a variety of beach types, and data are readily available to us.

2. Location

Beaches identified as low energy (Table 1) occur in a wide range of coastal environments, including those in ocean bays and sounds (FitzGerald et al., 1989; Ekwurzel, 1990; Suhayda and Oivanki, 1993), gulfs (Inman and Filloux, 1960), seas (Barusseau et al., 1994; Guillen and Palanques, 1996), straits (Fig. 1), estuaries (Fig. 2) including drowned river valleys (Rosen, 1980; Jackson and Nordstrom, 1992), lagoons protected by coastal barriers (Fig. 3) (Chaney and Stone, 1996; Nordstrom et al., 1996), artificially created marinas and lagoon developments in residential areas (Nordstrom, 1992), and in the lee of islands or submerged barriers such as reefs or submarine ridges (Fig. 4) (Ragan and Smosna, 1987; Hegge et al., 1996).

Different degrees of sheltering from waves generated in adjacent larger water bodies may create a variety of low energy forms in a given region. The coast of Western Australia in the vicinity of Perth (Fig. 5) illustrates many of the site-specific conditions under which low energy beaches occur due to the presence of semi-submerged and discontinuous Pleistocene ridges locally referred to as 'the reef' (Searle and Semeniuk, 1985; Sanderson and Eliot, 1999). Beaches are sheltered from the effects of ocean waves due to their location on the landward side of ocean islands (Site A), in the lee of the reef facing the ocean (Site B), in sounds in the lee of islands (Site C) on the landward side of islands in sounds (Site D), in the lee of islands in bays of sounds (Site E), or in the lee of human structures in sounds (Site F). Greater sheltering from ocean wave inputs may occur in estuaries (Figs. 2 and 5), and examples of low energy estuarine beaches include beaches in ocean entrances (Site G), beaches on windward and leeward sides of estuarine basins (Sites H and I) and beaches in tributaries (Site J).

The degree of sheltering from ocean waves that can occur in the lee of the reef and islands depicted in Fig. 5 is provided by comparing data, published by Marine Works Branch (1977), from wave rider buoys located in the Indian Ocean seaward (B1) and landward (B2) of the fringing reef and in a bay in Cockburn Sound (B3) on the landward side of Garden Island (Fig. 5). The annual offshore wave height in the region is 2.0 m (Lemm, 1996). On 18 July 1970, incident wave conditions seaward of the reef (B1) were characterized by a significant wave height of 3.0 m and a period of 10.4 s. Landward of the reef (B2), the significant wave height was 0.9 m with a period of 6.1 s. At the most protected site (B3), the significant wave height at that time was 0.2 m with a period of 2.0 s. On 31 July 1970, the significant wave heights at sites B1, B2 and

Table 1
Location and characteristics of sites identified by the authors cited as low energy, sheltered, protected or fetch-limited beach environments during non-storm conditions

Geographic location (basin site)	Wave height (m)	Wave period (s)	Tidal range (m)	Fetch distance (km)	Foreshore slope (deg)	Bars	Grain size (mm)	Source
Australia SW Coast								
Forrest	0.24[a]	10.7	0.5	nd	5.9	nd	0.28	Hegge (1994);
Kingston	0.12[a]	8.6	0.5	nd	5.1	nd	0.38	Hegge et al. (1996)
Sulfur	0.04[a]	8.0	0.5	nd	5.2	nd	0.23	
Gulf of Saint Lawrence								
Magdalen Islands								
East Site	0.58[b]	4	0.7	nd	nd	A	0.27	Owens and Froebel (1977)
West Site	0.83[b]	5	0.7	nd	nd	A	0.31	Owens and Froebel (1977)
Craig Bay	0.90[a]	3–4	3.4	< 100	4.4	U	0.17–0.42	Hale and McCann (1982)
Kattegat Hald	0.70[c]	2–3	0.4	< 165	nd	U	0.15	Aagaard (1988)
Balearic Sea								
Ebro Delta	1.0[b]	3.5	nd	nd	nd	nd	0.24	Guillen and Palanques (1996)
Gulf of Lion	< 1.2[a]	nd	0.26	nd	nd	A	nd	Barusseau et al. (1994)
Rhone-Delta	0.28[b]	4.0	0.28	nd	7.3	U	0.21	Makaske and Augustinus (1998)
Gulf of California								
San Felipe	0.43[a]	3.6	7.0 s	nd	8.3	U	0.70	Inman and Filloux (1960)
Boston Harbor								
Thompson Island	0.20	nd	nd	< 2	nd	nd	nd	Rosen and Brenninkmeyer (1989)
Buzzards Bay	0.75[b]	6.0	1.1	nd	nd	nd	nd	FitzGerald et al. (1989)
Cape Cod Bay								
Race Point	0.42[b]	nd	3.5 s	30	nd	none		Ekwurzel (1990)
Long Island Sound								
Napatree Beach	0.10[b]	0.7	0.79	nd	4.8	nd	0.68	Sakalowsky (1975)
Great South Bay								
Sailors Haven	0.09[a]	2.1	0.21	< 12	8.0	A	0.33	Sherman et al. (1994); Nordstrom et al. (1996)
Raritan Bay								
Sandy Hook								
Site 3	0.21[a]	3.9	1.4	nd	3.5	nd	0.46	Nordstrom (1977, 1980)
Site 4	0.17[a]	3.6	1.4	nd	6.3	nd	0.48	
Cliffwood Beach	0.16[a]	3.1	1.5	22	nd	U	0.51	Jackson and Nordstrom (1994)
Staten Island	0.04–0.06[a]	1.8–2.5	1.6	nd	nd	nd	nd	Nordstrom et al. (1990)
Delaware Bay								
Green Creek	0.12[a]	2.6	1.6	< 48	6.0	U	0.50	Jackson and Nordstrom (1992);
Fortescue	0.19[a]	2.8	1.6	< 27	nd	nd	nd	Nordstrom and Jackson (1992); Jackson (1995)
Chesapeake Bay	nd	nd	0.52	nd	7.7	nd	nd	Rosen (1977, 1980)
Gulf of Mexico								
Mesa del Gavilan	0.10	nd	0.10	< 9	nd	nd	0.16	Tanner (1960)
St. James Island	0.06[b]	nd	nd	nd		A	nd	Niedoroda and Tanner (1970)
Mississippi Sound								
Belle Fontaine	0.3–1.0[a]	2.0–3.5	nd	< 18	10–14	nd	0.13–0.5	Suhayda and Oivanki (1993)
West Ship Island	0.30[a]	nd	0.5	< 24	nd	nd	0.33–0.56	Chaney and Stone (1996)

