North Friesien Coast

PART II

COASTAL SEDIMENT PROBLEMS

Westerland, Island Sylt

WAVE POWER AND BEACH-STAGES: A GLOBAL MODEL

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ABSTRACT

A three-dimensional morphodynamic model of sequential beach changes is presented. The model is based on variations in breaker wave power generating a predictable sequence of beach conditions. The spectrum of beach conditions from fully eroded-dissipative to fully accreted-reflective is characterised by ten beach-stages. Using the breaker wave power to beach-stage relationship the model is applied to explain temporal, spatial and global variations in beach morphodynamics.

INTRODUCTION

Beach and surfzone morphodynamics have received increasing attention in recent years (for review see Wright and Thom, 1977). While much progress has been made there exists a general lack of understanding and awareness of the total spectrum of beach conditions. Individual beach studies in diverse locations, wave conditions and coastal environments are often difficult to relate or compare, and in general there is no overall conceptual model within which beach studies and their results can be framed. Most studies are of too short a duration and too limited range of wave and beach conditions to generate data for a larger model. This paper presents a model within which all previous beach studies can be framed (Short, in preparation) and which can be applied globally to all microtidal, open coast, sand beaches. The model is the result of more than 2½ years of daily observations of beach morphodynamics (Figure 1) and associated deepwater and breaker wave characteristics. The main field site was located at Narrabeen Beach, New South Wales, a 4km long, medium to fine sand beach ($M\ \phi = 1.3\ \phi$) receiving moderate to high power, east coast swell on a microtidal coast. These observations are supplemented by ground and aerial surveys and aerial photographs of the 3,300 km southeast Australian coast, a microtidal coast which receives east and west coast swell wave conditions, on beaches composed of fine to coarse sand (Short, 1978).

Using the 30 month time series of wave and beach conditions a three-dimensional model of sequential beach changes was formulated. The model depicts continuous changes in beach morphodynamics, with decreasing breaker wave power leading to onshore bar migration, beach accretion and reflective surfzone conditions, and increasing wave power generating

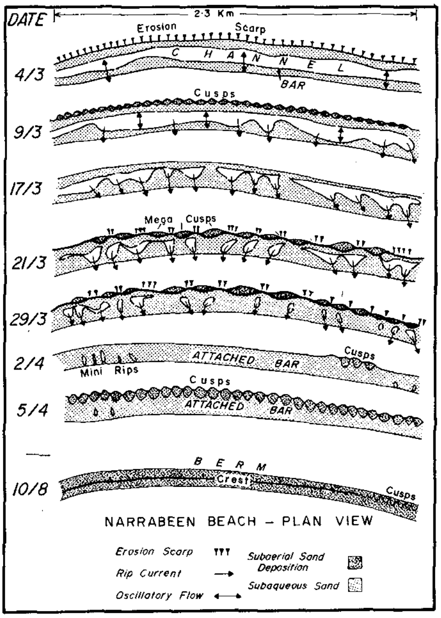


Figure 1 :

An example of the field observations during a four week accretionary period under low wave conditions (4.3 to 5.4.1977 and 10.8.1977) illustrating the migration of a parallel bar (4.3.77) onshore; resulting in crescentic bars (9 and 17.3.77); accretionary rip cells (21.and 29.3.77); welded bar, mini-rips and cusps (2 and 5.4.77); and at a later stage a continuous subaerial berm (10.8.77).

beach erosion, bar-channel formation and dissipative surfzone conditions. The model applies to the subaerial beach and subaqueous surfzone to the seaward slope of the inner bar (- 3 m at Narrabeen Beach). Second and outer bars are not included.

The model is now briefly presented. It is then applied to explain temporal, spatial and global variations in beach morphodynamics.

THE MODEL

The time series of wave and beach conditions was separated into ten *beach-stages*, four erosional, four accretional with two terminal stages of fully eroded and fully accreted (Figure 2). The ten stages represent ten characteristic beach morphodynamic conditions in a continuum of beach changes. Movement through the model is generated by variations in breaker wave power. At any stage the direction of movement to adjoining erosional or accretionary stages depends on the direction of change in wave power. Increasing wave power causes movement through the erosional stages, decreasing power produces movement through the accretionary stages. The model is now outlined for an idealised situation of continuously decreasing wave power, the accretionary sequence, and increasing wave power, the erosional sequence. It assumes waves arrive normal to shore on an open, microtidal sand coast. For a more complete description of the model see Short (in preparation).

