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The Effect of Tide Range on Beach Morphodynamics and Morphology: A Conceptual Beach Model

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ABSTRACT

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Natural beaches may be grouped into several beach types on the basis of breaker height (H_b), wave period (T), high tide sediment fall velocity (w_s) and tide range (TR). These four variables are quantified by two dimensionless parameters: the dimensionless fall velocity ($\Omega = H_b/w_sT$) used by WRIGHT and SHORT (1984) to classify micro-tidal beaches, and the relative tide range ($RTR = TR/H_b$) introduced in this paper. The value of the dimensionless fall velocity indicates whether reflective, intermediate or dissipative surf zone conditions will prevail. The relative tide range reflects the relative importance of swash, surf zone and shoaling wave processes.

A conceptual model is presented in which beach morphology (beach type) may be predicted using the dimensionless fall velocity and the relative tide range, whereby the mean spring tide range (MSR) is used to calculate the relative tide range. The model consists of the existing micro-tidal beach types, which as RTR increases, shift from reflective to low tide terrace with and finally without rips; from intermediate to low tide bar and rips and finally ultra-dissipative; and from barred dissipative to non-barred dissipative and finally ultra-dissipative. Using this model, all wave-dominated beaches in all tidal ranges can be classified.

ADDITIONAL INDEX WORDS: *Beaches and tide range, micro-tidal, macro-tidal, beach model, beach change.*

INTRODUCTION

On all natural beaches, processes and morphology are predominantly influenced by waves and tide. Whereas the importance of waves is self-evident and well documented (WRIGHT *et al.*, 1984, 1985), the influence of tides, though recognised (*e.g.* WRIGHT *et al.*, 1987), is more subtle and less well understood. Tide ranges have been classified by DAVIES (1964) as being micro- (< 2 m), meso- (2–4 m) or macro-tidal (> 6 m). Consequently, beaches can be classified accordingly. However, as DAVIS and HAYES (1984) indicated, beach morphology is not simply dependent on the absolute wave height or tide range, but on the interaction of the two.

Existing micro-tidal beach models assume a micro-tide range (< 2 m) in the presence of oceanic waves. Therefore, they can not automatically be applied to macro-tidal beach environments. SHORT (1991) addressed this problem, suggesting the micro-tide threshold be raised to 3 m, and proposing a grouping of macro-tidal beaches into higher wave planar, moderate wave multi-bar, and low wave to tidal flats. This grouping, while illustrating the range of morphologies associated with macro-tidal beaches, is still based largely on wave height and does not enable differentiation based on tide range > 3 m.

This paper addresses this problem by combining wave height and tide range into a single dimensionless parameter, and calibrating the applicability of this parameter using field data and the literature.

BACKGROUND

Several beach models are available to predict beach state as a function of wave and sediment parameters (SONU, 1973; WRIGHT and SHORT, 1984; SUNAMURA, 1989; LIPPMANN and HOLMAN, 1990). The models are generally representative of micro-tidal beaches and do not take account of the tide. Numerous studies (reviewed later) have also investigated the effect of tides and increasing tide range on beach morphodynamics. However, the overall contribution of tides to beach morphology remains unresolved.

The model of WRIGHT and SHORT (1984) is use-

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ful in describing the morphodynamic variability of micro-tidal surf zones and beaches. This model describes plan and profile configurations of six major beach states. In addition to providing a spatial classification, the model enables the prediction of beach change and equilibrium beach states (WRIGHT *et al.*, 1984, 1985). The beach states are related to wave and sediment characteristics via the dimensionless fall velocity, $\Omega = H_b/w_sT$ (GOURLAY, 1968; DEAN, 1973), where H_b is the breaker height (m), w_s is the sediment fall velocity (m/sec) and T is the wave period (sec).

According to WRIGHT and SHORT (1984), conditions when $\Omega < 1$ result in a reflective beach state. The beach face will be steep and is generally cusped, and a pronounced step is usually present at the base of the swash zone. Generally wave height is small and beach sediments are relatively coarse. Intermediate beaches have values of Ω ranging from 1 to 6 and are characterized by bar and rip morphology. Four different intermediate beach states are defined and with increasing Ω, these states are low tide terrace (LTT), transverse bar and rip (TBR), rhythmic bar and beach (RBB) and longshore bar trough (LBT). When $\Omega > 6$, the beach is in a dissipative state. On dissipative beaches, the wave energy level is generally high, sediments are fine and the surf zone is wide. Subdued bar morphology may be present but rips are usually absent.

The model of WRIGHT and SHORT (1984) was developed on and for micro-tidal environments (TR <2 m) and the tide range is not accounted for, preventing application of the model to environments with larger tide ranges. The first, and so far only, attempt to include the tide into some sort of conceptual beach model is by SHORT (1991) who proposed a tentative grouping of micro- to macro-tidal beach and tidal flat systems. According to SHORT (1991), beaches with macro-tidal ranges (> 3 m) may form the transition between wave-dominated micro-tidal beaches and tide-dominated tidal flats. He distinguishes three types of macro-tidal beaches on the basis of the wave energy level. High waves (H_b >0.5 m), and particularly swell, produce moderate gradient (1–3°), concave, planar beaches. Moderate waves and sea conditions result in lower gradient (0.5°), multibar (ridge and runnel) topography. As wave energy drops even further, a third type is produced with a high tide beach fronted by a tidal flat.

This grouping, however, is primarily based on H_b and as a result includes in single groups beaches with highly variable tide ranges, sediment sizes and morphologies. In order to examine the relative contribution of both H_b and TR, this paper combines and extends the ideas in WRIGHT and SHORT (1984) and SHORT (1991) by considering the relative effects of waves and tides on beach morphology. Following a suggestion in DAVIS and HAYES (1984:Figure 8), the relative tide range RTR is introduced as a new parameter. The relative tide range is given by the ratio of tide range to breaker height ($RTR = TR/H_b$). Large values of RTR indicate tide-dominance and small values express wave-dominance.

A conceptual model is presented according to which the beach state is a function of dimensionless fall velocity Ω and relative tide range RTR. Beaches on the macro-tidal central Queensland (Australia) coast and the literature are used to illustrate the model.

EFFECT OF TIDES ON SURF ZONE DYNAMICS

According to DAVIS (1985), tides play a passive or indirect role in sediment transport and changes in beach morphology. The primary role of the tide is to alternately expose and submerge a large portion of the beach and the inner surf zone. The net result of this movement of sea level is to retard the rate at which sediment transport and changes in morphology take place. This may be illustrated by the findings of DAVIS *et al.* (1972) who showed that bar migration rate decreases with increasing tide range.

However, the tide does more than just retard surf zone processes. During a tidal cycle, the position of the swash zone, surf zone and shoaling wave zone is shifted with the tide both vertically and horizontally, causing the intertidal beach profile to be influenced to varying degrees by each of these processes every 12 hours. This is illustrated in the results of a simulation model developed by MASSELINK (in press) which investigates the importance of swash, surf zone and shoaling wave processes over the beach profile as a function of relative tide range.