nd—no data reported; s—spring range; A—attached bars; U—unattached bars.
[a] Significant wave height.
[b] Mean wave height.
[c] 50% exceedance wave height.

Fig. 1. Menai Strait, Wales, near Llanedwen.

Fig. 2. Como Beach in Swan River Estuary, Western Australia (see location H in Fig. 5).

Fig. 3. Petit Bois Island, Gulf Islands National Seashore, USA. The Gulf of Mexico is located on the lower right and Mississippi Sound is located on the upper left.

Fig. 4. Reef sheltered beach at Shoalwater Bay, Australia, showing wrack accumulation and vegetation on lower foreshore (see location B in Fig. 5).

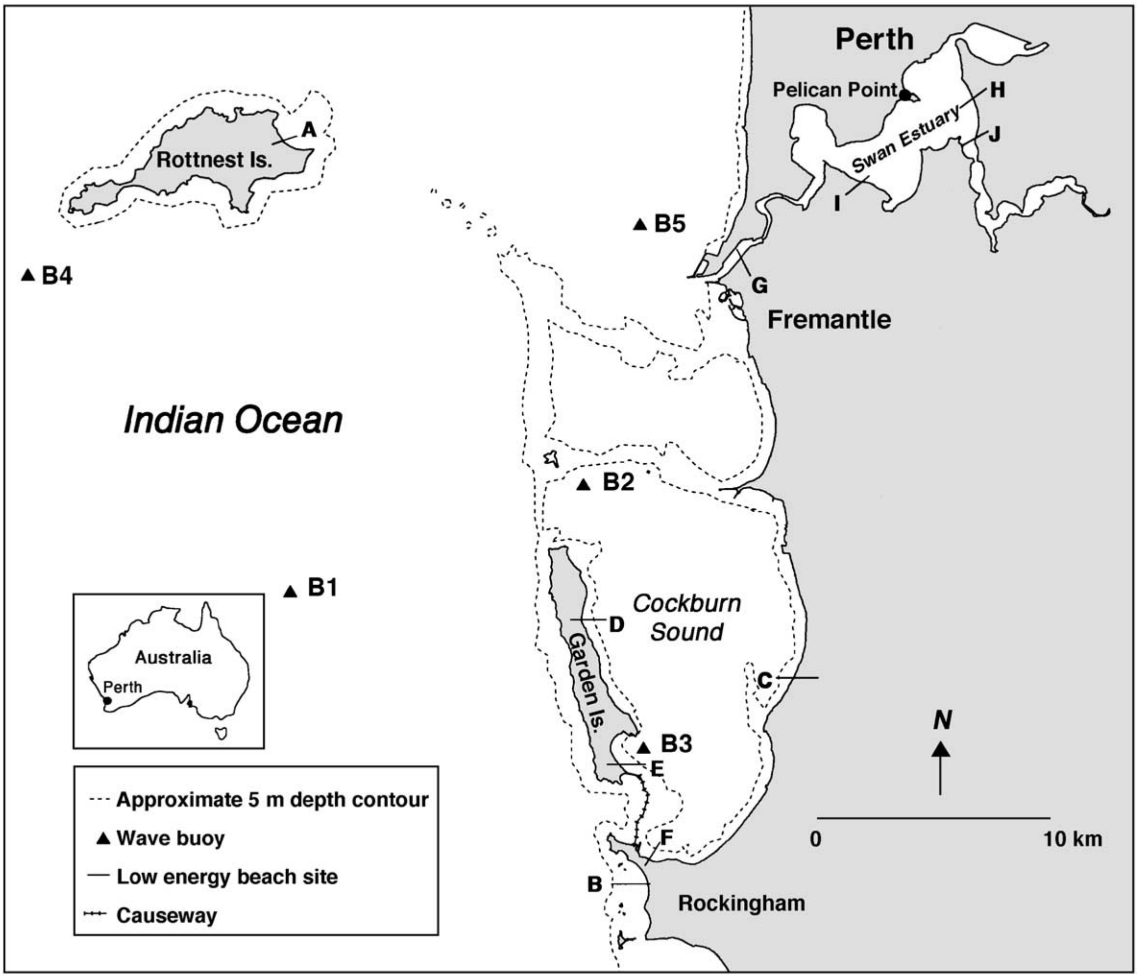

Fig. 5. Map of the coastline of Western Australia, in the vicinity of Perth, showing the location of low energy beaches.

