Beach face and berm morphodynamics fronting a coastal lagoon

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Abstract

This study documents two different modes of berm development: (1) vertical growth at spring tides or following significant beach cut due to substantial swash overtopping, and (2) horizontal progradation at neap tides through the formation of a proto-berm located lower and further seaward of the principal berm. Concurrent high-frequency measurements of bed elevation and the associated wave runup distribution reveal the details of each of these berm growth modes. In mode 1 sediment is eroded from the inner surf and lower swash zone where swash interactions are prevalent. The net transport of this sediment is landward only, resulting in accretion onto the upper beach face and over the berm crest. The final outcome is a steepening of the beach face gradient, a change in the profile shape towards concave and rapid vertical and horizontal growth of the berm. In mode 2 sediment is eroded from the lower two-thirds of the active swash zone during the rising tide and is transported both landward and seaward. On the falling tide sediment is eroded from the inner surf and transported landward to backfill the zone eroded on the rising tide. The net result is relatively slow steepening of the beach face, a change of the profile shape towards convex, and horizontal progradation through the formation of a neap berm. The primary factor determining which mode of berm growth occurs is the presence or absence of swash overtopping at the time of sediment accumulation on the beach face. This depends on the current phase of the spring-neap tide cycle, the wave runup height (and indirectly offshore wave conditions) and the height of the pre-existing berm. A conceptual model for berm morphodynamics is presented, based on sediment transport shape functions measured during the two modes of berm growth.
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1. Introduction

The wave-dominated coastline of New South Wales, Australia, has approximately 130 estuaries. Many of these are coastal lakes or lagoons with entrances that naturally cycle between being briefly open to the ocean and being closed off by a wave-built berm for extended periods of time (Roy et al., 2001). The beach berms responsible for closing off coastal lagoons are created through the deposition of sediment at the landward extent of wave runup, resulting in the beach face profile growing both vertically and horizontally seaward. This tends to produce an increasing profile gradient approaching the berm crest on the seaward side and a horizontal to gently dipping back-beach profile on the landward side.

Berms are ubiquitous on steep, coarse-grained beaches and several early studies proposed a simple relationship between berm height above mean sea level and wave height (Bagnold, 1940; Bascom, 1953; King, 1972). Subsequent studies have proposed relationships that include not only wave height but also wavelength (period)
sediment transport and the switch to a bar-profile (Dean, 1953; Rector, 1954; Watts, 1954; Saville, 1957). Later studies by Broad (1975) and Takeda and Sunamura (1982) concluded that berm height was independent of grain size in the range 0.22–1.30 mm. Okazaki and Sunamura (1994) found it necessary to include a ‘reduction factor’ in their predictive equation for berm height in order to account for bed roughness and permeability, which are both directly related to grain size.

The dependence of berm height upon wave runup leads to what is known as the ‘berm-height paradox’, i.e., increasing offshore wave heights increase the wave runup height and therefore the berm crest height, but the largest waves ultimately erode the beach face and result in a reduction in berm height (e.g. Bascom, 1953; Komar, 1996; Hughes and Turner, 1999). The key element to resolving the berm height paradox is through improved prediction of the direction of cross-shore sediment transport (onshore versus offshore). Early laboratory work showed that the initiation of offshore sediment transport and switching from a berm-to a bar-profile occurs at a critical value of deepwater wave steepness, though this value varied between studies (e.g. King and William, 1949; Rector, 1954; Watts, 1954; Saville, 1957). Later studies considered the effect of the sediment fall velocity, which improved the predictive capability for initiation of offshore sediment transport and the switch to a bar-profile (Dean, 1973; Kraus and Larson, 1988; Larson and Kraus, 1989).

A different approach was investigated by Kemp (1975) who showed that swash interaction, specifically impendence, has a controlling effect on the sediment transport direction and resulting beach profile (bar or berm). While some nearshore morphodynamic models have tried to account for swash zone processes (e.g. Larson and Kraus, 1996; Masselink and Li, 2001), the transition to an accretory berm type profile requires accretory transport above the still water level for which there is still no validated sediment transport model (see Elfrink and Baldock, 2002, for a recent review).

Hine (1979) described three mechanisms for berm growth. The first mechanism is attributed to the landward migration and welding of an intertidal swash bar to the beach face. This creates a gently seaward dipping beach-face terrace, which rapidly steepens to create a new berm (e.g. Aagaard et al., 2006). A second, similar mechanism involves rapid vertical growth of an intertidal swash bar. During neap tides, waves runup is inhibited and results in the steepening of the seaward face of the swash bar. Later infilling of the landward runnel by overtopping during spring tides subsequently develops a wide berm ridge. In the case of the third mechanism, differences in tidal elevations over a spring-neap cycle are again crucial. During neap tides, wave runup is unable to overtop the pre-existing berm crest, resulting in the accumulation of sediment lower on the beach face in what is termed a ‘neap-berm’. At spring tide, the sediments composing the neap-berm are transported onto the top and over the crest of the higher ‘spring-berm’. Although Hine (1979) argued that differences in the longshore sediment transport rate determined which berm growth mechanism occurred at a given site, all of the mechanisms described are effectively the result of cross-shore sediment transport.