This simulation model calculates over half a tidal cycle (from low water to high water) the relative amount of time that different locations on the beach profile are in the swash, surf and shoaling wave zone. The swash zone is defined as the zone between the quasi-stationary mean sea level (tide level) and the maximum runup height. The surf zone is defined as the area between the tide level and the wave break point and, the shoaling wave zone extends seaward from the breakpoint. For each zone, an empirical relationship between the equilibrium beach gradient and wave and sediment characteristics is assumed. The simulation model combines these relationships with the relative occurrences of swash, surf zone and shoaling wave processes for different parts on the beach profile and computes an "equilibrium" beach profile. Input parameters to the model are wave height, wave period, sediment size and tide range. For more details, see MASSELINK (in press).

Figure 1 illustrates the results of the simulation model using wave height = 1 m, wave period = 8 sec, sediment fall velocity = 0.03 m/sec and varying the tide range from 2 to 15 m. It shows that the contribution of swash and surf zone processes decreases as the relative tide range and the contribution of shoaling waves increases. Swash and surf zone processes always dominate the upper intertidal and have a secondary maximum around low tide level where the tide level remains relatively stationary during the turn of the tide. The lower part of the intertidal profile, however, may become completely dominated by shoaling waves for large relative tide ranges (RTR >10). Other results of the simulation model further suggest that as the contribution of shoaling waves increases with increasing tide, beach gradient decreases (MASSELINK, in press).

The dominating role of shoaling waves on beaches with large relative tide ranges has been verified in the field by WRIGHT *et al.* (1982b) who conducted field experiments on Cable Beach, Western Australia (mean spring tide range 9.5 m and RTR = 12). They concluded that under modal wave conditions in the low- to mid-tidal zones, most of the work was performed by unbroken shoaling waves rather than surf zone processes, and only in the high tide zone did surf zone processes dominate.

The movement of the three morphodynamic zones across the profile during each tidal cycle has strong implications for cross-shore bar formation and morphology. Laboratory studies have shown that the presence of a tidal range inhibits offshore bar formation (*e.g.* WATTS and DEARDUFF, 1954), while HEDEGAARD *et al.* (1991) found that the formation of bars is suppressed when RTR > 3. From field experiments on micro-tide beaches, WRIGHT *et al.* (1986, 1987) concluded that increasing tide range resulted in more subdued bar-trough topography during spring tides, compared to the more accentuated topography during neap tides.

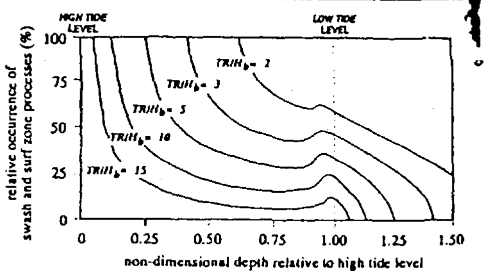

Figure 1. Relative occurrence of swash and surf zone processes over a dimensionless beach profile for relative tide ranges (TR/H_b) of 2, 3, 5, 10 and 15 calculated over half a tidal cycle (low tide to high tide). The importance of swash and surf zone processes decreases as relative tide range increases. Swash and surf zone processes show a secondary maximum of occurrence around low tide level, where the tide remains relatively stationary for some time. The relative occurrences are calculated by a simulation model described by MASSELINK (in press). The input parameters to the model are wave height = 1 m, wave period = 8 sec, sediment fall velocity = 0.03 m/sec and tide range = 2, 3, 5, 10, 15 m.

In addition, tides have three pronounced effects on three dimensional water circulation in the nearshore zone. First, in rip current systems, rips are strongest at low tide, when the water is sufficiently shallow to concentrate the flow of the current within the rip channels (SHEPARD *et al.*, 1941). Maximum rip current velocities occur during the falling tide (MCKENZIE, 1958); and according to COOK (1970), on most beaches, rips become better developed when the tide is falling or low. Second, offshore directed bottom flow (often misnamed as "undertow") is also enhanced at the falling tide, as shown by RUSSELL *et al.* (1991), who monitored suspended sediment transport during a storm (H_b = 3 m) on a beach with a large tidal range (up to 9 m). They found a distinct asymmetry in the cross-shore suspended sediment transport about high tide, with little net transport on the flooding tide, and strong net offshore transport on the ebbing tide. Third, on beaches with large tide ranges, shore-parallel tidal currents play an increasing role in longshore sediment transport on the lower intertidal and subtidal zone of beaches (WRIGHT *et al.*, 1982b).

The following points may be summarized about the influence of the tide on beach morphodynamics: (1) increasing tide range retards the rate at

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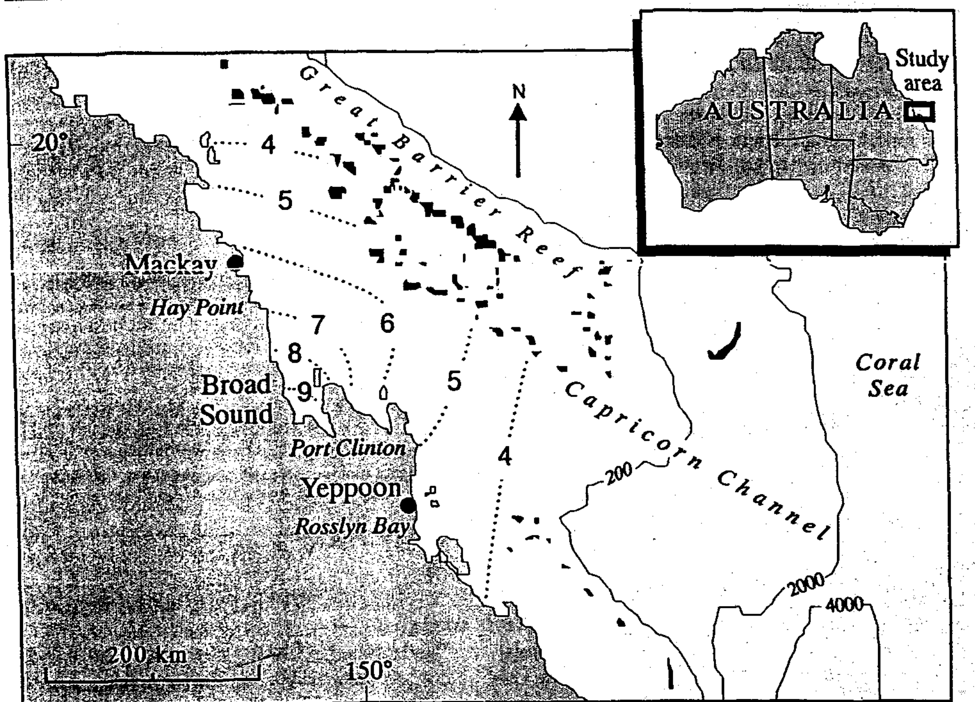

Figure 2. The macro-tidal central Queensland coastline and the co-tidal lines of the maximum spring tide range (co-tidal lines after BPA, 1979). Depth contours are in meters.

which sediment transport and morphological changes take place, (2) an increase in tide range results in an increase in the importance of shoaling wave processes which in turn produce lower beach gradients, (3) large relative tide ranges inhibit offshore bar formation and even on micro-tidal beaches can suppress accentuated bar-trough morphology (RBB and LBT states), (4) rip circulation and seabed return flow is enhanced at low tide and diminishes at high tide, and (5) on macro-tidal beaches shore parallel, usually reversing, tidal currents become increasing dominant seaward of the lower intertidal zone.