B3 were 3.7, 1.0 and 0.3 m, respectively. Marine Works Branch (1977) estimates that a significant wave height of 1.3 m would only be exceeded 1 day in 100 years in the bay at B3 and that this condition would occur when strong easterly winds generated local waves within the bay. Steedman (1977) compared wave heights collected off the western tip of Rottnest Island (B4) with those measured in the Fremantle Harbour navigation channel (B5) (Fig. 5) and found that the inshore wave height was approximately 40% of the offshore wave height. Because wave energy is proportional to the wave height squared, this represents more than a sixfold decrease in the wave energy level.

3. Wave characteristics

Energy is most often described by only one wave characteristic (usually significant, mean or modal wave height), although beach morphology may be more properly understood by examining the relative contribution of combinations of process variables, especially wave height and tidal range (Davis and Hayes, 1984; Nordstrom and Jackson, 1992; Masselink and Short, 1993). Significant wave heights reported for beaches described by authors as ‘low energy’ ‘sheltered’ or ‘fetch-limited’ are usually <1.0 m under non-storm conditions (Table 1). On some of these beaches, wave heights may be <0.15 m, even under strong onshore winds with mean values ranging from 8.0 to 13.0 m s^{-1} (Sakalowsky, 1975; Nordstrom et al.,1996).

Waves in low energy environments can be generated locally or non-locally. Locally generated waves are primarily found in fetch-limited environments such as (semi-) enclosed basins. Non-locally generated waves are characteristic of sheltered environments in the lee of islands, behind submerged barriers, or near the entrances to larger external basins. The two types of wave regimes are different, but often not mutually exclusive. With the exception of lakes and enclosed lagoons, low energy environments are usually fetch-limited and sheltered at the same time and experience a mixture of local and non-local waves.

In fetch-limited environments, wave heights generated by local winds depend principally on wind conditions (speed, direction and duration) and basin dimensions (width, length and depth). Fig. 6 reveals the influence of basin size on the height of waves in the nearshore of two different estuaries (Great South Bay, New York and Delaware Bay, New Jersey, USA) measured at high water. Great South Bay is a lagoon protected by a coastal barrier, and basin depth is < 5 m. Data presented in Fig. 6 were gathered at a location where fetch distance for local wave generation is < 12 km. Delaware Bay is a funnel-shaped estuary and basin depth is < 12 m outside the navigation channel. Data presented in Fig. 6 were gathered at a location where fetch distance for local wave generation is < 48 km. Low onshore wind speeds (< 6.0 m s^{-1}) generate significant wave heights less than 0.15 m in both estuaries. Increasing wind speed does not significantly affect wave heights at Great South Bay because of short fetch distances and shallow water depths (Nordstrom et al., 1996), but increasing wind speed increases significant wave heights at Delaware Bay, attaining a maximum of 0.52 m with wind speeds in excess of 12 m s^{-1}.

In sheltered environments, inshore wave heights depend on the offshore wave energy level and the configuration of the sheltered area (i.e., size of offshore islands, permeability and depth of submerged reefs, dimensions of the bay or gulf, depth of the inshore area, shoreline orientation). A characteristic of sheltered environments is that large variations in wave energy level can be found within short distances alongshore because controls are highly site-specific.

There are a number of fundamental differences between the wave regimes of fetch-limited and sheltered environments. Locally generated waves in fetch-limited environments generally have short periods. These waves are less affected by wave refraction and may approach the shoreline at relatively large angles, increasing the potential for strong longshore currents for a given wave height. Waves that enter

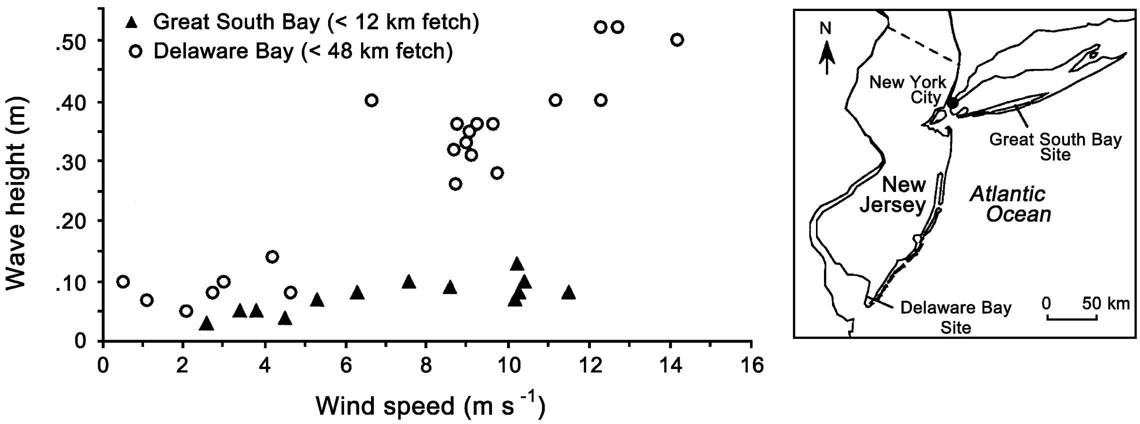

Fig. 6. Relationship between significant wave height and average onshore wind speed at two beach sites within two estuarine basins. Wave height data are from a transducer placed on the low tide terrace just seaward of the upper foreshore. Wind speed data are from an anemometer placed just landward of the active backbeach at 6 m elevation. Wave energy spectra indicate that these waves are locally generated (see Jackson, 1995; Nordstrom et al., 1996 for methodologies and representative spectra).

