SEDIMENT DISPERSAL ON THE N.S.W. CONTINENTAL SHELF

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ABSTRACT

This paper presents a semi-empirical model for describing sediment dispersal on the central New South Wales (N.S.W.) continental shelf. Results from a program of field experiments identify wind speed and direction, wave height and frequency distribution of near-bottom currents as being the dominant factors influencing near-bottom current asymmetry on this shelf. A combination of theoretical prediction and field experiment has been used to define the seaward limits for onshore/offshore sediment exchange and the modes of sediment transport operating within this active zone.

INTRODUCTION

A unified theoretical basis for continental shelf sediment dispersal is yet to be fully established. In such a situation, empirical models may provide useful tools in interpreting sediment dispersal patterns for specific shelf regions. This contribution presents such a model for the central N.S.W. shelf. Field data is used to identify the basic nature of the near-bottom flow field and resulting sediment transport on this shelf. The model also represents a framework from which future local investigations of sediment dispersal may be planned.

SIMPLIFICATIONS

A number of simplifying assumptions have been made which consist of eliminating those elements which account for only relatively minor contributions to the local sediment budget. These assumptions are:

(i) Coastal streams do not supply significant quantities of sand-sized sediment to the shelf at the present time.

(ii) Longshore transport is an ineffective dispersal mechanism along much of the compartmentised central N.S.W. coast.

(iii) Coastal estuaries do not act as sinks for sediment derived from the adjacent shelf.

(iv) The major contribution to the shelf sediment budget comes from onshore/offshore exchange.

FRAMEWORK OF THE MODEL

The model developed to document onshore/offshore exchange operates by rationalising the spectrum of atmosphere/ ocean/substrate interactions into a finite number of categ- ories. The resulting classification system is derived from four years of ocean observations in the Sydney region. These observations suggest a classification system based on parameters of average wave period (Tav), significant wave height (Hs), swell approach direction, wind speed and orientation to the coastline (Table 1). The wave period and height parameters define a number of alphanumeric

TABLE 1. SHELF WEATHER CLASSIFICATION

WAVE PARAMETERS	WIND PARAMETERS
Average Wave Period (Tav)	Wind speed
A. Tav $\leqslant$ 7 seconds	< 20 km/hr (av)
B. 7 seconds < Tav $\leqslant$ 10 seconds	> 20 km/hr (av)
C. Tav > 10 seconds	
Significant Wave Height (Hs)	Orientation of Wind to coastline
1. Hs $\leqslant$ 1 m	- Onshore (including S)
2. 1m $\leqslant$ Hs < 3m	- Offshore (including N)
3. 3m $\leqslant$ Hs $\leqslant$ 5m	
4. Hs > 5m	
Swell Direction	Key:
- Arriving from the NE quadrant (including E)	< less than
- Arriving from the SE quadrant (including S)	> greater than
	$\leqslant$ less than or equal to

divisions (A1-C4). Swell direction and wind parameters account for a further numeric subdivision (categories 1 to 49). The classification is informally referred to herein as the Inner Shelf Process-Response Model (I.S.P.R.M.)

EXPERIMENTAL PROGRAM

An experimental program was conducted at Palm Beach, some 30 km north of Sydney, to identify characteristic responses in the near-bottom current field and patterns of sediment transport for each category in the model. Data collection utilised a mechanical current meter based on a design by Summers *et al.* (1969).

NEAR BOTTOM CURRENT ASYMMETRY

Onshore/offshore sand transport depends on near-bottom current asymmetry. Initiation of sediment motion on wave-dominated coasts such as that of central N.S.W. depends on orbital velocities resulting from oscillatory wave currents. Rates and directions of sediment transport are determined by unidirectional currents superimposed on oscillatory wave motion (Bagnold, 1963). Unidirectional currents may be produced by the waves themselves (e.g. Longuet-Higgins, 1953) or they may result from other mechanisms such as wind stress (e.g. Murray, 1972), tidal motion (e.g. Huthnance, 1972), rip currents (e.g. Cook, 1970), or backwash (e.g. Kemp, 1975).