CENTRAL QUEENSLAND MACRO-TIDAL BEACHES

In order to investigate the morphological characteristics of beaches with large (relative) tide ranges, several beaches on the macro-tidal central Queensland coast were selected for field investigations (Figure 2). The aims were to assess the relative contribution of grain size, wave height and tide range to beach morphology. To achieve this, a number of sites were selected having different sediment, wave and tide characteristics.

Following a visual survey of around thirty beaches located around Mackay and Yeppoon (Figure 2), 11 were selected for more detailed field investigation, with 15 transects surveyed across these beaches. For the purpose of this study, the following data were collected at each site: beach morphology and cross-sectional profile, beach sediments, modal wave height and period and tide characteristics.

All beaches were surveyed at low tide using a theodolite and level. Sediment samples were collected from the high tide swash zone and analysed using a settling tube. Wave characteristics were extracted from the Queensland Beach Protection

Table 1. *Mean spring tide range, inferred modal wave conditions, sediment characteristics for the high tide beach, relative tide range and the dimensionless fall velocity of the studied beaches.*

Location	MSR (m)	H_b (m)	T (sec)	D_{ht} (mm)	RTR	Ω
Central Queensland Field Sites						
Grass Tree B.	4.9	0.4	5	0.87	12	0.6
Lambert's B.	4.6	0.6	5	0.59	8	1.3
Cooee Bay	3.6	0.3	6	0.29	12	1.3
Armstrong B.	4.9	0.3	5	0.34	16	1.3
Harbour B.	4.6	0.6	5	0.52	8	1.5
Emu Park B.	3.6	0.35	6	0.24	10	1.9
Nine Mile B. south	3.9	0.65	6	0.35	6	2.2
Sarina B.	4.9	0.5	5	0.30	10	2.4
Nine Mile B. central	3.9	0.75	6	0.26	5	3.7
Bucasia B.	4.6	0.4	5	0.18	12	4.1
Farnborough B. south	3.6	0.4	6	0.16	9	4.1
Farnborough B. central	3.6	0.6	6	0.21	6	4.1
Ball Bay	4.6	0.3	5	0.13	15	4.7
Nine Mile B. north	3.9	0.75	6	0.21	5	5.1
Farnborough B. north	3.6	0.5	6	0.14	7	5.9
Wright *et al.* (1982b)						
Cable B.	9.5	0.8	10	0.25	12	2.4
Jago and Hardisty (1984)						
Pendine Sands	7.5	0.8	7	0.17	9	5.8
King (1972)						
Blackpool B.	7.6	0.5?	6?	0.22	15	3
Druridge Bay	4.3	0.5?	6?	0.84	9	0.6

MSR = mean spring tide range (m); H_b = inferred modal breaker height (m); T = modal wave period (sec); D_{ht} = mean high tide beach sediment size (mm); RTR = relative tide range (MSR/H_b); Ω = dimensionless fall velocity

Board's coastal observation program (COPE) and from offshore wave rider stations at Yeppoon (BPA, 1979) and Mackay (BPA, 1986). Tidal characteristics are published for the Standard ports Hay Point and Mackay, and the secondary ports Port Clinton and Rosslyn Bay (Figure 2) in Australian Tide Tables (1992). The high tide beach sediment size, modal wave height and period are used to compute the dimensionless fall velocity Ω, and the mean spring tide range together with the modal wave height is used for obtaining the relative tide range (Table 1). Cross-sections of all listed beaches are illustrated in Figure 3. They have been positioned on the basis of their dimensionless fall velocity (Ω) and relative tide range (RTR) value.

The beaches with a mean spring tide range <4 m are from the Yeppoon region, the other beaches are found around Mackay. In addition to the central Queensland beaches, several beaches from other macro-tidal coastlines, extracted from the literature, are also listed in Table 1.

Based on Table 1 and Figure 3, four types of beaches can be identified. The Queensland beaches with Ω <2 and RTR <15 (Lambert's Beach, Harbour Beach, Emu Park Beach, Grass Tree Beach, Cooee Bay) all possessed three characteristics. First, a steep reflective high tide beach, usually cusped and composed of coarser sand. Second, the high tide beach terminates at a distinct break in slope and sediment, and finally, seaward of the slope break is a lower gradient, finer sediment, more dissipative, low tide terrace. Usually the beach groundwater outcrop (effluent line) is located at the slope break, resulting at low tide in a dry upper beach and a wet low tide terrace.

Where Ω > 2 and RTR < 15, the beaches either have a low gradient mid-intertidal zone and bar/rip morphology around low tide level (Nine Mile Beach north, central and south, Farnborough Beach central) or are flat and featureless throughout (Farnborough Beach north and south, Sarina Beach, Bucasia Beach). These two types of beaches can not be discriminated on the basis of Ω. They do, however, have distinctly different relative tide ranges (Table 1, Figure 3). The barred beaches all have relative tide ranges <7, while the flat and