sheltered environments from external basins often have longer wave periods and approach the shoreline with their crests parallel to the coast. The wave climate of fetch-limited environments reflects the local wind climate and is therefore characterized by alternating high energy events (strong winds) and quiescent periods (weak or no wind). Sheltered environments may also display a temporal variability in the wave regime in response to variations in the offshore wave climate, but a background wave energy level from externally generated waves is likely to be more conspicuous at all times.

4. Profile shape and diagnostic features

4.1. Profile shape

Profile characteristics of low energy sandy beaches include narrow foreshores that are often steep (Jackson and Nordstrom, 1992; Suhayda and Oivanki, 1993), planar (Nordstrom, 1980; Hegge et al., 1996) and without a backshore. The horizontal widths of the foreshores are narrow, although widths on fine-grained low energy beaches may be comparable to widths of coarse-grained high energy beaches. Seaward of the foreshore a low gradient terrace, often referred to as a 'low tide terrace', is generally present and can extend for more than a kilometer. The terrace may be well vegetated and the benthic substrate markedly bioturbated. Under relatively high energy conditions, sediment mobilization may occur across the entire profile, including the foreshore and the low tide terrace. Transport of sediment on low tide terraces may be maximized when strong winds accompany water level set-down (Armbruster, 1997). On low energy estuarine beaches, extreme dissipative conditions prevail on the low tide terrace and beach profile change is restricted to the steep foreshore (Jackson and Nordstrom, 1992).

Low energy beaches display a variety of cross-shore profile shapes. Hegge et al. (1996) developed a profile classification based on 15 low energy sites on the southwest coast of Australia. The majority of these sites were located in sheltered environments in the lee of reefs or on the landward side of islands (similar to those portrayed in Fig. 5). Four low energy morphotypes (Fig. 7) were identified from cluster analysis of beach characteristics derived from 52 profiles. The four beach morphotypes were distinguished by their dimensions, slope, curvature and grain size, and included: (1) concave; (2) moderately concave; (3) moderately steep; and (4) stepped. Discrimination of the different morphotypes revealed sediment size as a strong morphological control. The 1-day experiments at each site did not provide enough data to relate the different morphotypes to hydrodynamic controls.

The work of Wright and Short (1984) forms the basis of many morphodynamic models on exposed high energy beaches (Lippmann and Holman, 1990; Masselink and Hegge, 1996). Field application of these models to low energy beaches has revealed limited success in predicting two-dimensional morphology. This is primarily because the high energy beach morphotypes identified by Wright and Short (1984) are based on the occurrence and configuration of breaker bars and rip currents in the surf zone. Nearshore bar/rip morphology is not present on low energy beaches and according to the high energy beach nomenclature, low energy beaches could be classified as either reflective or dissipative. The diagnostic morphodynamic characteristics attributed to reflective beaches (cusps, steps) and dissipative beaches (multibarred, infragravity wave energy) in high energy environments are often lacking in low

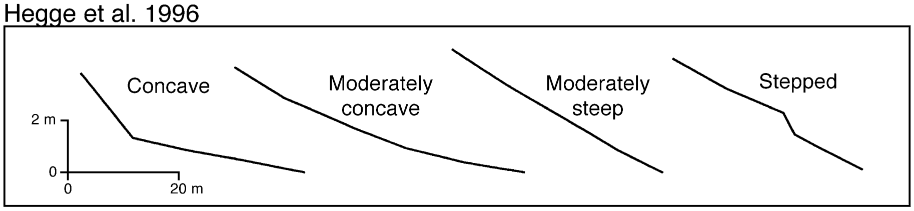

Fig. 7. Low energy beach morphotypes (Hegge et al., 1996).

energy environments. In addition, post-storm beach recovery on low energy beaches is often inhibited due to restricted alongshore sediment supply and insufficient wave energy following a storm. As a result, low energy beach morphology may represent a storm artifact or state of partial recovery rather than the equilibrium condition (Nordstrom, 1980; Aagaard, 1988; Hegge et al., 1996). Morphology may also be inherited from overwash events originating in adjacent water bodies (Stone and Wang, 1999; Stone et al., 1999). Finally, local controls, such as shoreline configuration (Phillips, 1986), orientation (Jackson and Nordstrom, 1992; Hegge et al., 1996), sheltering (Hegge et al., 1996) and nearshore topography (Sakalowsky, 1975; Rosen, 1977), may alter wave characteristics on low energy beaches to vary both the magnitude and extent of sediment reworking across the profile.