The controlling influence of the tide on maximum berm height is not limited to whether the beach accretion occurs during spring or neap tides. Grant (1948) hypothesised that on the flooding tide the beach face should accrete, particularly above the landward limit of the groundwater effluent zone (water table exit point) where swash infiltration is enhanced and the transport competency of the uprush is superior to the backwash. Similarly, on the ebbing tide he hypothesised that the beach should erode, particularly below the landward limit of the groundwater effluent zone where swash infiltration is impeded and the transport competency of the backwash is superior to the uprush. This hypothesis is consistent with subsequent field measurements presented in Duncan (1964) and Strahler (1966). In a recent study, Austin and Masselink (2006) present concurrent hydrodynamic and sediment transport measurements demonstrating reduced transport competency and deposition due to swash infiltration above the water table exit point on a gravel beach. They concluded that both tidal elevation and sediment deposition linked to swash infiltration controlled berm positioning on their beach.

Beyond these early qualitative studies and that by Austin and Masselink (2006) on a gravel beach, there has been no study of berm development on a sandy beach that integrates both morphological and hydrodynamic data with a temporal resolution sufficient to explore behavioral response of the berm at both inter- and intra-tidal timescales. This represents a significant gap in our understanding of beach morphodynamics. While the processes relating to beach erosion (elevated water levels at the shoreline and largely surf processes) have been widely studied and are reasonably well-described by broad-scale numerical engineering models, the processes relating to beach accretion (swash processes) are poorly understood and are largely excluded from such models (e.g. Schoones and Theron, 1995; Elfrink and Baldock, 2002). This paper addresses this point by...
presenting integrated hydrodynamic and morphological data collected during two different accretionary periods of berm growth. Field data and methods are described in Section 2. The data presented in Section 3 delimit hydrodynamic zones and related (localised) erosion and accretion that, when migrated across the beach with the tide, ultimately lead to berm growth. Two modes of berm growth are documented. Section 4 quantifies the sediment transport shape functions responsible for each of these modes and presents a conceptual model for berm morphodynamics. Discussion and conclusions follow in Sections 5 and 6.

2. Field site and methods

2.1. Avoca Beach

Two field campaigns were conducted over the periods 13–22 October, 2003, and 15–18 November, 2004, at Avoca Beach, New South Wales, Australia. The NSW coast is a high energy, wave-dominated environment, with a long-term offshore average significant wave height and period of 1.59 m and 8.0 s, respectively (Short and Trenaman, 1992). The coastline experiences semi-diurnal microtides, with an average spring tidal range of 1.6 m and a maximum spring range of 2 m (Easton, 1970). Avoca is a 1.5 km long beach facing east–southeast and bounded by two large sandstone headlands (Fig. 1). The entrance to Avoca Lagoon is situated approximately halfway along the beach and is intermittently open to the ocean during and following times of heavy rainfall. To avoid flooding of properties along the lagoon foreshore, the entrance is usually opened artificially when water level inside the lagoon reaches 2.1 m Australian Height Datum (0 m AHD is approximately mean sea level).

The field measurements reported here were obtained immediately in front of Avoca Lagoon. The beach face at this site is uniformly composed of coarse sand. A surface sediment sample collected from the mid-swash zone had a mean grain diameter of 0.525 mm, and is representative of the entire profile. During the first experiment, the beach morphology was characterized by a steep beach face with a gradient (\(\tan \beta\)) that ranged from 0.097 to 0.133. During the second experiment the beach face gradient ranged from 0.067 to 0.100.

2.2. Field experiments

The first field campaign was conducted over neap tides and the second over spring tides. During each campaign the beach morphology between the lagoon and inner surf zone was surveyed daily with a total station along shore-normal transects. Additional higher resolution measurements of morphological change in the swash zone were obtained from a single line of bed elevation rods inserted at 2-m intervals across the beach face. The rod heights were measured to within half a centimetre every 15 min over most or all of a semi-diurnal tide cycle on 8 occasions during the two field campaigns. The methodology is sufficiently accurate to resolve changes in bed elevation of 1 cm or greater (Masselink et al., 1997). The tops of the rods were surveyed at the start of each experiment and reduced to a common datum (AHD). Thus, the measured rod heights provided beach profiles

![Fig. 1. Sketch map showing the location of the experiment site at Avoca Beach, on the central coast of New South Wales (shaded region of inset), Australia.](image-url)
measured every 15 min throughout the tide cycle. In total 310 profiles from 8 separate tidal cycles are presented here. Difficult wave conditions or failing daylight sometimes prevented logging over a full tide cycle.