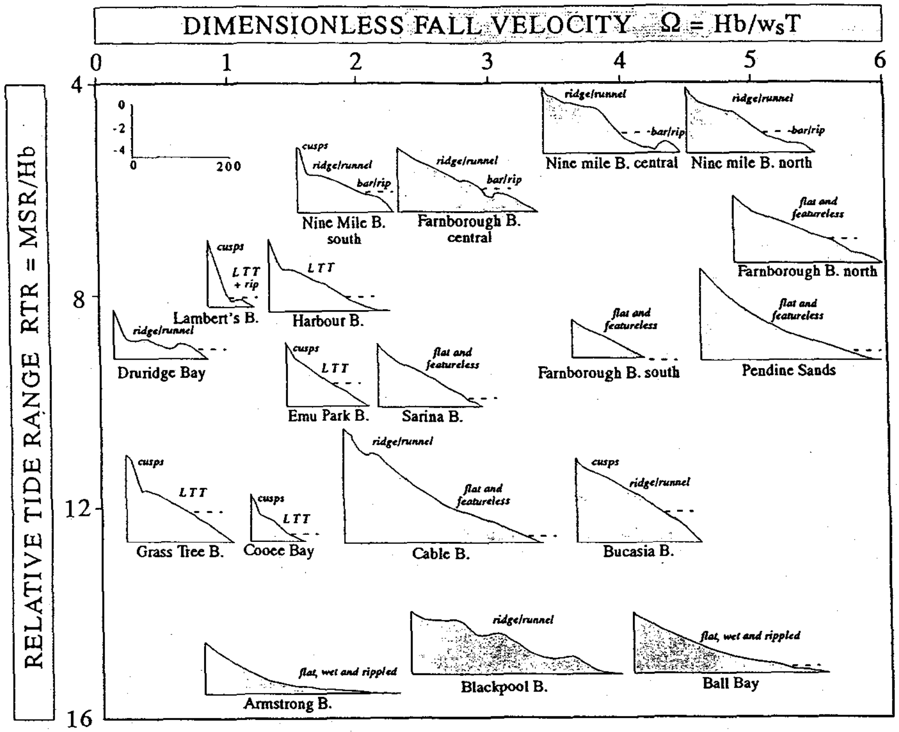

Figure 3. Plot of macro-tidal central Queensland beach profiles and several other macro-tidal beaches listed in Table 1. The beaches have been positioned in the graph on the basis of their dimensionless fall velocity ($\Omega = H_b w_s T$) and relative tide range (RTR = TR/H_b). Mean spring tide range (MSR) is used to calculate RTR and the high tide sediment fall velocity is used to calculate Ω. Positioning of the beaches is based on the center of the beach profiles, but in order to avoid overlapping of beach profiles, the position of some beaches may be slightly off center. The origin of the profiles is the mean high water spring level and the dashed lines indicate the mean low water spring level. Beach morphology is indicated on each profile including low tide terrace (LTT) and three dimensional bar/rip topography. Note that examples of micro-tidal beaches where RTR <3 are not shown, nor are tidal flats where RTR ≫ 15.

featureless beaches have RTR >7. This suggests that when Ω > 2 a RTR threshold exists around 7, which controls the presence (< 7) or absence (> 7) of low tide bar and rip morphology.

Macro-tidal beaches with rhythmic topography at low tide level are not uncommon on the central Queensland coast. Analysis of three series of aerial photographs from the area north of Yeppoon showed numerous beaches, including Nine Mile Beach, with various low tide bar configurations and rhythmic wave lengths ranging from 150 to 300 m. The photos were taken just before the tropical cyclone season, suggesting that the bars reflect modal trade wind wave conditions, rather than the artifact of a high wave cyclone event. Unfortunately, the majority of these beaches are not readily accessible and, hence, exact morphodynamical data is not available.

Finally, the Queensland beaches with large relative tide ranges (RTR >15) are fronted by very fine inter- and sub-tidal sediment (0.1 mm) and a rippled very low gradient (< 0.5°) intertidal zone. The upper intertidal zone, however, may be either steep and relatively coarse grained (Armstrong Beach) or may consist of very fine sediments and have a very low gradient (Ball Bay). These beaches form the transition to tidal flat environments (SHORT's (1991) Group 3) as indicated by Ball Bay

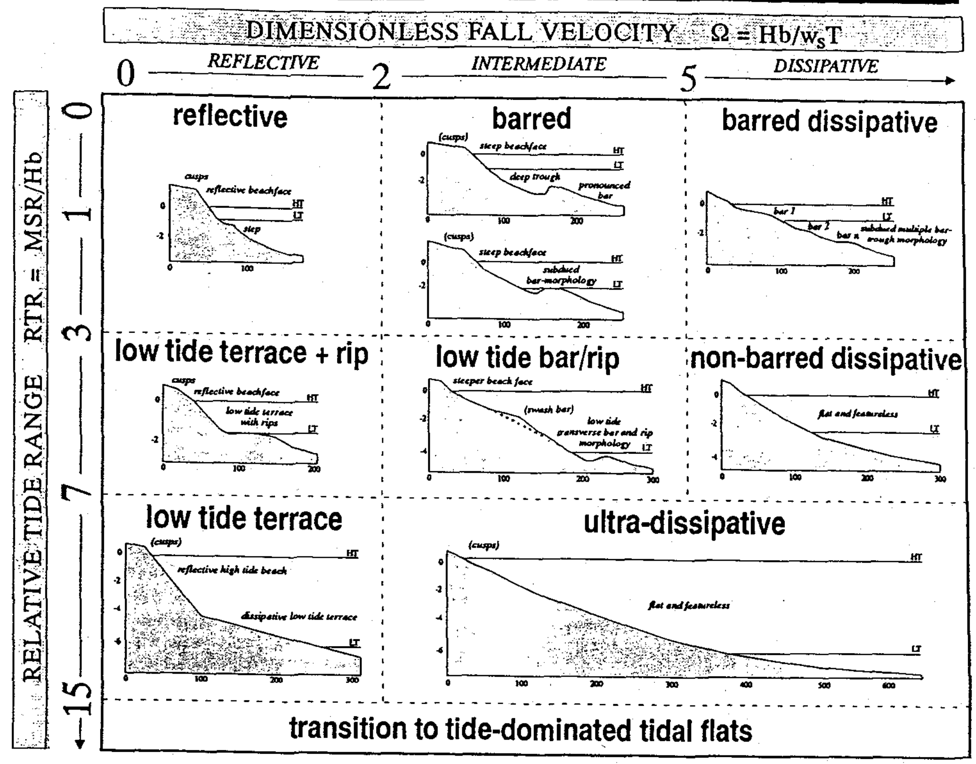

Figure 4. Conceptual beach model. Beach state is a function of dimensionless fall velocity ($\Omega = H_b/w_s T$) and relative tide range (RTR = TR/H_b). HT and LT refer to mean high tide and mean low tide level, respectively.

having some salt tolerant vegetation around the high tide level.

CONCEPTUAL BEACH MODEL

Figure 4 presents a conceptual model based on the micro-tidal beach literature (RTR <3) and the macro-tidal beach literature and field data illustrated in Figure 3 and Table 1 for RTR > 3. The usefulness of the dimensionless fall velocity Ω in classifying micro-tidal beach morphology is well documented and in Figure 4 is indicated by those beaches where RTR <3. Figure 3 shows that as both Ω and RTR increase, a logical sequence of change in beach morphodynamics occurs and that micro- and macro-tidal beaches may be morphologically grouped into different beach types on the basis of these two dimensionless parameters.

The different beach types illustrated in Figure 4 are: reflective beaches, grading with increasing RTR into low tide terrace beaches with rips and low tide terrace beaches without rips, intermediate barred beaches grading as RTR increase into beaches with bar/rip-morphology at low tide level, dissipative beaches with subdued bars produced by low RTR, grading with increasing RTR into featureless non-barred dissipative beaches, and finally both low tide bar/rip and non-barred dissipative beaches grading into ultra-dissipative beaches when RTR > 7. When RTR > 15, the beaches begin the transition to tidal flats along the lines of SHORT's (1991) Group 3. Even larger relative tide ranges (RTR ≫ 15) will result in true tidal flats.

In the following section, each beach type is discussed and illustrated with examples from the central Queensland sites and from the coastal literature. Unfortunately, many sites described in the literature provide only limited information on characteristics such as wave height and period, tide range, grain size and beach gradient (profiles). Therefore, many well known macro-tidal beach sites cannot be used owing to the lack of sufficient environmental documentation in the literature.

IMPACT OF SPATIAL VARIATION IN Ω AND RTR

Reflective Group (Ω < 2)

Reflective Beaches

Fully reflective beaches only exist in environments when Ω < 2 and RTR < 3. The beach face is steep and commonly cusped, and a pronounced coarse step is usually found at the base of the swash zone fronted by a lower gradient, finer grained subtidal zone (WRIGHT and SHORT, 1984). The height of the step increases with wave height and grain size (HUGHES and COWELL, 1987; SUNAMURA, 1989). Waves are generally surging or plunging on the beach and most of the wave energy is at incident and subharmonic (twice the wave period) frequencies (HUNTLEY and BOWEN, 1975; WRIGHT and SHORT, 1984).