The *accretionary sequence* (Figure 2a and 3) begins at *beach-stage 6*, a parallel bar-channel system, where the position of the bar is

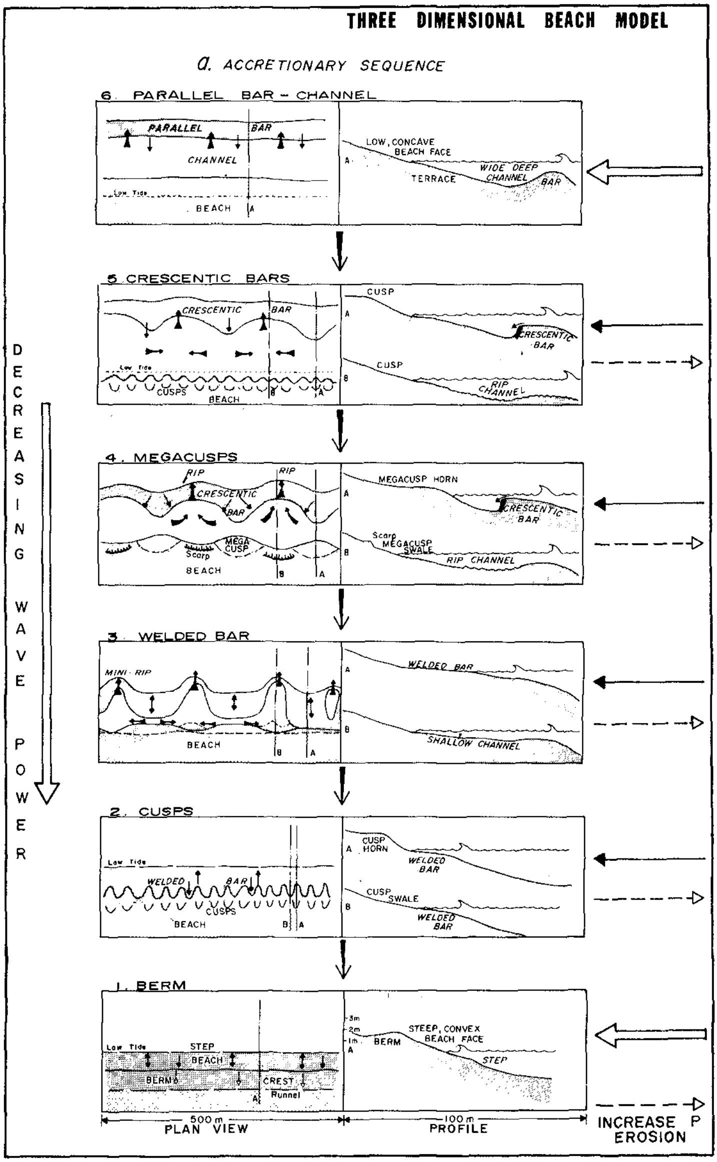


Figure 2 : The three dimensional beach model. Connecting arrows indicate direction of movement within model, solid-decreasing wave power (P) and movement to accretionary stages, broken - increasing power and movement to erosional stages. Within each *beach-stage*, heavy arrows indicate surfzone current flow at low frequencies, small arrows indicate flow at incident wave frequency.

a. The accretionary sequence, *beach-stages 6* to *1* generated by decreasing wave power.

(Fig. 2 continued)

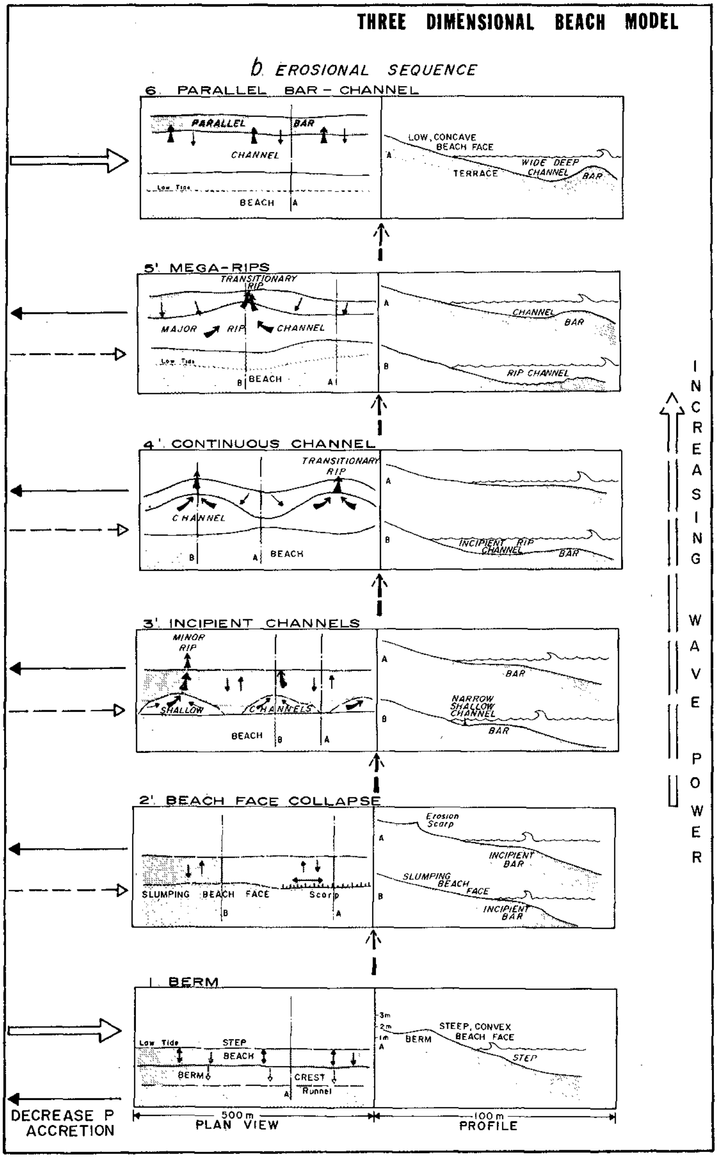


Figure 2 : The three dimensional beach model, continued.

b. The erosional sequence, *beach-stages 1 to 6*, generated by increasing wave power.