Concurrent with collection of the high-resolution morphology data, the wave runup height distribution was measured using a shore-normal array of pressure sensors installed across the beach face. In the first experiment this array consisted of 12 pressure sensors of varying makes (Druck, Van Essen Diver, In-Situ Mini Troll) and sampling capabilities, which were logged at a rate of either 2 or 10 Hz for 30-min bursts each hour over the period that the morphology was being monitored. In the second experiment the shore-normal array contained 13 Druck PTX pressure sensors, logged at a rate of 10 Hz for 15-min bursts every half hour with an additional Van Essen Diver self-logging pressure sensor logging continuously at 2 Hz. The latter was deployed at the berm crest to record the number of swash overtopping events. All pressure sensors were deployed at or just below the sand surface. The pressure sensor data were only used to tally the number of waves passing each pressure sensor, \( n_i \), and the total number of waves, \( N \), were then counted. Wave runup heights are expected to be well-described by the Rayleigh distribution (Battjes, 1971; Nielsen and Hanslow, 1991), in which case, measurements of the number of waves transgressing each elevation plotted against elevation should follow a straight line if the former is scaled as \( \sqrt{-\ln(n_i/N)} \) and the latter as \((Z_i-Z_o)\) (Fig. 2). A total of 134 wave runup height distributions obtained over 8 separate days showed that the Rayleigh distribution provides a good description of wave runup at Avoca Beach, with correlation coefficients (\( R^2 \)-values) from linear regression ranging from 0.907 to 0.986. Given that the Rayleigh distribution is a good description of the wave runup on Avoca Beach, we assume that the following relations exist:

\[
Z_{50\%} = Z_o + 0.83L_z
\]

\[
Z_{\text{sig}} = Z_o + 1.42L_z
\]

\[
Z_{2\%} = Z_o + 1.98L_z
\]

(e.g. Nielsen and Hanslow, 1991) where \( L_z \) is the vertical scale of the distribution, which equals the root mean square (rms) of the runup elevations, \( Z_{50\%} \) is the elevation exceeded by 50% of waves, \( Z_{\text{sig}} \) is the significant runup elevation (i.e. exceeded by 33.3% of waves) and \( Z_{2\%} \) is the elevation exceeded by 2% of waves.

2.3. Data processing

Wave runup exceedence statistics were obtained from the wave runup height distribution constructed from each 15-min pressure record. The highest elevation on the beach that was continuously inundated in each 15-min record, \( Z_o \), was determined first. The elevation of each pressure sensor \( Z_i \) relative to \( Z_o \) was obtained from the survey data. The numbers of waves passing each pressure sensor, \( n_i \), and the total number of waves, \( N \), were then counted.

Intersection of the groundwater table with the beach face (water table exit point) was also measured in the second experiment. Four stilling wells were inserted into the sand and periodically moved up and down the beach face with the tide in order to identify the elevation of the mean water surface through the swash zone and into the beach. Linear interpolation of the water surface between wells was used to obtain the water table exit on the beach face. Measurements were made every 15 min.

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**Fig. 2.** Example of an observed wave runup height exceedence distribution (symbols) measured at 11:00, October 16, 2003, and the Rayleigh distribution (solid line).

**Fig. 3.** Example of a pressure record showing two swash events, the first containing an overrunning wave (measured at 09:14, October 16, 2003).
Swash motion is not always simply the uprush and backwash of a single wave on the beach face. If the incident wave period is shorter than the swash period, then a second wave may arrive before the swash cycle of the previous wave is completed, resulting in swash interaction (e.g., Kemp, 1975; Hegge and Eliot, 1991). An example of one swash event experiencing overrunning by a subsequent wave is shown in Fig. 3. The swash event is identified by the bed being ‘dry’ at the start and finish of the event and waves are identified as one or more secondary peaks in the water depth. It was considered important in this study to determine the landward limit of interacting swash, since flow accelerations, turbulence levels, hydraulic jumps and the potential for enhanced suspended sediment transport are all likely to be where swash interactions are occurring. To quantify the landward limit of swash interactions, the total tally of waves (solid line) and the total tally of swash events (dotted line) recorded by each pressure sensor were plotted against sensor elevation (Fig. 4). The point of convergence of these two lines is considered to be the maximum elevation of swash interaction ($Z_{int}$). Seaward of this elevation there are more waves than swash events so several waves must overrun the swash lens. Landward of this elevation there is one swash event associated with each wave.