4.2. Common diagnostic features

Secondary features found on the profile of low energy beaches are of smaller scale compared to those same features on a higher energy beach. The presence or absence of these landforms is sensitive to small absolute changes in wave energy. Diagnostic features that commonly occur on low energy beaches include: (1) longshore and transverse bars and biogenic features on the low tide terrace; (2) swash bars; (3) vegetation and wrack accumulations on the intertidal foreshore; (4) pebbles and/or shells; and (5) small aeolian dunes.

Longshore bars are often found seaward of the beachface in low energy environments (e.g., Nilsson, 1978). They appear to represent stranded features that are not part of the cyclic sediment exchange system with the foreshore that is common on high energy beaches. Offshore losses of sediment from the foreshore to these bars are rarely compensated by transport back to the foreshore. Transverse bars are common, particularly on the low tide terrace of estuarine beaches (Brunner and Smosna, 1989; Nordstrom et al., 1996). Niedoroda (1966) observed wave refraction over transverse bars at water depths < 0.40 m, in northwest Florida, producing a complex pattern of cross-shore and longshore currents within the nearshore. Transverse bars appear to have an influence on foreshore morphology, especially on beaches with low mean wave heights (Niedoroda and Tanner, 1970; Nordstrom et al., 1996).

Small swash bars may be found on the foreshores of low energy beaches. They can be highly mobile due to their small size. Observations of a swash bar that formed on Pelican Point in the Swan River estuary (Fig. 5) indicate that a feature of this scale (< 0.1 m elevation and < 2 m wide) can be eliminated by swash uprush associated with waves resulting from a single boat passage. The small zone of wave reworking and limited amounts of sediment involved in cyclic exchanges mean that onshore migration of storm eroded deposits in the form of swash bars can keep up with rising tide (Jackson, 1995) and occur in a very short time (overnight at Pelican Point). Recovery time is longer in locations where there is a sediment deficit.

Vegetation may grow in the intertidal zone (Fig. 1) on the upper foreshore (Rosen, 1980) or on the low tide terrace fronting low energy beaches (Fonseca, 1996). Beach litter in wrack lines or strewn about the foreshore is generally more prevalent on low energy beaches, due to the large amounts of vegetation growing in sheltered waters (especially in estuaries), the contribution of cultural materials from urban populations, and the enhanced trapping caused by the numerous breaks in shoreline orientation. The accumulation of wrack lines on the upper beach occurs in wider and thicker bands than on higher energy beaches. Foreshore litter that occurs below the uppermost wrack lines has a more random distribution with a “dumped” appearance caused by the inability of individual swash uprushes to redistribute stranded clumps. The litter on high energy beaches is often in patterns representative of individual swash uprushes, and the amount of litter in each swash line is often small. Beach litter, whether as wrack or foreshore litter, plays a greater role in geomorphic evolution of low energy beaches under non-storm conditions. Patchy accumulations of vegetational detritus have pronounced effects on beach topography, creating nonsystematic and highly localized zones of accretion and scour, in contrast to the rhythmic features that are more common on high energy beaches.

Pebbles and shells are often conspicuous on predominantly sandy low energy beaches (Ekwurzel, 1990; Nordstrom and Jackson, 1993). Pebbles are often found on the backshores of high energy beaches as lag features following aeolian deflation. The narrow widths of dry beach in low energy environments restrict aeolian transport. Pebbles on the upper foreshores of low energy beaches are more likely to be stranded particles that are exhumed and preferentially moved by low energy waves than aeolian lag features. Pebbles low on the foreshore are more likely to be wave-related lag features (Nordstrom and Jackson, 1993). Shell particles are common in wrack lines on both high and low energy beaches. They are more likely to be found in banded patterns and cusp horns on high energy beaches.

Restrictions to aeolian transport may result in decreased likelihood for dune formation on low energy beaches, and active dunes are small. Narrow beaches restrict sediment source widths and increase susceptibility of dunes to storm wave attack (Nordstrom and Jackson, 1994). Overwash lobes will also be small relative to high energy beaches due to the limited energy of storm waves that overtop the beach and foredune.

4.3. Role of tides and surge

In low energy coastal environments, the effects of tidal and surge-related water level fluctuations become increasingly important and may affect beach morphology and processes. In this context, the term 'surge' refers to water level changes that are not associated with tides or wind-generated wave action. It includes set-down due to offshore winds and/or high barometric pressure, set-up due to onshore winds and/or low barometric pressure and also seiching. In estuaries, seasonal water level changes associated with flood discharge can also contribute to non-tidal water level fluctuations.

The effect of tides is to move different hydrodynamic zones (swash, surf and shoaling waves) up and down the intertidal profile, thereby reducing the amount of time waves can rework a given portion of the beach (Masselink, 1993) and inhibit the formation of nearshore bar morphology. The tidal translation rate is an important factor and depends on tidal range and the intertidal beach gradient. A useful parameter to quantify the importance of the tide with respect to beach processes is the ratio of tidal range to wave height, or the relative tide range (Masselink and Short, 1993). Low energy beaches with large relative tide ranges (>10) are generally characterized by a steep, reflective upper foreshore fronted by a low gradient, dissipative low tide terrace (Inman and Filloux, 1960; Nordstrom and Jackson, 1992). Tidal channels may be present on the low tide terrace, and bioturbation features are conspicuous where wave energies are minimal, in particular on the lower part of the profile.