Low Tide Terrace with Rips

As relative tide range increases to between 3 and 7, and Ω remains <2, the steep, reflective high tide beach remains, while a relatively flat terrace forms around low tide level with rips. Usually the high tide beach consists of significantly coarser sediments than the low tide terrace. The textural discontinuity is associated with a distinct break of slope and often the low tide beach groundwater outcrop (effluent line) is located at this position saturating the low tide terrace (Figure 5a). Beach cusps may be present around high tide level and the low tide terrace can be dissected by small (mini) rip channels.

At high tide, surf zone processes are similar to those on reflective beaches and waves are generally breaking or surging up the beach face, whereas during low tide the surf zone will be dissipative with several lines of spilling breakers. For relative tide range values of up to 7, surf zone processes play a significant role on the low tide terrace resulting in the formation of rip channels.

Low Tide Terrace without Rips

As the relative tide range exceeds 7, the very wide and dissipative low tide terrace becomes increasingly dominated by unbroken shoaling waves (see Figure 1) which produce a uniform, featureless low tide terrace (*e.g.* Harbour Beach, Figure 5b) without the formation of rip channels. According to CARTER (1988), this type of low tide terrace beach is commonplace on high latitude coasts where the high tide beach consists of gravel fronted by a fine grained low tide terrace. KOMAR (1976) shows an example of this type of beach from the coast of Wales (Figure 11–6, p. 297) and KING (1972) presents data on Druridge Bay (Northumberland, England), a low tide terrace beach with ridges and runnels (Figure 3). In addition, they have been reported along the Gulf of California (INMAN and FILLOUX, 1960) and in NW Western Australia (HESP, *personal communication*).

Intermediate Group (Ω = 2–5)

Intermediate values of the dimensionless fall velocity (Ω = 2–5) and a relative tide range of <7 will result in beaches with distinct bar-morphology and cellular rip circulation. Two types of beaches may be distinguished.

Barred Beaches

For the lowest relative tide ranges (RTR <3) several types of bars may occur (*e.g.* LIPPMANN and HOLMAN, 1990). The bar-topography may consist of alternating transverse bars and rips, whereby the bars are attached to the shoreline and rip currents flow between the bars (*e.g.* SONU, 1972; WRIGHT and SHORT, 1984; SHAW, 1985; JAGGER *et al.*, 1991). Alternatively, the bar may have a sinuous crescentic form (*e.g.* GREENWOOD and DAVIDSON-ARNOTT, 1979; GOLDSMITH *et al.*, 1982; AAGAARD, 1988a) or be linear (SALLENGER *et al.*, 1985; WRIGHT *et al.*, 1986). WRIGHT *et al.* (1986, 1987) found that even on micro-tidal beaches increasing spring tide range suppresses the formation of the LBT and RBB with their deeper shore-linear troughs in favour of shallower rip-driven TBR. Thus, an increase in (relative) tide ranges will result in more subdued bar-morphology, but with enhanced rip circulation at low tide.

Low Tide Bar/Rip

As the relative tide range increases (RTR = 3–7), the beaches maintain the relatively steep upper intertidal zone, but are fronted by a low gradient mid-intertidal zone, possibly with swash bars, and then bar and rip morphology around low tide level (*e.g.* Nine Mile Beach, Figure 5c). These beaches have more complex morphodynamic signatures and may experience reflective (high tide), intermediate and dissipative (low tide) surf zone conditions through the tidal cycle. The bar and rip morphology only exists on the low tide beach and is active only on either side of low tide. Recent work on Nine Mile Beach suggests that the bar and rip morphology is mainly driven by processes occurring during neap (low) tides (*unpublished data*). The higher energy central Queensland beaches (Nine Mile Beach and Farnborough Beach central) and the meso-tidal beaches (TR ≈ 4 m; H_b ≈ 1–2 m) of the Oregon (AGUILAR-TUNON and KOMAR, 1978; FOX and DAVIS, 1978) and the New England coasts (ZEIGLER and TUTTLE, 1961) belong to this group.