Figure 3 : Examples of accretionary beach-stages from south east Australia. a. Beach-stage 6, The Coorong, South Australia. 3-4m high waves are breaking on the outer bar and flowing into shore parallel channel.

Figure 3 b : Beach-stages 5, Fens Embayment, New South Wales (N.S.W.). Note crescentic bars (spacing approximately 200 m) and beach cusps, with megacusps (indicated by arrows) beginning to form inshore of more shoreward advanced crescentic bars.

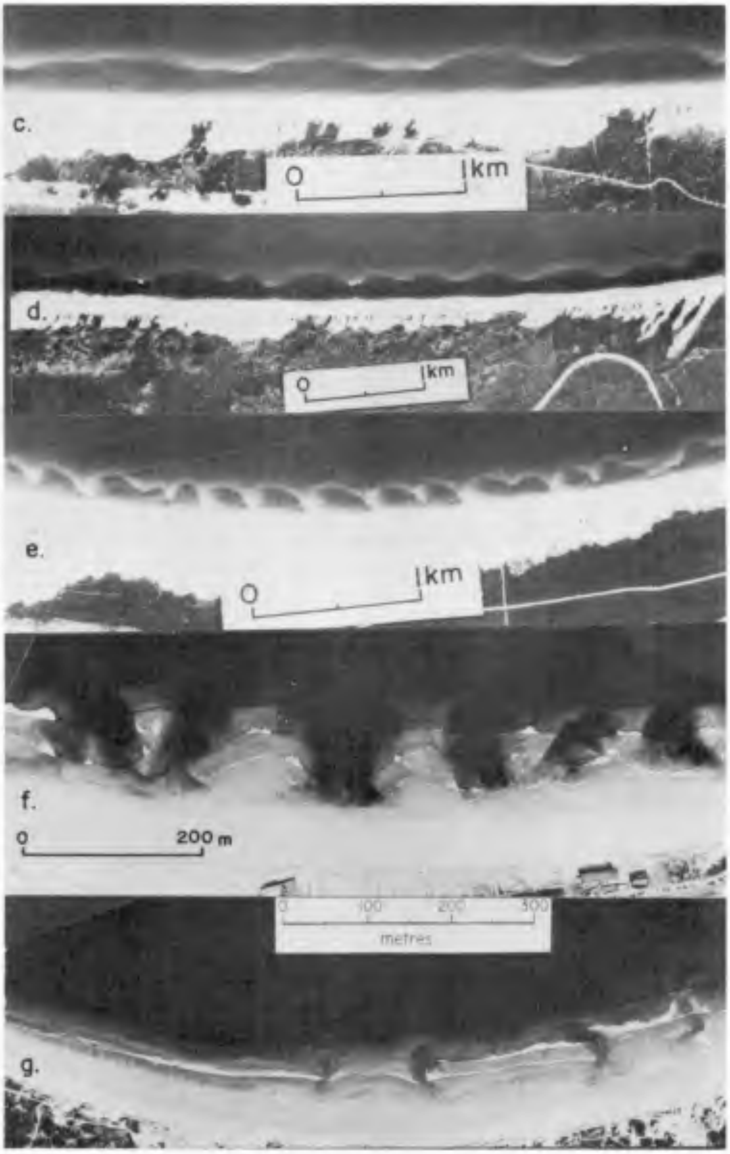


Figure 3 c : Beach-stage 5, Fens Embayment, N.S.W.
d : Beach-stage 5, Fens Embayment, N.S.W.
e : Beach-stage 4, Fens Embayment, N.S.W.
f : Beach-stage 3, Cronulla Beach, N.S.W.
g : Beach-stage 3 → 2, Cronulla Beach, N.S.W.

Figure 3 h : Beach-stage 3, Narrabeen Beach, N.S.W. Note welded bar and remants of megacusps.
i : Beach-stage 2, Narrabeen Beach, N.S.W. Cusps horns indicated by arrows.
j : Beach-stage 2 → 1, Warriwood Beach, N.S.W. Cusps embayments fill as a continuous berm developes.
k : Beach-stage 1, Narrabeen Beach, N.S.W. Note straight berm crest and backing runnel.