3. Experimental results

3.1. Typical berm dimensions at Avoca Beach

To place the detailed experimental data described below into a broader context, monthly surveys (made at spring tide) of berm height and width fronting Avoca Lagoon for the period July 2003 to August 2005 are shown together with the corresponding deepwater significant wave height in Fig. 5. From a lagoon management viewpoint it is interesting to note that the maximum berm height at Avoca is largely constant across a wide range of offshore wave conditions (Fig. 5). Our visual impression from monthly survey visits is that when erosion occurs the berm crest (swash limit) migrates landward as the beach face is cut back and the berm width is reduced. There is rarely a large reduction in the berm crest height, however, since the back-beach slopes at less
than 1° between the berm crest and the lagoon. Any major change in the maximum berm height that does occur is related to the opening (mechanical or natural) and subsequent closure of the lagoon entrance. For example, October–November 2004 and July 2005, both of which coincide with artificial openings (Fig. 5). These artificial openings are followed by rapid berm growth, as the lower berm height allows large swash overtopping volumes (see Weir et al., in press). In summary, the berm crest height at Avoca Lagoon is typically 2.8 to 3.0 m AHD except briefly during lagoon opening and subsequent closure events. The horizontal position of the berm crest (and beach face) is far more dynamic, migrating up to 25 m horizontally. There appear to be two modes of berm response during periods of beach accretion: (1) vertical growth following opening of the lagoon entrance, and (2) horizontal growth during periods of extended lagoon closure. Both of these modes are documented in the experimental data presented below.

3.2. Berm Growth Mode 1: vertical growth (swash overtopping)

The mechanism for vertical berm growth was documented during a field campaign that commenced 2 weeks after an artificial opening of Avoca Lagoon. Over the course of the campaign deepwater significant wave height ranged between 0.77 m and 1.95 m (Fig. 6a). Wave direction was dominantly from the southeast quadrant, which is the direction of maximum exposure for Avoca Beach (Fig. 6b). Berm height at the start of the campaign was 1.2 m AHD, which is substantially lower than the typical berm height at Avoca Beach and consistent with the recent opening of the lagoon (see Section 3.1). Spring tides (Fig. 6c) and the lower berm height during this period resulted in frequent overtopping of the berm crest by swash.

Detailed measurements of beach face morphology over 4 consecutive days (15–18 November) during spring...
tides showed a consistent pattern in berm development and profile response to wave forcing (Fig. 7). The principal feature of Berm Growth Mode 1 is a net accumulation of sediment on the upper beach face and berm crest at high tide. The largest net accumulation was immediately seaward of the berm crest and resulted in vertical and horizontal growth of the berm (Fig. 7a). There is also significant deposition up to 15 m landward of the berm crest. This mode of berm growth is strongly dependent upon swash overtopping, with larger amounts of overtopping resulting in more rapid berm growth. For example, on November 15, the berm crest grew 7.5 cm vertically and 1.95 m horizontally over 10 h in response to 40% of swash events surpassing the berm crest at high tide. In comparison, on November 18, the berm crest only grew 3 cm vertically and 0.90 m horizontally in response to only 10% of swash events overtopping the berm crest.

The main source of sediment during this mode of berm growth appears to be the lower half of the active swash zone and, thus, ultimately the inner surf zone. During the flooding tide on 15 November (07:30 to 10:30 in Fig. 7b) erosion occurred at the landward end of the surf zone and seaward end of the swash zone (i.e. immediately either side of \( Z_0 \)). Accretion occurred slightly seaward and everywhere landward of \( Z_{int} \) and \( Z_{50\%} \), which follow each other closely through most of the tide cycle. During the rising tide the boundary between erosion in the lower swash and accretion in the upper swash is abrupt. During the falling tide such a boundary is less obvious (12:00 to 16:00 in Fig. 7b), as indicated by mottled coloring in the figure across the entire swash zone. The heightened degree of morphological variability indicated by the mottled coloring may represent the passage across the swash zone of small ridges up to 5 cm high with a period of several minutes, as first noted by Sallenger and Richmond (1984) and frequently observed by the authors on steep beaches. Generally accretion occurred across most of the swash zone and erosion occurred in the inner surf zone. At high tide (10:30 to 12:00 in Fig. 7b) there is erosion in the inner surf zone and accretion across most of the swash zone as well as over the berm crest. Note that at high tide \( Z_{int} \) and \( Z_{50\%} \) diverge, due to a large number of swashes overtopping the berm crest. At all times bed elevation changes were insignificant (<1 cm) landward of \( Z_{2\%} \).

The pattern just described is generally repeated over the next 3 days, although it does differ in detail. On the 16 November the erosion/accretion boundary is stronger on the falling rather than the rising tide and follows the location of \( Z_{int} \) over the entire tide cycle, whereas on the 17 and 18 November the behavior is almost exactly the same as the 15 November. There is a clear trend towards the 18 November of a reduced range in bed elevation changes on the beach face and reduced accretion over the berm crest. This is consistent with the reduction in swash overtopping mentioned previously.

In summary, Berm Growth Mode 1 involves erosion of the lower beach face and accretion of the upper beach face and berm crest. The erosion/accretion boundary on the beach face is most marked during periods of rising and high tide when there is substantial swash overtopping. This is analogous with berm behavior at spring tide reported by Hine (1979) on a sandy beach and by Austin and Masselink (2006) on a gravel beach. The difference here is that berm overtopping is not necessarily restricted to spring tides, due to the presence of a lagoon entrance. The final outcome is a steepening of the beach face gradient, a change in the profile shape towards concave and both vertical and horizontal growth of the berm. In the case documented here the gradient steepened from 0.067 to 0.100, the berm crest increased in elevation by a total of 30 cm and grew horizontally seaward by a total of 2.6 m over a 4-day period (8 tide cycles).