Under conditions such as those experienced during the Palm Beach field experiments, net water transport is expressed as inequality of onshore and offshore surges. For each cycle under shaling conditions, non-linear wave theories (e.g. Stokes theory) suggest onshore surges should become stronger while offshore surges should occupy a longer time interval. The field data from Palm Beach did not conform with these predictions. Current meter records exhibited current maxima in both the onshore and offshore directions. Similar variations occurred in the relative amount of time occupied by onshore and offshore flow. This data therefore indicates that other factors in addition to wave motion determine near-bottom currents at Palm Beach. To identify any other contributing factors, a statistical correlation analysis was performed on the data. In particular, investigations were made of the relationship between near-bottom currents and the parameters which define the I.S.P.R.M. such as wind velocity, wave height and wave period. Other parameters considered likely to influence near-bottom currents such as tidal motion or bedslope were also included for analysis.

Net bottom drift was the dependent variable chosen for correlation. This parameter is derived by summing individual current speed and direction values over an entire record. The resultant thus takes into account both current velocity and duration. Statistical tests for this analysis consisted of a diagonal correlation coefficient (D.C.C.) designed to identify relationships between directional parameters (such as net bottom drift and wave direction) and a rank correlation (R.C.) to identify relationships between parameters whose magnitude could be compared (such as wave height and net bottom drift).

The most significant correlations occurred between net bottom drift, wind and wave parameters. In particular, the direction of bottom drift correlated strongly with wind direction. Bottom drift magnitude correlated best with wave height and spectral distribution of near-bottom currents. Poor correlation resulted from the other parameters considered, including tidal motion and sea floor topography (Table 2).

1. Wind-Induced Effects

Wind direction and wind speed both showed good correlation with net bottom drift. A D.C.C. value of 0.77 (the highest value for all parameters investigated)

TABLE 2

PARAMETER	TEST	LEVEL OF SIGNIFICANCE	CORRELATION COEFFICIENT
Wind Direction	DCC	-	0.77
Wave Height	RC	>90%	0.56
Wind Velocity	RC	>90%	0.55
Spectral Distribution	DCC	-	0.50
Bed Slope	RC	<90%	0.30
Bed Roughness	RC	<90%	0.30
Depth	RC	<90%	0.30
Wave Period	RC	<90%	0.21
Tidal Direction	DCC	-	0.09
Wave Direction	DCC	-	0.02

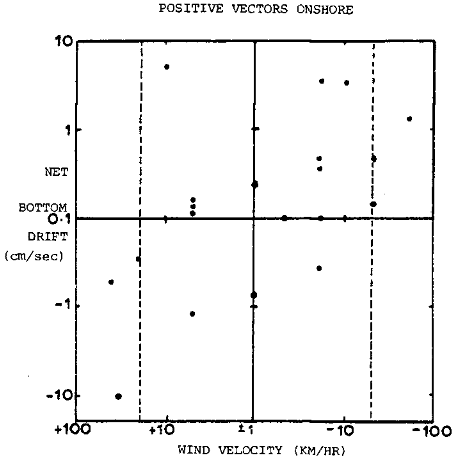


FIGURE 1
WIND VELOCITY VERSUS NET BOTTOM DRIFT

was found to exist for correlation between wind direction and the direction of net bottom drift. The R.C. test indicated a dependence existed between wind speed and net bottom drift magnitude at greater than the 90% level of significance. The correspondence between wind parameters and net bottom drift is graphically illustrated in Fig. 1. Data values tend to cluster in the upper right and lower left quadrants of the graph, with a further tendency to be along the diagonal between the two. This indicates onshore winds are associated with near-bottom currents directed offshore while offshore winds are associated with near-bottom currents directed onshore. Stronger winds tend to produce higher values of net bottom drift.