determined by low frequency standing waves generated by waterlevel setup in the channel during high wave power conditions, (Figure 3a). If the offshore slope is gentle multiple bars result. All flow is shore normal and no rips are present, the beach is in 'equilibrium', with no longshore variation in profile or dynamics. With a decrease in wave power, resonance generated by reflection of the incident waves off the beach face, and possibly lower mode reflection against the inside of the bar, results in edge waves that respectively generate systematic longshore variations in waterlevel on the beach face and bar. The longshore variations in waterlevel result in preferential shoreward flow of water across the beachface and bar at the antinodes of the edge waves. This flow in turn produces greater shoreward movement of sediment at those points initiating cusps and crescentic bars (Narrabeen mean bar spacing 150m), (*beach-stage 5*, Figure 2a and 3b, c and d). Decreasing wave power causes the crescentic bars to migrate shoreward during *stage 4*, filling the now overfit channel, (Figure 3 d and e). The increasingly crescentic bar-channel morphology produces marked longshore variations in wave power and direction at the beach face generating a second phase reworking of the beach face as megacusps horns are deposited and embayments eroded. During *stage 3* the accretionary rip channels completely infill as the bar welds to the base of the beach, (Figure 3 e - h). Continuing low wave power conditions moves the 'bar' up the beach face (*stage 2*) where increasing beach steepness and beach reflectivity usually result in edge waves and cusp deposition (Wright, et. al., 1977) (Figure 3 i and j). Finally the cusp swales fill (Figure 3 j and k) and a continuous berm is formed (*stage 1*). The berm face is now too reflective for edge wave generation resulting in a straight berm crest,(Figure 3k). The beach is again in an 'equilibrium' condition with no longshore variation in beach morphology or dynamics. The *erosion sequence* (Figure 2b) begins with increasing wave power generating saturation and collapse of the steep berm face. The slumping sand is moved immediately seaward of the beach face as a narrow attached bar (*Stage 2'*). As wave power continues to increase in *Stage 3'*, narrow channels are initiated at the apex of the beach face and bar. The channels permit storage and longshore transport of water before it pluses seaward at lower frequencies. In *Stage 4'*, increasing wave power results in greater onshore flow of water which requires larger storage and transport channels. The resulting channel excavation moves the bar and breakpoint further seaward. At this stage relative closely spaced (spacing 200-500m), poorly developed erosional rips are initiated to facilitate seaward return of the water. The spacing of the rips is probably controlled by edge waves generating longshore variation in water level. As wave power continues to increase the size of the edge waves also increases resulting and more widely spaced megarip currents by *Stage 5'* (spacing 500-1,000m). Finally by *Stage 6* the longshore channel is large enough to temporarily store water moving shoreward so as to allow it to return to normal to the shore, instead of being transported laterally into high velocity rip currents. The shore normal return is achieved by a water level set-up in the channel that returns seaward in the form of a low frequency standing wave. It is this standing wave and its seaward effect that in turn determines offshore bar or bars spacing.

In nature wave power rarely moves smoothly between such extremes, rather depending on the wave environment it oscillates with varying amplitude and frequency around a modal wave power. The effect of these oscillations is to generate smaller cycles within the sequence shown in Figure 2. Cycles of this nature are shown in Figure 4, which plots part of the time-series of deepwater wave power and height, beach-stage and subaerial sand volume over a period of 13 months for Narrabeen Beach. Note the close correlation between all parameters as wave power varies. Increasing wave height and power produces higher beach-stages and erosion of the subaerial beach (January to June, 1978), while decreasing height and power result in low beach-stages and subaerial beach accretion (August-December, 1977). Also note that the transit time between erosional beach-stages is faster than between accretionary stages. This reflects the relative power associated with the erosive and accretive conditions. However, the absolute amount of wave power required to erode a beach is balanced over a longer period by the same magnitude of lower wave power through the accretionary sequence.

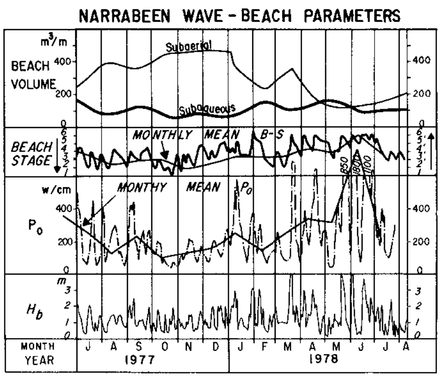


Figure 4 :
A time series of wave and beach parameters at Narrabeen Beach. Note the close correlation between breaker wave height (Hb), deepwater wave power (Po), beach-stage, and subaerial beach volume. Subaqueous beach volume (0 to - 3 m) reflects the movement of eroded subaerial sediment to beyond the - 3 m depth contour.

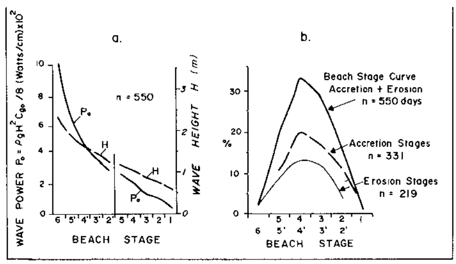


Figure 5 :
a. Correlation between erosional (6 to 2') and accretionary (5 to 1) beach -stages and deepwater wave power (Po) and height (H) for Narrabeen Beach.
b. Narrabeen Beach beach-stage curves, plotting the percent frequency of occurrence of erosion, accretion and combined beach-stages between April 1976 and January 1978.