3.3. Berm Growth Mode 2: horizontal growth (no swash overtopping)

The mechanism for horizontal berm growth was documented during an extended period of lagoon closure, when the elevation of the pre-existing berm crest was 2.93 m AHD (close to the modal elevation). Deepwater wave conditions varied substantially throughout the field campaign. The largest deepwater significant wave height of 3.48 m occurred at the beginning then decreased to a minimum of 0.62 m on the 18 October, followed by an increase to 2.42 m on the 20 October (Fig. 6d). Waves were mostly from the southeast quadrant (Fig. 6e). Although waves were large early in the campaign there was no overtopping of the pre-existing berm crest, primarily because neap tides occurred during this period (Fig. 6f).

Daily measurements of the beach profile during this campaign indicated no significant change in the pre-existing berm elevation. Horizontal progradation of the
beach face is clearly evident, however, through the development of a prominent lower or neap berm (Fig. 8a). A beach profile surveyed approximately 1 month later at spring tide (28 November) shows that this lower berm appears to have migrated landward and accreted onto the pre-existing berm (Fig. 8a).

The principal feature of Berm Growth Mode 2 is a net accumulation of sediment on the mid to upper beach face resulting in horizontal progradation of the beach face, but no vertical growth of the pre-existing berm. The details of this behavior are evident in Fig. 8b–e. The data coverage is not as comprehensive as that available from the November 2004 experiment (Fig. 7), because of difficult wave conditions in the inner surf zone and the tide cycles not falling neatly within daylight hours. During the flooding tide on the 14 October erosion occurred across the entire zone extending from Z_o to Z_{sig}, i.e. across the entire lower two-thirds of the active swash zone (07:30 to 10:30 in Fig. 8b). A relatively small amount of accretion occurred in the zone between Z_{sig} and Z_{2%}. Landward of Z_{2%} bed elevation changes are insignificant (<1 cm). Although we do not have profile closure on the upper beach on this day, given the relatively minor amounts of change recorded in this region it is reasonable to conclude that the large amount of sediment eroded from the mid and lower swash zone on the rising tide moved offshore. During the falling tide the beach face recovered with accretion occurring across the entire active swash zone (11:30 to 15:00 in Fig. 8b). The only possible source for this accreted sediment is the inner surf. The development of the neap-berm was initiated on this day through the minor accretion that persisted during almost the entire tide cycle landward of Z_{sig}. The total amount of net accretion cannot be determined because the profile data are not closed at the landward end in this case. This problem was rectified on subsequent days.

The general pattern observed on the 14 October was repeated on the 16 October (Fig. 8c), although the range of bed elevation changes was reduced in the latter case, probably due to the 50% reduction in offshore wave height over the 3 days (Fig. 6d). On the 20 October we only have data for the rising tide (Fig. 8d), but the pattern differs from the rising tides in the previous two panels. Accretion occurred across the region between the inner surf and Z_{int}, erosion occurred across the zone between Z_{int} and Z_{sig}, and further accretion occurred between Z_{sig} and Z_{2%}. Again, there were no significant bed elevation changes landward of Z_{2%}. This pattern is repeated on the 22 October (Fig. 8e).

In summary, Berm Growth Mode 2 involves erosion of sediment from the lower swash zone and deposition in the mid to upper swash zone to develop a neap berm below the principal berm. This is also consistent with berm behavior reported by Hine (1979) on a sandy beach and by Austin and Masselink (2006) on a gravel beach. The final outcome is a steepening of the beach face, a change of the profile shape towards convex, and only horizontal growth of the principal berm (well below its crest). Sediment accumulation rates responsible for this profile change are significantly less than for Berm Growth Mode 1. In the case documented here the gradient steepened from 0.097–0.133, the neap berm achieved a maximum thickness of only 40 cm and maximum horizontal progradation seaward of only 2.1 m over a 9-day period (18 tide cycles).

4. Sediment transport shape functions and conceptual berm growth model

Sediment transport shape functions have previously been used with some success in investigating beach morphodynamics (e.g. Russell and Huntley, 1999; Masselink, 2003). These shape functions describe the sediment transport rate as a function of distance across the beach profile, and have been calculated here to aid the development of a conceptual (and ultimately numerical) model for the morphodynamic behavior of berms during accretionary growth. The net cross-shore sediment transport rates at specific locations along the beach face profile were calculated using the quarter-hourly beach elevation measurements and the mass conservation equation:

$$Q_i = Q_{i-1} + (1-p) \frac{\Delta \bar{\eta}}{\Delta t} (Z_i - Z_{i-1})$$

where \(Q_i\) is the sediment transport rate in \((m^3/m.s)\) at the cross-shore position \(i\), \(Z_i\) is the bed level at different time steps, \(\Delta \bar{\eta}\) is the cross-shore distance step, \(\Delta t\) is the time step and \(p\) is the sediment porosity. Positive and negative values of \(Q_i\) indicate onshore and offshore sediment transport, respectively. A total of 247 sediment transport shape functions were calculated from the available data summarized in Figs. 7 and 8, one for each quarter-hourly beach profile.