Surge can play an important role on low energy beaches, particularly when surge levels exceed the tidal range. For example, Armbruster et al. (1995) report surge levels of 0.89 m above high tide on the microtidal bayside of Santa Rosa Island in a bay of the Gulf of Mexico where the mean tidal range is only 0.43 m. Surge is expected to be of greatest importance in locations that are sheltered from both waves and tides (such as near the head of estuaries) and on the landward side of barrier islands near inlets (where surge levels are forced by processes occurring in the larger ocean basin). An inverse relationship between surge height and onshore winds can occur on low energy beaches on the sheltered side of barriers and spits near entrances to larger ocean basins (Armbruster et al., 1995; Nordstrom et al., 1996).

Analogous to the effect of water fluctuations due to tides, surge causes a variation in the location on the beach profile where wave processes may operate. A primary distinction between tidal and surge features on the upper foreshore derives from the periodicity of the water level changes. The frequent inundation and reworking by waves during tidal rise and fall results in a more homogenous cross-shore surface and better sorted sediment. The infrequent inundation of the upper foreshores of beaches affected by surge results in pronounced differences in characteristics between the active lower foreshore and the relict upper foreshore. The relict upper foreshore of surge-affected beaches may reveal small-scale landforms (including those created by aeolian processes) associated with litter stranded on the beach at the uppermost wrack line and at wrack lines created by swash at falling water during waning periods of high-surge events. These features remain on the beach until arrival of a storm of comparable or increased magnitude. Locations where surge elevations are externally forced and wave energies are low will be characterized by poor sediment sorting and a shoreline characterized by multiple strand lines of flotsam.

5. Beach profile dynamics

Nordstrom and Jackson (1992) present a profile change model for estuarine beaches based on differences in wave characteristics observed on 21 sand beaches with a tidal range near 2.0 m. Two types of beach profile response are identified, depending on whether cross-shore or longshore sediment transport dominates (Fig. 8). In both cases, sediment exchange is limited to a zone between the upper limit of swash at high water and the break in slope separating the foreshore from the low tide terrace. On beaches where cross-shore transport is the dominant process, sediment exchange between the upper and lower foreshore is accomplished by changes in the locally generated wave energy level due to variations in wind speed. An increase in the wave height causes erosion of the upper foreshore and deposition on the lower foreshore, whereas a decrease in wave height returns sediment to the upper foreshore. Changes in wind direction and wave angle are responsible for inducing longshore sediment transport and may be responsible for parallel foreshore retreat (and advance) that is not accompanied by a conspicuous change in slope. Dominance of cross-shore or longshore processes is a function of shoreline orientation to the dominant winds and fetch, and the presence of shore-normal obstacles (such as shore protection structures) that act as sediment traps. The process data depicted at the top right of Fig. 8 indicate differences in cross-shore and longshore current velocities under similar wind speeds and water levels, but different wind directions. As wind angle increases relative to shoreline orientation, there is a shift from longshore to cross-shore dominance of foreshore processes.

Makaske and Augustinus (1998) present a model of changes on the beachface (defined as the area where swash and backwash processes are dominant) on a micro-tidal beach on the Rhone-Delta (Table 1). Three types of beachface morphology were identified from profile and wave data gathered over a spring-neap cycle (Fig. 8): (1) straight profiles that are short, steep and have a slope of >3° on the lower beachface; (2) concave profiles with a slope of <3° on the lower

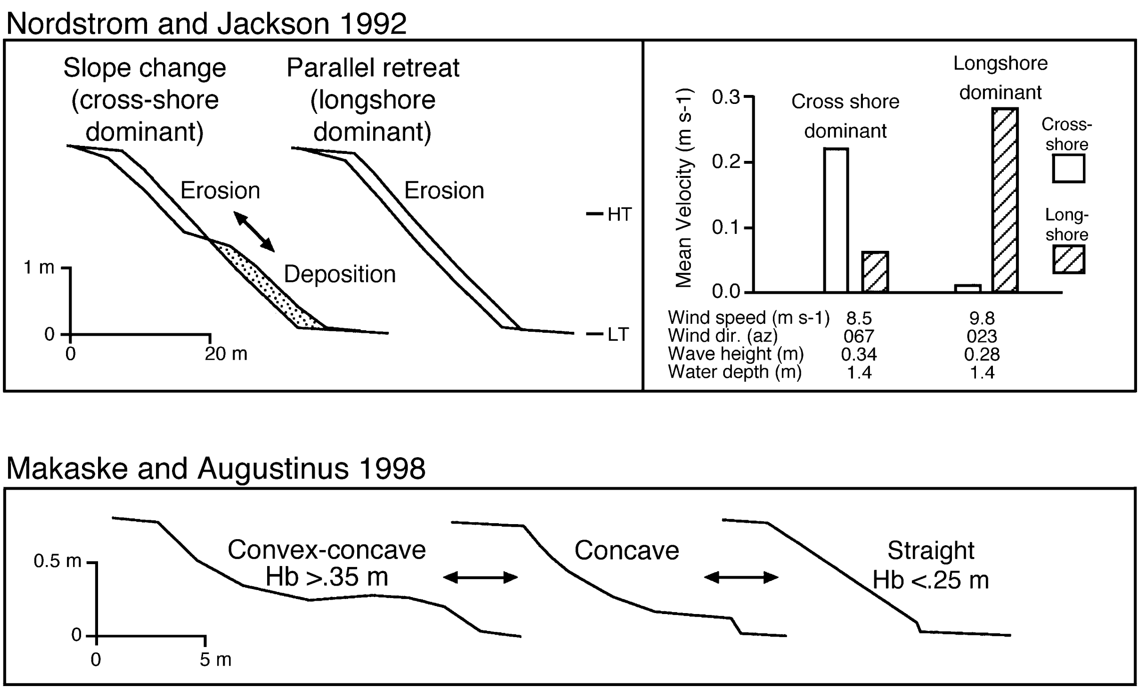

Fig. 8. Profile change models for low energy beaches including: meso-tidal estuarine beaches (Jackson and Nordstrom, 1992) with process data from Delaware Bay (Fig. 6), and microtidal sheltered beaches (Makaske and Augustinus, 1998).