WAVE POWER AND BEACH STAGES

Absolute Wave Power

The model is based on the response of beach morphodynamics to variations in the level of absolute deepwater and breaker wave power, Po and Pb respectively, where

$$Po = pgH^2Co/8 \text{ W cm}^{-1} \text{ wave crest}$$

where p is seawater density, g gravity, H significant wave height and Co wave group velocity. Figure 5 a indicates the level of H and Po associated with the 10 *beach-stages* on Narrabeen Beach. High stages are associated with high wave power, and erosive stages with the highest power. A threshold appears to exist at around H = 1.2m and P = 3 x 10^2 Wcm^{-1} above which erosive stages dominate and below which accretion dominates. Therefore for a given level of absolute deepwater and breaker wave power a corresponding beach-stage is generated with its associated morphology, dynamics and relative level of subaerial sediment volume.

Temporal Variations in Wave Power

Temporal variations in deepwater wave power produce variations in breaker wave power and thereby temporal variations in beach-stage. Over time the deepwater wave climate, will through its spectrum of wave power affect a corresponding spectrum of beach-stages. The amplitude and frequency of wave power oscillations determine beach-stages cycles. The frequency of occurrence of a particular beach-stage reflects the occurrence of the associated deepwater and breaker wave power. In order to apply this association to the model the beach-stage curve is now presented.

The *beach-stage curve* plots the percent frequency of occurrence of all beach-stages over a given time period for a particular site. Because of the direct linkages between accretion and erosion beach-stages of the same level (Figure 2) they can be combined as one in a total curve. The annual or total beach-stage curve is therefore the summation of the accretion and erosion beach-stage curves, which plot the occurrence of their respective beach-stages. Figure 5b illustrates the beach-stage curve for Narrabeen Beach. The modal breaker wave (T = 10 sec, H = 2 m) which arrives 10% of the time explains the modal 4/4' *beach-stage*. Rarer occurrences of very high (> 3 m, 5%) and low (< .5 m, 4%) waves explain the infrequent excursions to *stages 6* and *1* respectively. The *mode* and *range* of the beach-stage curve reflect the modal breaker wave power and range of wave conditions respectively. The beach-stage curve depicts quantitatively the morphodynamic character of a beach. It not only provides a mechanism for rigorously classifying and describing a beach but also for comparing it to beaches in other locations and wave environments.

APPLICATION

Temporal variations in wave power account for the morphodynamic character of a beach over time. In order to apply the model more widely the effect of spatial variations in deepwater and breaker wave power are now incorporated.

Spatial Variations in Breaker Wave Power

For a given deepwater wave climate the breaker wave power varies longshore in response to wave attenuation across the shelf (Wright, 1976) and wave refraction and diffraction. Along a coast the deepwater wave power will be attenutated and redistributed at the breakpoint depending on the shelf, nearshore and coastal morphology.

Longshore variations in breaker wave power affect a longshore variation in the relative level of beach-stage generated. In an idealised embayment (Figure 6), the longshore variation in breaker wave power generates a longshore variation in beach-stage, with low wave power producing lower stages, and high power higher stages. This effect is apparent on Narrabeen Beach which is protected in its southern portion (Collaroy Beach) from the dominant southeast swell. As a result when southeast swell dominates Narrabeen has a modal *stage 4*, while Collaroy with significantly lower breaker wave power has a modal *stage 2* (Figure 7a). However during the period of dominant northeast waves, Figure 7b, when the entire beach is equally exposed, the modal beach-stages are more similar. The annual beach-stage curves (Figure 7c) reflect the long term bias toward higher stages at Narrabeen and lower stages at Collaroy.

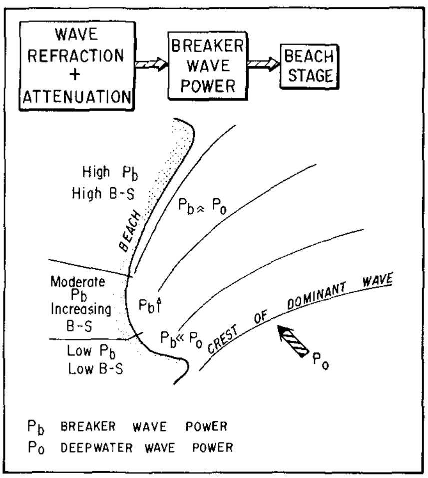
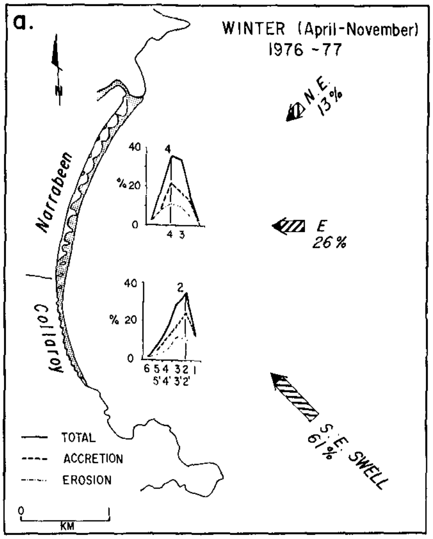
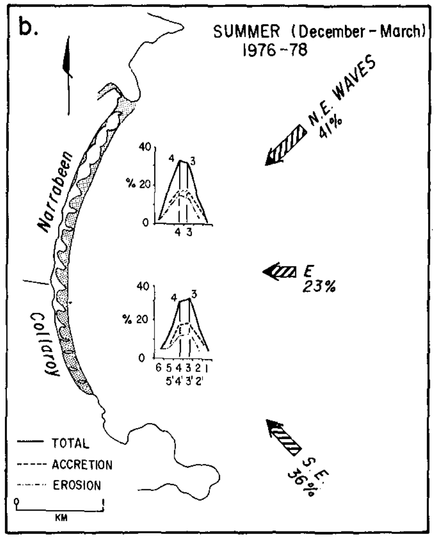