For the purpose of developing the conceptual model presented here, the magnitudes associated with the shape functions are irrelevant, only the form of the shape function is important. All 247 calculated sediment transport shape functions could be classified as one of three basic shapes, with one shape including subgroups. The basic shapes are represented by the curves shown in Fig. 9. All 247 shape functions were assigned to one of the 3 groups (plus one subgroup). The position in the swash zone was normalized against the vertical extent of the runup,...
distribution corresponding to each shape function and the sediment transport rate was normalized against the maximum for each shape function. The normalized shape functions were then ensemble-averaged within each group. This was done by first interpolating the value of the sediment transport rate at successive increments of 0.1 of the swash height and then averaging the values for each increment across all functions in the group. The vertical bars in Fig. 9 indicate one standard deviation about the ensemble-mean. The variability in the magnitudes is reasonably large and due at least in part to the fact that calculation of the ensemble-averaged transport rates involved interpolation between data points. Further discussion of the variability in magnitude of the transport rates is presented in Section 5. Here we are most concerned with the predominance of the 3 basic shapes. Shape I is characterized by a relatively large onshore sediment transport rate in the lower swash zone and a gradual decline to zero seaward of the upper swash limit (Fig. 9a). In the case of Shape II onshore sediment transport takes place across the entire swash zone, including close to the upper swash limit, with Shape IIb characterized by substantially larger sediment transport rates at the upper swash limit than Shape IIa (Fig. 9b and c). The sediment transport rate does not drop to zero at the upper swash limit, because Shape II occurs during swash overtopping. When swash overtops the berm it can carry considerable sediment without climbing higher in elevation, since the beach becomes close to horizontal landward of the berm crest. While Shape IIa and IIb are qualitatively similar there is a considerable difference in the relative magnitude of the sediment transport rate at the top of the beach—20% versus 60% of the peak transport rate. This has a profound effect on the rate of vertical berm growth, and it will be seen below that the two shapes also correspond to different berm growth modes, thus justifying their inclusion as individual subtypes. Shape III is characterized by offshore sediment transport in the lower to mid-swash zone and a narrow region of onshore transport in the mid-to upper swash zone that diminishes to zero well seaward of the upper swash limit (Fig. 9d).

The columns on the right hand side of Figs. 7 and 8 indicate when each shape function occurs over the monitored tide cycles. During Berm Growth Mode 1 (vertical growth with swash overtopping), Shape Function I occurred on the rising and falling tides and Shape Function II occurred at high tide (Fig. 7). Shape Function III rarely occurred. In contrast, during Berm Growth Mode 2 (horizontal growth with no swash overtopping), Shape Function I generally occurred on the falling tides and Shape Function II on the rising tides (Fig. 8). Shape Function II was absent, consistent with the absence of swash overtopping the berm.

Fig. 10 depicts a conceptual model for the growth of berms fronting coastal lagoons on energetic, relatively steep, intermediate-type beaches (see Wright and Short (1984) for a full description of this beach type). In each panel the dashed profile represents the existing profile from the previous stage and the solid profile represents the new profile developed in the current stage of the cycle. Following a lagoon opening (or simply a significant erosional event in the absence of a lagoon) the beach face profile is characterized by a lower than typical beach face gradient and berm crest height (Fig. 10a). On some beaches the berm form (i.e. steep beach face, crest and subhorizontal back-beach) may disappear entirely, particularly on sediment starved beaches backed by cliffs or seawalls. On the relatively steep and wide beaches characteristic of the central New South Wales coast, however, the beach face profile maintains a crest and gently sloping back-beach even during considerable beach cut (Section 3.1).

As wave conditions become conducive to onshore sediment transport following the period of beach cut, berm growth occurs in both the vertical and horizontal direction (Fig. 10b). Sediment transport Shape Function I operates during the rising and falling tide, delivering sediment from the inner surf and lower swash zones to
higher up the beach face, resulting in horizontal progradation. Shape Function II operates at high tide when swash overtopping of the berm delivers this sediment landward of the berm crest, resulting in vertical accretion. Shape Function IIb occurs when overtopping is substantial and IIa when it is limited. This stage continues until the berm crest height has increased sufficiently or the high tide level has dropped sufficiently towards neaps for swash overtopping of the berm crest to cease.