The above results are in agreement with comparable studies conducted by Cook and Gorsline (1972) and Murray (1972). A simple, steady-state model proposed by Jeffries (1923), adequately accounts for the observed generation of near-bottom currents by wind stress. On the N.S.W. coast, Jeffries' model predicts onshore-directed bottom currents to result from westerly winds and offshore-directed bottom currents from easterly winds on the inner shelf. Wind stress control over near-bottom currents may be generalised via the Jeffries model for inclusion in the I.S.P.R.M. classification. Strong offshore-directed current asymmetry, derived from wind stress effects, may be found in Categories 5, 6, 11, 12, 17, 18, 23, 24, 29, 35, 36, 41, 42 and 49. Strong onshore-directed current asymmetry from the same source occurs in Categories 3, 4, 15, 16, 21, 22, 33, 34, 39, 40 and also 49.

2. Wave-Induced Effects

Wave height, wave period and water depth are the variables which occur in the expression for volume transport resulting from wave motion in both Stokesian and solitary waves (Inman in Shepard, 1963). Inspection of the Palm Beach data revealed wave height to be the most significant of these variables in determining net bottom drift. The magnitude of net bottom drift in the direction of wave advance increased exponentially with wave height (Fig. 2).

Values of net bottom drift also tended to increase with increasing wave period but here the relationship was less well established (Fig. 3). A similar result has been reported by Cook and Gorsline (1972). However, this result does not conform with theoretical predictions, such as the Longuet-Higgins mass transport concept (Longuet-Higgins, 1953), which suggest net bottom drift is inversely related to wave period. Several factors may help to interpret the Palm Beach results.

a. Long average wave period is commonly associated with larger waves on the central N.S.W. coast. This was the case for all Palm Beach experiments. It was difficult (especially using in situ recording techniques) to monitor occasions where wave height remained constant over a range of wave periods.

b. Conditions of low average wave period are commonly associated with a wide frequency distribution of wave energy rather than the monochromatic swell conditions for which theoretical relationships are derived. This is reflected in the high correlation found to exist between frequency distribution of near-bottom currents and direction of bottom drift. Narrow-band frequency distributions were associated with stronger onshore bottom drift. Wide-band frequency distributions often resulted in low and offshore-directed values of bottom drift. In addition, under field conditions, low average wave period is frequently the result of shorter-period wind waves generated by an onshore wind and superimposed on pre-existing swell.

3. Relationship of Current Asymmetry to the I.S.P.R.M.

Insufficient data has been collected during the present study to accurately determine the quantitative contribution of individual processes to current asymmetry. The value of the present work lies in identifying the parameters controlling current asymmetry and incorporating

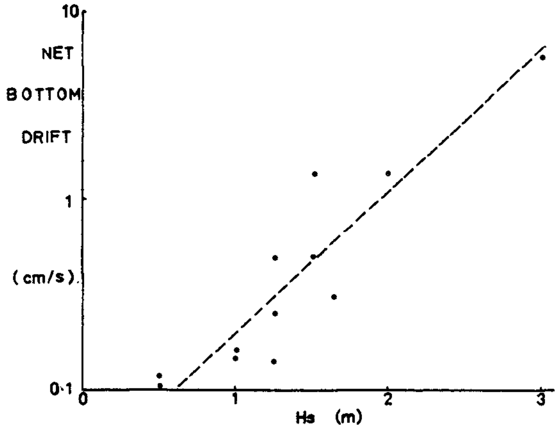


FIGURE 2
NET BOTTOM DRIFT VERSUS WAVE HEIGHT
(positive values only)

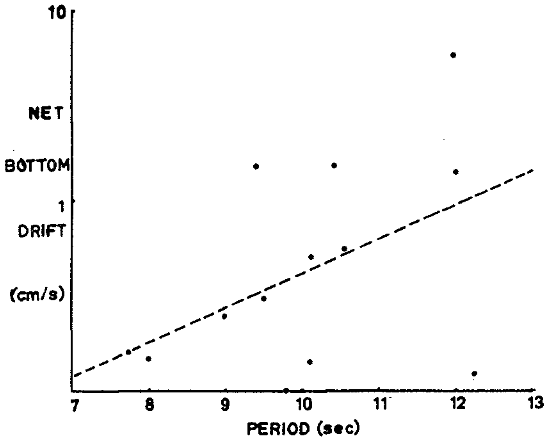


FIGURE 3
NET BOTTOM DRIFT VERSUS WAVE PERIOD
(positive values only)

these parameters into a qualitative model (the I.S.P.R.M.). The present form of the model is suitable for constructing a conceptual framework for shore-normal shelf dynamics which predicts the relative effectiveness of individual processes.