beachface; and (3) convex–concave profiles that are wide and flat, with a convex slope of $<3°$ on the lower beachface. The occurrence of each type of beachface morphology was due to changes in wave height, with straight profiles resulting from low wave heights ($H_b < 0.25$ m) and concave–convex profiles resulting from relatively high wave heights ($H_b > 0.35$ m). Morphologic change on their beach occurred over a period of hours, despite the low wave heights.

On low energy beaches, the response of the foreshore profile to a storm event is proportional to the increase in the wave energy level. Fig. 9 shows the time-averaged profiles of two estuarine beaches (Great South Bay and Delaware Bay) and their response to a storm. The greatest change in bed elevation on the beach in Great South Bay occurred on the steep upper foreshore after the first tidal cycle following the storm, and was only 0.03 m in elevation and confined to a horizontal zone of <5.0 m. Due to the larger fetch length and basin depth, storm waves in Delaware Bay can attain significant heights of 0.36–0.52 m, causing significant changes to the foreshore profile. During the storm, erosion of the upper foreshore and deposition on the lower foreshore occurred, in line with the slope change model reported in Nordstrom and Jackson (1992). In Delaware Bay, non-storm significant wave heights average 0.12 m, and may result in onshore swash bar migration as part

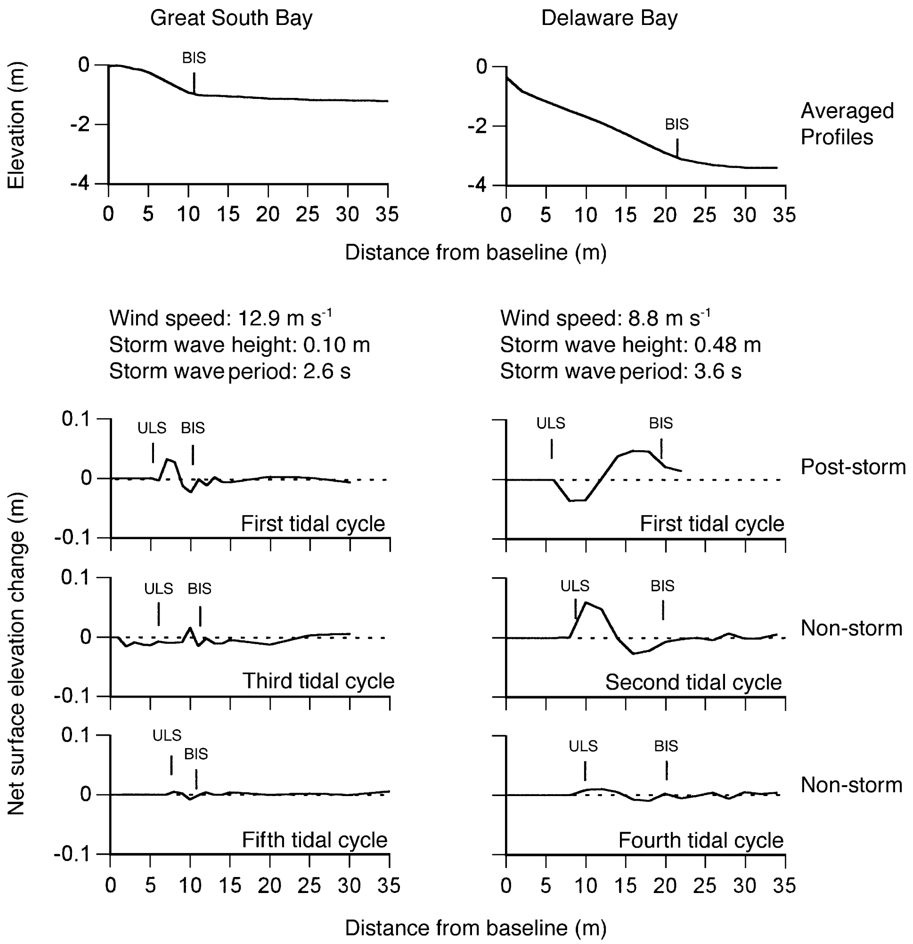

Fig. 9. Average profiles and net change in surface elevation during storm and non-storm sequence at Great South Bay and Delaware Bay. ULS refers to the location of the upper limit of swash and BIS refers to the location of the break in slope.

of the storm-recovery process. The time scale for profile recovery is short due to the ample supply of sediment within the beach system and the lack of offshore transport bayward of the break in slope (Jackson, 1995).