Once swash overtopping of the berm ceases the next stage begins where only horizontal growth occurs (Fig. 10c). Shape Function III occurs on the rising tides with offshore transport in the lower swash zone causing steepening of the profile and minor onshore transport in the mid-upper swash zone contributing to the development of a neap berm. Shape Function I occurs on the falling tides delivering sediment from the inner surf zone to the lower beach and from the lower beach to the neap berm. No

Fig. 10. Diagram showing a conceptual model for berm growth following a lagoon breakout event (or a significant erosional event in the absence of a lagoon) on steep intermediate-type beaches with an energetic wave climate. (a) Stage 1, the beach face profile is characterized by a lower than typical beach face gradient and berm crest height; (b) Stage 2, rapid vertical growth of the berm crest during swash overtopping, with additional horizontal progradation of the berm; (c) Stage 3, slower horizontal progradation of the principal berm through accretion of a lower neap berm when swash overtopping ceases; (d) Stage 4, migration of the neap berm onto the principal berm on the following spring tide.
change in the elevation or horizontal location of the principal berm occurs during this stage.

The neap berm ultimately migrates upwards as swash action is translated higher up the beach face with the successively more elevated high tides approaching springs. During spring tides Shape Function III operates on the rising tide, eroding the neap berm and depositing material higher up the beach (Fig. 10d). Shape Function II operates at high tide when swash overtopping deposits this material onto the berm crest to produce vertical growth. Shape function I operates on the falling tide, so there is no sediment lost seaward. At any stage in the described cycle, the situation may revert to Fig. 10a, thus re-initiating the cycle. A complete cycle through all four stages is only possible given sufficient time between lagoon openings (or significant erosion events in the absence of a lagoon). For the energetic Avoca Beach sufficient time is one spring-neap tide cycle. Once the berm is re-established to its maximum crest height then only horizontal progradation of the beach continues, by cycling between stages 3 and 4 (with the absence of significant overtopping at spring tides).

This conceptual model represents intra-tidal processes occurring over the rising versus the falling limbs of the tide and stage changes occurring over the growth of the berm that occur on the timescale of a neap-spring tide cycle at Avoca Beach. The model is based on 310 beach profiles measured quarter-hourly over both the rising and falling limbs of the tide, corresponding wave runup height distributions for each beach profile, and a sediment transport shape function determined from the bed elevation changes between each consecutive beach profile. These concurrent data were obtained from eight separate semi-diurnal tide cycles spread over the neap-spring cycle. The processes and stage changes represented in the model are therefore substantiated at the level of the data.

5. Discussion

This study has documented berm morphodynamics at Avoca Beach on the central coast of New South Wales, Australia. The results of this study indicate that the berm height on this intermediate-type beach can be remarkably constant. This is largely due to (1) the broad, nearly horizontal back-beach zone that accommodates extensive beach cut without any change in the maximum elevation on the beach, and (2) the rapid re-establishment of the berm crest height when rare lagoon openings do occur (usually within one spring-neap tide cycle). This has significant implications for the management of this and other intermittently closed and open lagoon entrances (ICOLs), which are characteristic of New South Wales and many other wave-dominated coasts of the world.

Management plans for these systems usually must balance conflicting outcomes, for example, the desire to maintain an open entrance for flood mitigation and improved flushing and the desire to maintain natural cycling of the entrance condition (i.e. alternating periods of opening and closure) to sustain existing ecosystems.

Avoca Beach is a relatively short, pocket beach with limited capacity for longshore sediment transport. These conditions contrast with those occurring on the beach studied by Hine (1979), where longshore transport was identified as the controlling parameter in determining berm growth rates. Our data demonstrate that, following a natural or artificial lagoon opening, subsequent closure can be achieved solely through cross-shore transport of sediment and re-establishment of the berm to its modal height, usually within one spring-neap tide cycle. Stages in this closure process have been described here in terms of sediment transport shape functions. A logical next step is to incorporate these shape functions into a numerical modeling framework to make predictions on rates of entrance closure for different initial conditions. This next step is not trivial. The general form of the shape functions is well constrained to 3 basic types at least during berm growth, but the actual magnitudes of the sediment transport rates represented by these basic types vary widely. The magnitudes related to each shape function are controlled in part by the wave runup distribution, and given the random wave conditions driving runup on a natural beach the variability in magnitude of the shape functions is perhaps not surprising. The complexity inherent in the strong Markovian behavior characteristic of beach systems will no doubt also be a factor (see Sonu and James, 1973).

It is important to note that although the transport shape functions are non-zero at the seaward boundary that does not necessarily imply the lower beach face will be continuously eroded. Sediment delivery from the inner surf zone can partially or completely offset this. The high degree of bed mobility in the inner surf zone of intermediate beach types like Avoca is therefore also expected to contribute variability to the magnitudes of the transport shape functions. A detailed process description for sediment delivery from the inner surf to the swash zone, suitable for model development, is beyond the current state of the art. Possible candidate processes include velocity skewness beneath bores, boundary-layer streaming, sediment advection and long wave effects. Developing the conceptual model in Fig. 10 into a predictive, quantitative model is, therefore, work in progress.