Figure 6 : Idealised coastal embayment showing the relationship between longshore variation in breaker wave power, due to wave refraction and attenuation, and corresponding level of beach-stage.





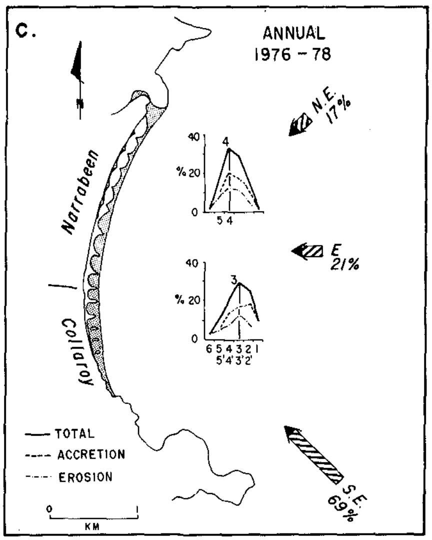


Figure 7 :

Beach-stage curves, wave directions and frequency of occurrence, and sketch of modal beach-stages for Narrabeen - Collaroy Beach.

a. Winter period, southeast swell dominates.

b. Summer period, northeast waves dominate.

c. Two year period, southeast swell dominates.

Collaroy Beach, being protected from direct southeast wave attack has correspondingly lower beach-stages during the winter and annual periods. Beach morphology depicts the modal beach-stage and its longshore variation.

The same effect can occur in longer embayments. The Coorong coast of South Australia is exposed to year round, high power, west coast swell, resulting in very high deepwater wave power. Along The Coorong however breaker wave power varies from very high in the northwest to zero in the southeast (Figure 8) due to nearshore wave attenuation over dunerock reefs in the southeast. The modal beach morphodynamics adjusts accordingly having modal *beach-stage 5* to *6* for the first 100 km, then

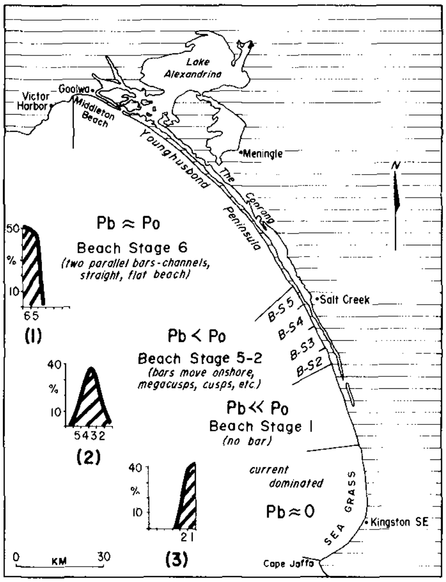


Figure 8 :

The Coorong, South Australia, illustrating the relative levels of deepwater (Po) and breaker (Pb) wave power, and corresponding effect on modal beach-stage (1), (2) and (3).

as breaker wave power decreases between 100 to 130 km a transition zone occurs with modal *beach-stage* decreasing from 5 to 2, and finally with very low breaker wave power from 130 to 160 km, *beach-stage 1* dominates. Beyond 160 km to Cape Jaffa, breaker wave power is zero and the shoreline is dominated by current-generated sand waves with seagrass growing to the shoreline.

Therefore while deepwater wave power will determine the potential mode and range of beach-stages, breaker wave power governs the actual mode and range for a given location.

Global - Absolute, Temporal and Spatial Wave Power

Global deepwater wave climates are associated with the oceans' wave environments. Davies (1964 and 1973) classified the ocean wave environments into storm wave, west coast swell, east coast swell, trade wind and monsoon influence, and tropical cyclone influence, (Figure 9). Using Davies' basic wave environments, the characteristic deepwater wave spectrum associated with each environment can be used to generate a characteristic beach-stage curve. Figure 10 presents idealised annual and seasonal beach-stage curves for the major wave environments as would be expected on open, microtidal, sand coasts receiving maximum breaker wave power.