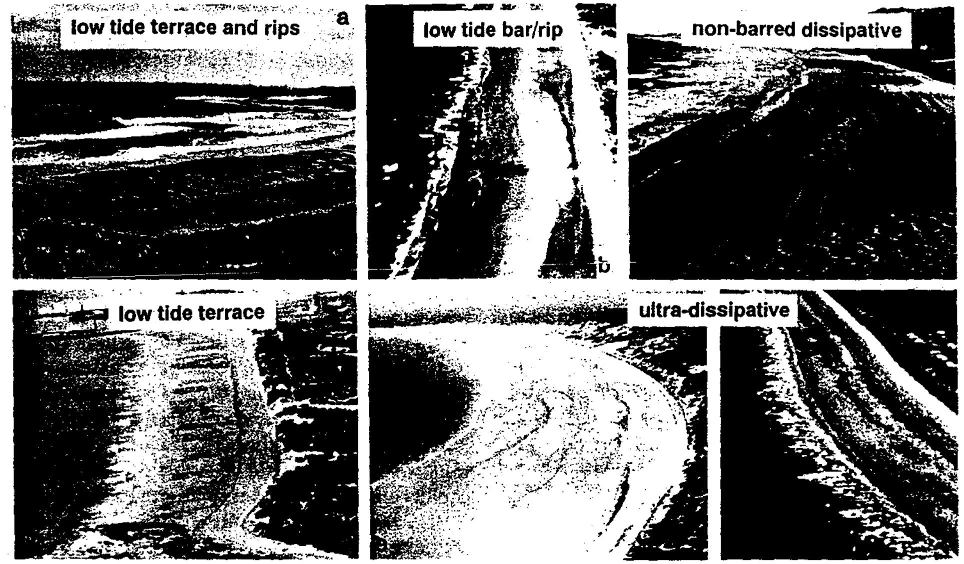

Figure 5. Examples of the different beach types for relative tide ranges larger than 3: (a) Low tide terrace with rips. Embleton Bay, Northumberland (U.K.) is a beach exposed to the North Sea with a mean spring tide range of around 4.5 m and coarse high tide beach sand. The photo shows the beach with a dry, reflective and cusped upper part of the profile, a wet and dissipative low tide terrace, and rip currents in the subtidal zone. (b) Low tide terrace without rips. Harbour Beach (Mackay, central Queensland) is a low tide terrace beach with a relative tide range of around 8 and a Ω value of 1.5. The upper part of the beach is steep and dry, and some evidence of cusping is visible at the lower end of the beach. A flat and wet low tide terrace characterises the lower part of the intertidal profile. Under modal conditions this beach is reflective at high tide and dissipative at low tide. (c) Low tide bar/rip. Nine Mile Beach (Yeppoon, central Queensland) is characterised by a relative tide range of 5–6 and Ω is around 3.5. Transverse bar-rip morphology is present on this beach as indicated by the dye pattern. The upper part of the profile is characterised by the presence of a low but extensive swash bar. During a spring tidal cycle, morphodynamic signatures on this type of beach are complex. At spring low tide, the surf is dissipative, from low-to-mid tide the transverse bar-rip system operates, from mid-to-high tide the surf zone is once again dissipative, and reflective conditions may occur at spring high tide. (d) Non-barred dissipative. Rhossili Bay, South Wales (U.K.) is exposed to Atlantic swell, consists of fine sediments and is subject to a mean spring tide range of 9.5 m. The beach is wide, planar and featureless. Dissipative surf zone conditions prevail throughout the tidal cycle. (e) Ultra-dissipative. Cable Beach (Broome, Western Australia) is an ultra-dissipative beach with a relative tide range of 12 and Ω is around 2.5. Although the intermediate value of Ω indicates that rhythmic topography may develop, the relative tide range is too large, resulting in a flat and featureless lower inter- and subtidal profile. A subdued ridge and runnel is often present around neap high tide level, while reflective conditions can produce cusps at spring high tide. (f) Ultra-dissipative. Farnborough Beach south (Yeppoon, central Queensland) is an ultra-dissipative beach with a relative tide range of 6 and Ω is around 4. The inter- and subtidal profile is featureless and dissipative surf zone conditions prevail throughout the tidal cycle.

Dissipative Group (Ω > 5)

Rip currents and associated rhythmic topography are generally absent on dissipative beaches (WRIGHT *et al.*, 1982a) and the surf zone is characterized by the presence of numerous spilling lines of breakers. Sediments are often fine to very fine and the beach gradient is low.

Barred Dissipative Beaches

For Ω >5 and RTR <3, the dissipative beach profile will be characterised by subdued longshore bar-trough morphology. Waves are of the spilling type and the water motion in the inner surf zone will be dominated by infragravity waves. Onshore mass transport is by spilling waves and bores while a strong offshore directed bottom flow dominates the return current pattern (WRIGHT *et al.*, 1982a; GREENWOOD and OSBORNE, 1990).

Non-Barred Dissipative Beaches

As RTR increases >3, the dissipative beaches, while maintaining similar dimensions, become flatter and more featureless with no bars. Examples are Farnborough Beach North, Rhossili Bay, Wales (Figure 5d) and Llangenith Beach, Wales (RUSSELL *et al.*, 1991).

Ultra-Dissipative Beaches (Ω > 2 and RTR > 7)

Beaches with Ω >2 and RTR >7 are considered to be ultra-dissipative beaches. The term "ultra-dissipative" is taken from MCLACHLAN (in press) and refers to both the extreme dissipativeness of the surf zone conditions with multiple lines of breakers and the extreme width of the low gradient dissipative profile. Ultra-dissipative beaches are generally flat and featureless and have very wide intertidal zones (Figure 5e and f). On ultra-dissipative beaches with intermediate Ω values (2–5), surf zone conditions at high tide may be intermediate to reflective (Cable Beach; WRIGHT *et al.*, 1982b) whereas on ultra-dissipative beaches with Ω >5 (*e.g.* Pendine Sands; JAGO and HARDISTY, 1984: Figure 3), surf zone conditions will be dissipative throughout the tidal cycle. Ultra-dissipative beaches are common in central Queensland (Farnborough Beach south, Sarina Beach, Bucasia Beach). Aspects of the dynamics and morphology of British ultra-dissipative beaches are described by BLACKLEY and HEATHERSHAW (1982), HAWLEY (1982), PARKER (1975) and JAGO and HARDISTY (1984).

IMPACT OF TEMPORAL VARIATION IN Ω AND RTR

The transformation of beach morphology illustrated in Figures 3 and 4 has several implications for both understanding and predicting beach change as tide range increases. Firstly, temporal and spatial change in beach morphology is a function of H_b, T and w_s as well documented through the dimensionless fall velocity Ω (SHORT, 1987). However, it is also a function of TR, and in combination with H_b, of RTR. In examining temporal change of a beach, T and particularly w_s may be considered as temporally constant parameters in comparison to H_b and TR (neap to spring) which usually experience greater change over time.

Wave height is the major variable involved in temporal beach change, as summarised by SHORT (1987). On micro-tidal beaches, waves drive beach change at rates dependent on the prevailing and equilibrium Ω. Also, the response to rising waves is faster than the response to falling waves (WRIGHT *et al.*, 1985). As tide range increases, waves remain the prime contributor to temporal beach change; however, as its energy is increasingly spread over a wider intertidal zone, the rates of sediment transport per unit beach diminish and beach change slows.

Tide range itself has a degree of temporal variability through the semi-diurnal inequality and the spring to neap tidal cycle. Minor impacts of the spring to neap tidal cycle on micro-tidal high wave energy beach morphology have been reported by CLARKE *et al.* (1984) and WRIGHT *et al.* (1986, 1987). A fourteen day study at Nine Mile Beach (Yeppoon, central Queensland; Figure 5c) revealed that the only clearly tide-induced morphological change was the migration of a swash ridge. The ridge formed during neap tides around high tide level and consequently moved up the beach as the tide range increased. Additional morphological change observed during this two week period, such as the removal of the swash bar and the transverse bar-rip morphology, was primarily wave-driven. The impact of the neap-spring temporal variation in tide range is therefore secondary to waves and will not generate any substantial change in morphology or produce a shift to an adjacent beach type. However, the tide range does determine the beach type and its location in Figure 4. Tide range is therefore more of a spatial then temporal variable regarding its influence on beach morphology.

Consequently, a beach type diagram can be constructed in order to locate beaches with certain environmental conditions and suggest how beach state may change under the influence of changing wave (and tide) conditions. Figure 6 illustrates such a diagram for a set wave period (T = 8 sec) and sediment fall velocity (w_s = 0.04 m/sec), but with variable H_b and TR.

As discussed above, beach morphology is relatively insensitive to temporal change in tide range (neap to spring cycle) and, in addition, increasing tide range retards beach response. Consequently, temporal beach change is primarily wave driven, and the amount and rate of temporal change will decrease with increasing tide range, and also with decreasing wave height (WRIGHT *et al.*, 1985). The response to rising waves is also larger than that of falling wave (WRIGHT *et al.*, 1985). The relative variability of temporal beach change as a function of wave height and tide range is indicated by the arrows in Figure 6.

As suggested by Figure 6, beaches with large relative tide range may be considered relatively stable beach systems. This is supported by results of JAGO and HARDISTY (1984) who monitored relatively minor temporal changes in morphology on Pendine Sands (MSR = 7.5) over a three year monitoring period. Another indication of the morphological stability of beaches with large RTR values is the often sharp break in grain size between the high tide and intertidal beach of the low tide terrace beaches.

IMPORTANCE OF SWASH, SURF ZONE AND SHOALING WAVE PROCESSES OVER A LUNAR TIDAL CYCLE AS A FUNCTION OF RTR

In the proposed model, three relative tide range thresholds are proposed on the basis of the relative importance of swash, surf zone and shoaling wave processes as illustrated in Figure 1. For RTR <3, swash and surf zone processes dominate the entire intertidal and the upper part of the subtidal zone. For RTR between 3 and 7, the upper part of the profile is dominated by swash and surf zone processes and the lower part is dominated by shoaling waves. For RTR >15, only on the extreme upper part of the beach profile do swash and surf zone processes play an important role.