During some of the tide cycles monitored in this study there is an asymmetry in morphological behavior about high tide, i.e. for a given tidal elevation the morphology behaves differently on the rising versus the falling limb of
the tide. This is particularly noticeable in Figs. 7d, e, 8b and c where erosion of the swash zone is predominant on the rising tide and deposition on the falling tide. This morphodynamic asymmetry corresponds with a similar asymmetry with respect to the runup distribution. In all of the cases just mentioned, for a given tidal level $Z_{50\%}$ sits relatively higher up the beach (i.e. closer to $Z_{2\%}$) on the rising compared to the falling limb of the tide. This effectively means that more waves penetrate deeper into the swash zone on the rising limb of the tide, which probably leads to greater swash interaction, enhanced turbulence and sediment suspension. The reason why more waves penetrate the swash zone on the rising versus the falling tide remains an open question.

Based on Grant’s (1948) hypothesis for beach profile behavior due to swash infiltration and its effect on sediment transport competency (Section 1), we might expect that the erosion/accretion boundary would migrate in concert with the water table exit point. Indeed, Austin and Masselink (2006) observed this to be the case on their gravel beach. On the 3 occasions that we tracked the water table exit point across the beach face at Avoca Beach the results were mixed (Fig. 7c to e). On the rising tides of the 16 and 17 November the water table exit point coincided with the boundary as expected. On the falling tides of these 2 days, however, both zones of erosion and accretion existed in the groundwater effluent zone (seaward of the water table exit point). Moreover, erosion occurred landward of the water table exit point at high tide on the 17 November, which is also contrary to Grant’s hypothesis. On the 18 November the water table exit point does not coincide with the boundary between beach face erosion/accretion at all.

Despite widespread acceptance of Grant’s hypothesis, our data from a sandy beach are inconsistent with its predictions over a wide range of wave conditions (0.7–2.0 m offshore significant wave height). Similar data presented by Holland and Puleo (2001) also show beach profile behavior on a sandy beach that is contrary to Grant’s hypothesis. On many occasions the boundary between swash erosion/accretion in our data corresponded more closely to the landward limit of swash interactions $Z_{int}$ (Figs. 7c, d, 8b–e), consistent with results reported by Holland and Puleo (2001). Kemp (1975) was the first to propose that wave–swash interactions might be important in determining the net direction of sediment transport and profile change. Where wave–swash interaction occurs on sandy beaches there will be increased sediment entrainment, due to greater turbulence and the frequent occurrence of hydraulic jumps (e.g. Butt and Russell, 2005). This suspended sediment is swept landward when Shape Functions I and II are active and seaward when Shape Function III is active. The fact that gravel is less likely to be raised into suspension may explain why the data reported by Austin and Masselink (2006) concur with Grant’s hypothesis. The detailed hydrodynamics determining the net transport direction in the swash interaction zone still need to be established before quantitative predictions of profile behavior can be achieved.

6. Conclusions

On relatively steep, intermediate-type beaches with a wide back-beach area, the beach can experience considerable cut and flattening of the gradient without any significant change in elevation at the top of the beach face. That is to say, a berm-like profile persists during periods of beach cut, due to the broad approximately horizontal back-beach area. A significant reduction in berm height does occur on these beaches when the beach is cut naturally or artificially by an open lagoon entrance, usually during periods of prolonged heavy rainfall. When the lagoon has a small tidal prism and the beach is exposed to an energetic wave climate, then the lagoon entrance rapidly closes off through vertical accretion of the berm fronting the lagoon. Depending on the phase of the neap-spring tide cycle closure can be achieved in a couple of days and almost always within one neap-spring tide cycle. As a consequence Avoca Lagoon, and others like it on the New South Wales coast, are intermittently open to the sea but typically closed for most of the time.

Two modes of berm growth were identified: (a) rapid vertical growth of the berm crest (associated with some horizontal progradation), and (b) slower horizontal progradation through the formation of a lower neap berm on the face of the principal berm. The primary factor determining which mode of berm growth occurred was the presence or absence of swash overtopping of the pre-existing berm at the time of sediment delivery to the beach face. This depends on the prevailing phase of the spring-neap tide cycle, the wave runup height (and indirectly offshore wave conditions) and the height of the pre-existing berm. Sediment transport shape functions were calculated and could be classified into 3 basic shapes. The two berm growth modes are clearly distinguished and characterized by unique combinations of these shape functions.

A conceptual model for berm growth is presented (based on the transport shape functions) that is considered to be generally applicable on steep, microtidal, intermediate-type beaches exposed to an energetic wave climate. Following Stage 1, erosion of the berm, a complete accretionary path through the model involves: (Stage 2) rapid vertical growth of the berm crest during swash overtopping with additional horizontal progradation of the berm, particularly during spring tides; (Stage 3)
slower horizontal progradation of the principal berm through accretion of a lower neap berm when swash overtopping ceases; and (Stage 4) migration of the neap berm up onto the principal berm on the following spring tide. During extended periods between erosional events the beach face probably cycles back and forth between Stages 3 and 4, but producing only horizontal progradation once the berm reaches its maximum possible crest elevation at springs. The sediment transport shape functions required to quantitatively model this berm behavior have been defined. While the model presented is based on measurements of berm behavior fronting a coastal lagoon, it is expected to be also applicable to the more general case of beaches without a lagoon.

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