Storm wave environments with persistent high wave power have a modal *stage 5 - 6* with rare excursions to lower stages (Figure 10a). West coast swell have high winter wave power and corresponding *stage 6*. In the northern summer low power dominates and *stage 2* and *1* persist

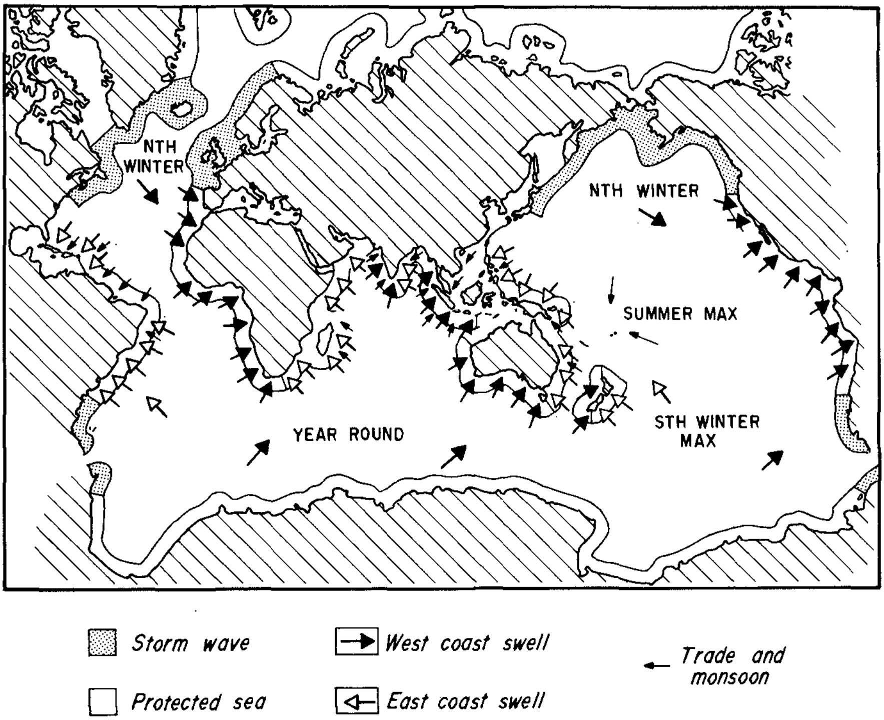


Figure 9 : Global wave environments. (Modified from Davies, 1973). Midocean arrows and lettering indicate direction and season of highest wave power.

(Winant and Aubrey, 1976), however in the southern hemisphere summer power remains high generating *stage 5* and *6* (Figure 10b). East coast swell environments, such as the study area and elsewhere (Wright et.al., in press), have a modal *stage 4* and experience the entire range from *6* to *1*, (Figure 10c). Trade wind coasts have a late summer maximum in wave power generating a modal *stage 4* to *6*, and a lower late winter wave power resulting in a modal *stage 3 - 4* (Figure 10d). Monsoon coasts have a moderate power summer maximum during the onshore monsoon generating a modal *stage 3 - 4*, and low winter wave power producing a modal *stage 2 - 1* (Figure 10e). Protected coasts away from background ocean swell rely on the passage of storms. They are therefore characterised by low beach-stages with infrequent storm generated higher beach-stages, (Figure 10f). Storm generated morphologies often remain as 'relic' forms in the absence of subsequent low waves to return the sand onshore. This is the likely explanation of the common occurrence of multiple parallel bars off relatively low power, through storm prone coasts, including the Mediterranean (King, 1972), Great Lakes (Davis and Fox, 1971) and Alaskan Arctic (Short, 1975).

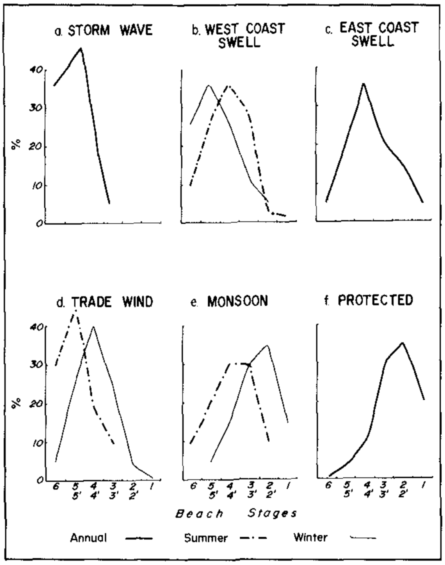


Figure 10 :

Idealised beach-stage curves for the major global wave environments. Curves describe expected occurrence of beach-stages on open coast, sand beaches receiving maximum deepwater wave power.

Other global implications of wave power and the beach-stage model are as follows.

The potential range of beach-stages is determined by the spectrum of absolute Po, whereas the actual range depends on Pb.

Daily variations in Po and Pb generate daily adjustments in the associated beach-stages. These adjustments may however have a lag of a few days particularly during low wave power (see Figure 4).