This analysis was extended by running MASSELINK's (in press) simulation model over half a lunar tidal cycle (neap to spring) rather than over half a tidal cycle (low to high tide) as in Figure 1. In order to generate a considerable neap to spring variation, two tidal constituents are considered, the principal lunar (M2) and the principal solar (S2), whereby S2 is given half the amplitude of M2. Spring tide range is then given by 2 (M2 + S2) and neap tide range is 2 (M2 − S2). Other input parameters to the simulation are H = 1 m, T = 8 sec and w_s = 0.03 m/sec. Three different runs were performed with spring tide ranges (and relative tide ranges) of 3, 7 and 15 m. It should be noted that running the model with different absolute H and TR, but with identical relative tide range (3, 7 and 15), would produce similar results with only swash processes slightly increasing in importance with decreasing H and TR.

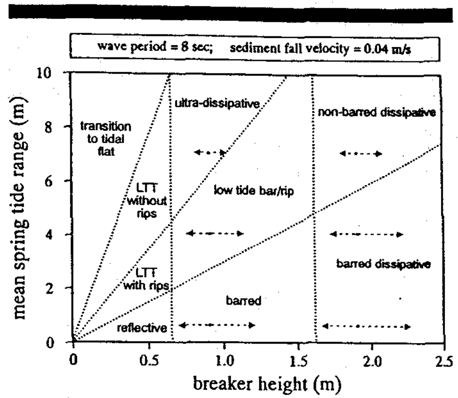

Figure 6. Location of modal beach types based on threshold values of breaker height and mean spring tide range for a beach with wave period T = 8 sec and the fall velocity w_s = 0.04 m/sec (D_{50} = 0.3 mm). The boundaries between beach types, as indicated by the dotted lines, will shift in response to changes in T and w_s. The arrows in the diagram indicate the direction and relative, not absolute, rate of response to temporal changes in wave height. Beach response decreases with increasing tide range and decreasing wave height, and response to rising waves is faster than to falling waves (WRIGHT *et al.*, 1985).

Figure 7 shows the relative occurrence of swash, surf zone and shoaling wave processes and the resulting beach profile for the three runs. It is apparent that for RTR <3, the majority of the intertidal zone is dominated by swash and surf zone processes, and only seaward of neap low tide level do shoaling waves start playing a significant role. At mean sea level, swash and surf zone processes operate 90% of the time.

For a RTR of 7, the occurrence of swash and surf zone processes displays 4 maxima, decreasing

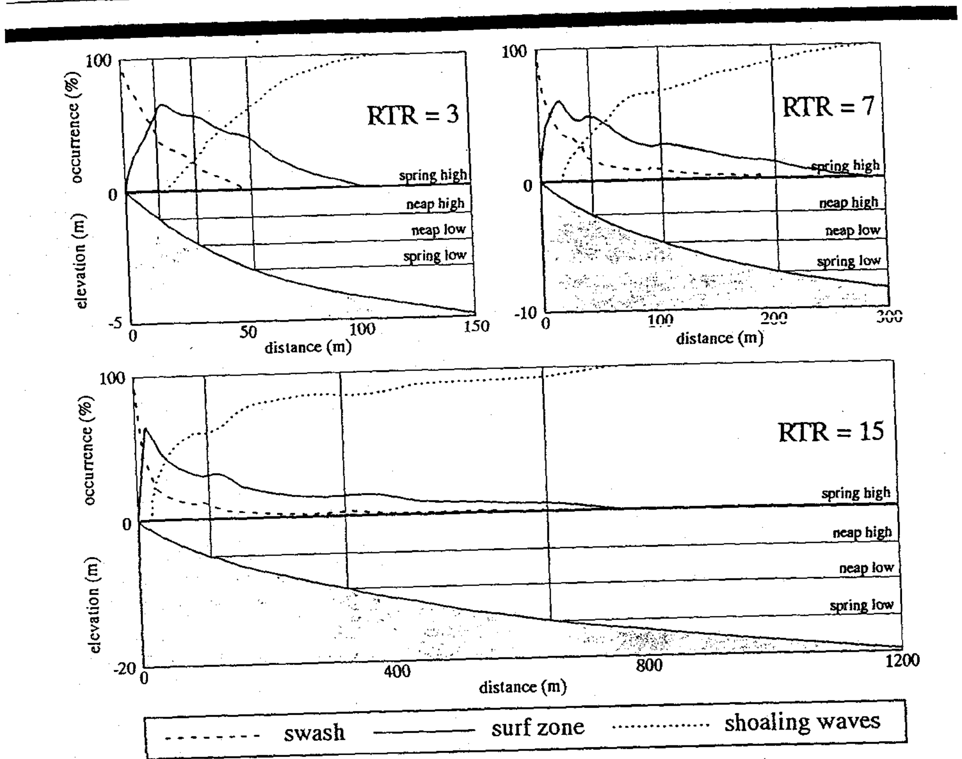

Figure 7. Relative occurrence of swash, surf zone and shoaling wave processes for relative tide ranges RTR of 3, 7 and 15 calculated over a complete half lunar tidal cycle (neap to spring) using a simulation model described by MASSELINK (in press). The input parameters to the model are wave height = 1 m, wave period = 8 sec, sediment fall velocity = 0.03 m/sec and tide range = 3, 7 and 15 m. Note that the vertical and horizontal scales for each beach are different, but the vertical exaggeration is kept constant.

in amplitude and cross-shore spacing in seaward direction. These maxima are associated with spring high tide, neap high tide, neap low tide and spring low tide level, respectively. At mean sea level, less than 50% of the time do swash and surf processes operate. On Nine Mile Beach, which is characterised by a RTR of 5–6, bar morphology was observed just below neap low tide level. Bar morphology may develop at this location because surf zone processes concentrate at this location for a sufficient amount of time, illustrated by the third maximum in surf zone occurrence in Figure 7. The fourth maximum around spring low tide level is too small and surf zone processes do not have enough time at this location too form bars. At the two upper maxima, associated with spring high and neap high tide level, surf zone processes can potentially form bars. However, at these locations swash processes play an important role and will tend to plane off any surf zone process-induced irregularity. Hence, no bars will form at these locations although swash bars may be found instead (Nine Mile Beach, Figure 5c). It may be suggested, on the basis of the simulation model, that in order to develop bar morphology, surf zone processes should dominate at least 25% of the time over a lunar tidal cycle.

For a RTR of 15, swash and surf zone occurrence display similar maxima as was observed for a RTR of 7 (Figure 7). However, only between neap high tide and spring high tide do swash and surf dominate over shoaling waves. At mean sea level, less than 20% of the time over a half lunar tidal cycle do swash and surf zone processes operate.