Wind stress provides the most effective control of current asymmetry. In the absence of a significant wind stress contribution, waves control the near-bottom current field. Wave control is most effective for conditions of larger waves which produce a concentration of near-bottom currents at low frequencies. Therefore, strong, onshore, near-bottom currents result from strong offshore winds, high energy swell conditions which produce oscillatory flows dominated by low-frequency components, and combinations of these two mechanisms. Such situations are present chiefly in I.S.P.R.M. Divisions C4, C3, C2 and B2, in Categories 49, 46, 44, 43, 40, 39, 38, 37, 34, 33 and to a lesser extent 20 and 19. Onshore flow extends to lower categories such as 22, 21, 16, 15, 4 and 3 under strong offshore wind conditions. Offshore near-bottom currents result from strong onshore winds and wide spectral distribution of oscillatory currents in Categories 5, 6, 11, 12, 17, 18, 23, 24, 29 and 30. Weak and variable near-bottom currents occur in the absence of higher energy swell or strong wind conditions such as in Categories 1, 2, 13 and 14, or when strong winds negate higher energy swell conditions. The above situations are summarised in Fig. 4.

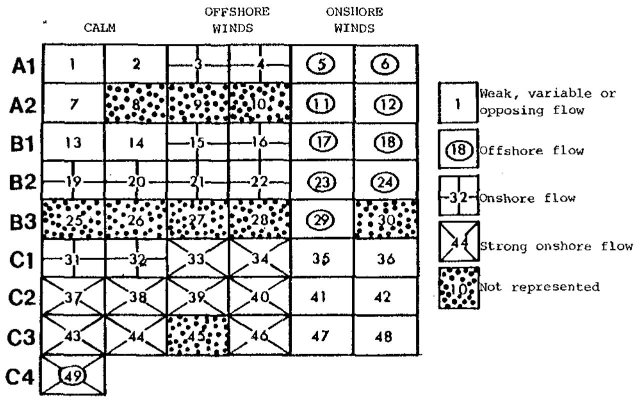


FIGURE 4
I.S.P.R.M. CLASSIFICATION OF NEAR-BOTTOM FLOW

SEDIMENT DYNAMICS

As a first step in determining sediment dynamics on the central N.S.W. shelf, the seaward limit to the zone of sediment activity resulting from wave processes was established for the range of shelf weather situations covered by the I.S.P.R.M. classification system. In addition, the modes of sediment transport operating within the active zone were observed and recorded during the field experiments at Palm Beach.

These field experiments conformed with a conceptual model of wave-generated sedimentary structures presented by Clifton (1976). Clifton recognised a typical shoaling sequence of structures resulting from wave-induced oscillatory flow. Beginning offshore and moving landward, these are (1) an inactive zone, (2) active symmetric ripples, (3) long-crested asymmetric ripples, (4) irregular asymmetric ripples, (5) asymmetric cross-ripples, (6) megaripples and (7) flat bed. This same sequence was commonly observed at Palm Beach.

Three important divisions exist within Clifton's model. These are:

(1) A division between active and inactive zones. This division corresponds to the shelf location where initiation of sediment motion begins.

(2) A division between symmetric and asymmetric bedforms. In the Palm Beach examples, this division also separated migratory and non-migratory bedforms. In the zone of symmetric bedforms, sediment was transported by grain translation close to the bed during each wave cycle and by intermittent suspension in ripple-lee vortices, formed as the oscillatory motion changed direction. In the zone of asymmetric bedforms, sediment transport was dominated by migration of individual bedforms and by the translation of a highly-concentrated, near-bed layer of suspended sediment.