The seasonality of Po will determine the bias toward erosional or accretionary stages during the seasons. Note that the commonly used terms of 'winter' cut and 'summer' fill are based on studies in California, a northern hemisphere, west coast swell environment. Application of these terms to other wave environments including southern hemisphere west coast swell coast is often inappropriate and has led to much confusion and misunderstanding. Contrary to the west coast U.S.A. beach cycles,one would expect erosion stages to dominate or be significant during the summer season in east coast swell, (see Figure 7a and b), trade wind, monsoonal, and low and high latitude protected sea coasts, with little seasonal variation in southern hemisphere west coast swell environments (Figure 10b). Only in northern hemisphere west coast swell and mid-latitude protected sea coasts, are the terms 'winter' cut and 'summer' fill applicable. Therefore the terms are quite meaningless on a global scale and if must be used, should be with caution. More important than the present grossly simplified, emphasis on seasonal beach cycles, the present model illustrates how in east coast swell environments 'cut' and 'fill' cycles can occur at relatively high frequency throughout the year, though seasonal trends may be apparent (Figure 4 and 7).

To understand the cycles of beach morphodynamics in a particular location we must know the deepwater wave climate, shelf and nearshore wave transformation and associated breaker wave climate. Given a time series of the wave and beach conditions and resultant beach-stages and beach-stage curves, beaches can be understood and compared temporally and/or spatially between and among any suite of open coast environments.

DISCUSSION AND CONCLUSIONS

A beach model is presented which relates three-dimensional changes in beach and surfzone morphodynamics to variations in breaker wave power. The model covers all beach conditions from fully eroded to fully accreted, linked by both erosional and accretionary sequences. The entire cycle of sequences are presented as ten characteristic beach-stages. Using the relationship between wave power and the beach-stages, the beach-stage curve is introduced. The curve plots the percent frequency of occurrence of the ten beach-stages, over a given time period for a given beach site. The beach-stage curve, enables for the first time, the morphodynamic character of the beach to be quantified. The mode, range and shape of the curve all rigorously define the morphodynamic character of the beach over time. Beach-stage curves for different beaches and time periods permit comparison of all sandy beach beaches both temporally and spatially.

Variations in wave power generate the following predictable response in the model and beach morphodynamics in general.

1. Absolute wave power through breaker wave power controls the level of beach-stage present at any point in time.

2. Temporal variations in Po and Pb affect sequential changes in beach-stages (Figure 1), the greater the variation in Pb the greater the range of stages.

3. Spatial variation in Pb produces longshore variation in beach-stage. Along a section of coast as Pb varies so does the associated beach-stage.

4. Global wave environments (storm wave, west and east coast swell, trade wind, monsoon and protected) through their characteristic Po spectrum will generate a characteristic beach-stage curve.

5. Locally, the spectrum of Pb at the shoreline will determine for any wave environment the actual beach-stage curve.

The model allows beach morphodynamics to be explained at any point, period or place in the time, and can be used to compare beaches in all open coast wave environments over any time scale. In doing so it provides a framework within which all past, present and future beach studies can be located, so that their results can be seen in the overall context of a single unified model. The model also indicates that the major proportion of beach morphodynamic situations (particularly *beach-stages 6, 5', 5, 4', 3', 2'*) have not been previously identified or rigorously investigated.

Finally the model illustrates the four-dimensional complexity of the beach and surfzone. This complexity must be taken into account when dealing with the coastal zone whether it be in field, laboratory or mathematical experiments, or in designing management or engineering criterion for safeguard of the zone.

ACKNOWLEDGEMENTS

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REFERENCES CITED

Davies, J.L., 1964, A morphogenic approach to world shorelines: Zeit. f. Geomorph., v. 8, p. 127-142.

__________, 1973, Geographical Variation in Coastal Development, Hafner, New York, 204 p.

Davis, R.A., Jr., and W.T. Fox, 1971b, Beach and nearshore dynamics in eastern Lake Michigan, ONR Tech. Rept. No. 4, Contract 388-392, 145 p.

King, C.A.M., 1972, Beaches and Coasts, 2nd ed., St. Martin's, New York, 570 p.

Short, A.D., 1975, Multiple offshore bars and standing waves: Jour. Geophys. Res., v. 80, p. 3838-3840.

__________, 1978, Characteristic beach morphodynamics on the southeast Australian coast: Fourth Australian Conf. on Coastal and Ocean Engineering, Adelaide, The Inst. of Engineers, Australia, National Conference Publication No. 78/11, p. 148-152.

__________, (in preparation) Three dimensional beach model: (submitted to Jour. Geol.).

Winant, C.D., and D.G. Aubrey, 1976, Stability and impulse response of empirical eigenfunctions: Proc. 15th Coastal Engineering Conf., p. 1312-1325.

Wright, L.D., 1976, Nearshore wave-power dissipation and the coastal energy regime of the Sydney-Jervis Bay region, New South Wales: A comparision: Australian Jour. Freshwater Res., v. 27, p. 633-640.

__________, Chappell, J., Thom, B.G., Bradshaw, M.P., and Cowell, P., (in press), Morphodynamics of reflective and dissipative beach and inshore systems: Southeastern Australia: Marine Geology.

__________, and Thom, B.G., 1977, Coastal morphodynamics: Progress in Physical Geography, v. 1, p. 412-459.

__________, __________, Cowell, P. Bradshaw, M., and Chappell, J., 1977, Field observations of resonant surf and current spectra on a reflective beach and relationship to cusps: Search, v. 8, p. 321-322.