Large differences between storm and non-storm wave energy conditions also can slow recovery of the beach profile following a storm event. Waves generated in high energy environments outside the basin in which a fetch-limited low energy beach is located may have heights and periods that are higher or longer than could be locally generated within the basin (Ludwick, 1987; Jackson, 1995), although considerable reduction in non-local wave height occurs due to refraction of waves entering from outside the basin (Carter, 1980). High storm waves can result in offshore transport of sediment beyond the non-storm wave base and may give rise to forms that are not generally associated with low energy beach morphology, such as longshore bars.

Large lags in profile recovery on low energy beaches can be influenced by sediment availability. Lack of wave energy to rework intervening unconsolidated headlands and establish a sustained sediment source can reduce the likelihood for short-term recovery after storms. Lack of profile recovery can occur at sites where longshore transport is dominant and updrift sources are restricted. On low energy beaches adjacent to the mouth of larger ocean basins, profile recovery is enhanced by longshore sediment inputs from more energetic environments (Nordstrom, 1980; Ekwurzel, 1990).

6. Implications and future research

It is easy to classify beaches as low energy if the wave heights are <0.1 m (Tanner, 1960). Beaches with conspicuously greater wave heights (e.g. 1.0 to 2.0 m) may be classified as low energy solely because of the way they are perceived in juxtaposition with other beaches (Davies, 1964). Developing a more objective and quantitative definition of the term low energy requires a better understanding of the occurrence and duration of morphological characteristics, and the type, magnitude and frequency of hydrodynamic controls that are responsible for these characteristics. Other future research efforts should be directed toward: (1) discriminating between fetch-limited and sheltered conditions; (2) identifying the relative contributions of tides and surge-related water level fluctuations on low energy beach shape; (3) estimating thresholds for change; and (4) quantifying sediment flux and transport pathways during storms.

Low energy beaches should be evaluated based on the degree to which wave and surge are forced by processes outside sheltered areas. Some beaches are dominated by locally generated wave energies under all conditions and are true fetch-limited environments. Many low energy beaches experience a mixture of both locally generated and non-locally generated waves and surge (Nordstrom, 1980; Jackson, 1995), and the relative contributions of each to the development and maintenance of profile morphology, as well as small-scale features, need to be identified.

The large difference in wave energy levels between storm and non-storm conditions on many low energy beaches points to the need for a wave parameter that is responsible for overall profile shape. While it is common to report mean or modal wave height, these summary measures may not be useful to classify low energy beach morphology. Overall morphology may be an inherited feature related to high intensity, low frequency conditions, whereas surface characteristics (presence of isolated gravel clasts, distribution of beach litter) may be related to low intensity, high frequency conditions.

The reduction in the significance of wave height on some low energy beaches increases the importance of surge-related water level fluctuations in explaining profile shape and the location of morphologic features (Hegge et al., 1996). Under these conditions, a wave-sediment model will not successfully discriminate between low energy beach types. Relative tidal range has been found useful in distinguishing among high energy beaches (Masselink and Short, 1993). The need exists for quantifying the frequency and magnitude of surge-related water level fluctuations to overall beach shape on low energy beaches.

The shallow water zone seaward of the foreshore of many low energy beaches plays a major role in wave energy reduction, but the role of this sub-environment as a source or sink for sediment is still unclear (Armbruster, 1997). There is a need to extend future investigations beyond foreshores to include the low tide terrace. Specific attention should focus on the identification of hydrodynamic changes across this environment as well as the magnitude and frequency of sediment exchange.

Small-scale sedimentary and biogenic features on low energy beaches are sensitive to small variations in wave energy conditions compared to overall profile shape. Effects of vegetation litter have been examined in terms of volume and duration on the beach (Schülte, 1968). There is a need to know the relationship between wave energy and litter density, position and volume to identify when litter becomes a significant morphological agent.

The degree to which low energy beaches may be regarded as scaled-down versions of high energy beaches is subject to debate and is an issue that deserves more attention. Many of the features found on low energy beaches are also present on higher energy beaches, although their dimensions and persistence may differ. In some instances, the geometries of high and low energy beaches are convergent. In other respects, the mid to upper foreshores of low energy beaches display a wide range of tide and surge related morphologies and surface features that are not present or do not persist in high wave energy environments. For example, wrack deposited during storms on low energy beaches may comprise a substantial substrate for dune formation and colonization of the backshore by vegetation. Indeed, the wrack may comprise a substantial volume of material forming the dunes. Other features, such as nearshore bars, usually are not formed on low energy beaches. There is not sufficient time for a sediment convergence zone to form, given the relatively large water level changes due to tides and surge on a low energy beach.

Based on the results of our review, we suggest that the term low energy be used in locations where non-storm significant wave heights are minimal (e.g. <0.25 m); where significant wave heights during strong onshore winds (>8.0 m s^{-1}) are low (<0.50 m); and where beachface widths are narrow (e.g. <20 m in microtidal environments). Beaches associated with these conditions reveal little evidence of cyclic cross-shore sediment exchange and little evidence of bar forms seaward of low still-water levels (excepting transverse forms). The inability of modal wave energies to rework microtopographic features and beach litter provides a useful means for distinguishing low energy beaches. A low energy beach is one where micro-topographic features can persist in the swash zone under non-storm wave conditions. Morphologic features include those inherited from higher energy events, either as micro-topography above normal wave reworking or as beach shape within the zone of normal wave reworking. Future refinement of these definitions should occur as new findings are available.

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