The relative time of occurrence of a certain process is not necessarily an absolute measure of the relative importance of this process. Swash and surf zone processes are more energetic than shoaling wave processes and may be more important even when they operate for a shorter time period. Results of WRIGHT *et al.* (1982b), however, suggest that the relative time of occurrence of swash, surf and shoaling waves may serve as a surrogate in assessing its importance. WRIGHT *et al.* (1982b) have calculated the time-averaged surf zone energy dissipation rate relative to the total dissipation rate and its distribution over the intertidal profile of Cable Beach over a half lunar tidal cycle. They only considered energy dissipation rate by bed friction, or equivalently the rate of doing work, which is probably fundamental to molding the beach morphology (WRIGHT *et al.*, 1982b). For H = 1.5 m, MSR = 9.5 m and T = 11 sec (RTR ≈ 6), they found that at mean sea level 45–50% of the total work being done by waves is by surf zone waves. According to the simulation model for a RTR of 7, around 50% of the time over a half lunar tidal cycle do swash and surf zone processes operate at mean sea level, in agreement with WRIGHT *et al.* (1982b).

DISCUSSION

A conceptual beach model is presented which relates the overall beach morphology (beach state) to hydrodynamic and sedimentological parameters. The model is a continuation of the work of WRIGHT and SHORT (1984) and SHORT (1991). Several elements from these studies are incorporated in the model presented here. In general, beaches with RTR <3 are found in micro-tidal environments and may be classified according to WRIGHT and SHORT (1984). Beaches with RTR between 7 and 15 largely overlap with Group 1 of SHORT (1991), which he summarized as macro-tidal beaches with a planar, concave upward beach profile. The transition to tidal flats (Group 3 of SHORT, 1991) is indicated in the present model by the beaches with RTR larger than 15. Beaches with RTR between 3 and 7 are generally high to moderate energy macro-tidal (TR >3 m) beaches which were not included in any of the previous models.

Beaches with ridge and runnel systems (Group 2 of SHORT, 1991) have not been identified as a separate beach type in the proposed model. According to SHORT (1991) and others (*e.g.* ORFORD and WRIGHT, 1978), ridge and runnel topography is formed under the influence of moderate energy, short period waves, large tide ranges and fine sediments. This encompasses a very wide range of environments and, therefore, not surprisingly, ridge and runnels have been observed on low tide terrace beaches (*e.g.* Druridge Bay, KING, 1972; Dundrum Beach, ORFORD, 1985), on beaches with bar/rip-morphology at low tide level (*e.g.* Nine Mile Beach, this study; Oregon beaches, FOX and DAVIS, 1978) and on ultra-dissipative beaches (*e.g.* Blackpool Beach, KING and WILLIAMS, 1949; West Lancashire, PARKER, 1975; WRIGHT, 1984), some of which are located in Figure 3. Therefore, rather than identifying ridge and runnel beaches as a separate group, we acknowledge ridge and runnel topography as being an additional morphological feature which may be present on beaches with a relative tide range larger than 3.

Another additional morphological feature which needs to be addressed is that of multiple bar systems. SHORT and AAGAARD (in press) have shown that on wave-dominated micro-tidal beaches (RTR <3), bar number increases with decreasing beach gradient and wave period. In Figure 4, multi-bar beaches should occur as multi-bar versions of the barred, the barred dissipative and the low tide bar/rip type. In fact, analysis of aerial photographs has revealed that Nine Mile Beach (Figures 4 and 5c) occasionally develops a double bar system.

Since wave energy level is only considered in a relative way, it is tempting to scale the model down and apply it to very low wave energy beach environments such as estuarine and bay beaches. Generally these environments have large relatively tide ranges (RTR >7) and variable dimensionless fall velocities. Using the model in Figure 4, these beaches may be described as low tide terrace or ultra-dissipative beaches (depending mainly on the sediment size) which agrees with what is observed in the field (NORDSTROM, 1992). However, the absolute wave energy level is also of importance due to the existence of wave energy thresholds. For example, the wave height may drop below some critical level below which the response time becomes infinite; *i.e.*, no change occurs. Also, a minimum wave energy level is required for the excitation of infragravity edge waves (GUZA and DAVIS, 1974), which are strongly implicated in the formation of rhythmic topography (BOWEN and INMAN, 1971; HOLMAN and BOWEN, 1982; AAGAARD, 1988b). If the wave energy level is too low, infragravity edge waves may not form and bar morphology may not develop, even when the values of Ω and TR/H_b predict the formation of bars. Therefore, care should be exercised when applying the model to very low wave energy environments (H_b <0.25 m).

Also as the converging threshold lines in Figure 6 indicate, at low values of tide range and wave height, small differences in one or the other can theoretically result in markedly different morphological response. The morphological sensitivity to small changes in environmental parameters has also been shown by DAVIS and HAYES (1984) for the micro-tidal low wave energy Florida coastline. More detailed observations of these systems are required to clearly delineate both the wave energy thresholds required to produce certain morphodynamic systems, such as standing and progressive edge waves and their morphological imprint, in addition to the relative contribution of waves and tides in these systems.

The absolute tide range is also of importance. Recent work of TURNER (in press) suggests that the formation of a low tide terrace is related to the drainage capacity of the beach in relation to the tide. Since this is a complex function of the sediment characteristics (permeability and porosity), beach gradient, the duration of the tidal cycle and the absolute tide range (TURNER, in press), the RTR value of 3 separating the reflective beaches from the low tide terrace beaches is rather arbitrary.

CONCLUSIONS

Natural beaches may be grouped into several beach types on the basis of breaker height (H_b), wave period (T), high tide sediment fall velocity (w_s) and tide range (TR). These four variables are quantified by two dimensionless parameters: the dimensionless fall velocity ($\Omega = H_b/w_sT$) and the relative tide range ($RTR = TR/H_b$). The mean spring tide range (MSR) is used to calculate the relative tide range. The value of the dimensionless fall velocity indicates whether reflective, intermediate or dissipative surf zone conditions will prevail. The relative tide range indicates the relative importance of swash, surf zone and shoaling wave processes.

Small values of Ω and low relative tide ranges produce the classic reflective beach type. Increasing relative tide range results in the formation a low tide terrace at the base of the beach face and low tide rips, grading with increasing tide range into a steep (reflective) beach face fronted by a wide dissipative low tide terrace. In areas of intermediate Ω (2–5), beaches with various bar configurations are produced in micro-tidal environments (RTR <3) (WRIGHT and SHORT, 1984), while increasing tide range moves the rhythmic surf topography down to the low tide level, producing low tide bar and rip morphology. On higher wave dissipative beaches (Ω >5), the beach contains multiple subdued bars on micro-tidal beaches. As tide range increases (RTR is 3–7), the bars disappear and a wide non-barred dissipative beach results. When RTR is 7–15 on both intermediate and dissipative beaches (Ω >2), wide, flat and featureless ultra-dissipative beaches result. As the relative tide range increases even more (RTR >15), it is suggested that the resulting beaches form the transition to tidal flats, which are fully tide-dominated.

It is stressed that the model presented in this paper is conceptual. Especially for the beaches with large relative tide ranges (low tide terrace beaches and ultra-dissipative beaches), our knowledge is quite restricted. More information is required on these systems to improve our understanding of their morphodynamics so that not only a better understanding of the controlling processes is attained, but also more rigourous thresholds can be delineated to separate the different beach types. The conceptual model presented in this paper may provide a framework in which this future work is carried out.

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