(3) A division between rippled beds and flat beds. This division corresponds to the appearance of a sheet flow mode of sediment transport.

It was decided to use the Clifton model as a basis for providing a conceptual documentation of sediment transport zones on the central N.S.W. continental shelf.

Sediment Transport Zones

For simplicity, Clifton's model was based on dimensional parameters derived from the work of Dingler (1974) and Komar and Miller (1973). It is generally accepted (see for example discussion by Komar (1976)) that sediment transport criteria are best described by a shear stress concept, such as that proposed by Shields (1936). Therefore shear stress criteria have been used to construct continental shelf "fences" defining the initiation of sediment motion and the onset of sheet flow for each division of the I.S.P.R.M. Following the methods of Nielsen (1979), a non-dimensional shear stress

$$\theta' = \frac{\tau'_{max}}{\rho(s-1)gd} \qquad \text{eqn. 1}$$

has been used to calculate the sediment transport depth zonation. Here ρ is density of water, s is grain density, g the acceleration due to gravity and d is grain diameter. Nielsen found that the concentration of moving sediment is related more closely to the skin friction (τ') than to the total shear stress. τ'_{max} may be calculated from the relationship;

$$\tau'_{max} = \tfrac{1}{2}\rho f_w (a\omega)^2 \qquad \text{eqn. 2}$$

where $\omega = \frac{2\pi}{T}$, a is water semi-excursion and f_w, a friction factor, is derived from Swart's (1976) formula

$$f_w = \exp\left[5.213 \left(\frac{k}{a}\right)^{.194} - 5.977\right] \qquad \text{eqn. 3}$$

Here k is the hydraulic roughness. Nielsen gives the critical θ' values for initiation of motion and onset of sheet flow as 0.045 and 1.0 respectively. An iterative solution was then developed (from eqn. 1) for critical water depths corresponding to θ' values of 0.045 and 1.0.

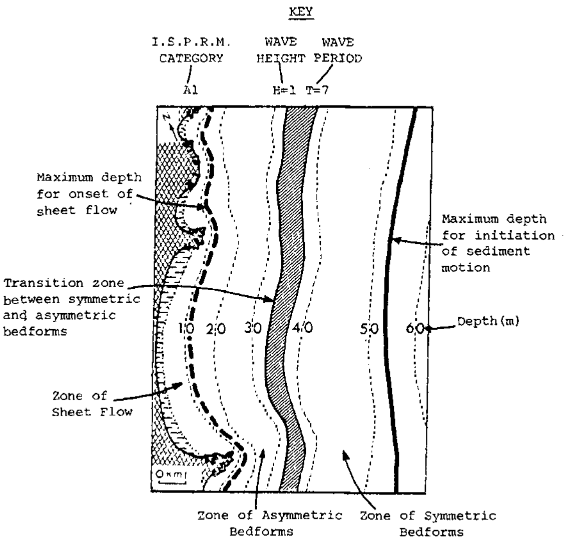
Bedform asymmetry is a function of near-bottom flow asymmetry. In Clifton's model, the transition between symmetric and asymmetric bedforms took place at velocity difference values between 1 and 5 cm/sec. Velocity difference is here defined as the sum of the maximum velocity under the wave crest in the direction of wave propagation (positive vector) plus the maximum velocity under the trough of the wave (a negative vector). In six of the seven examples of asymmetric bedforms observed at Palm Beach while simultaneously recording currents, the velocity difference lay between 1.1 and 9.5 cm/sec. It was thus concluded that the range of velocity difference between 1 and 5 cm/sec, proposed by Clifton, adequately defined the transition between symmetric and asymmetric bedforms. At present it is only possible to accurately predict the flow asymmetry derived from wave shoaling. In the following discussion other controlling influences of the near-bottom current field (such as wind stress) will not be considered. Velocity difference (V_d) values were quantitatively estimated from the Stokes second-order wave equations whereby

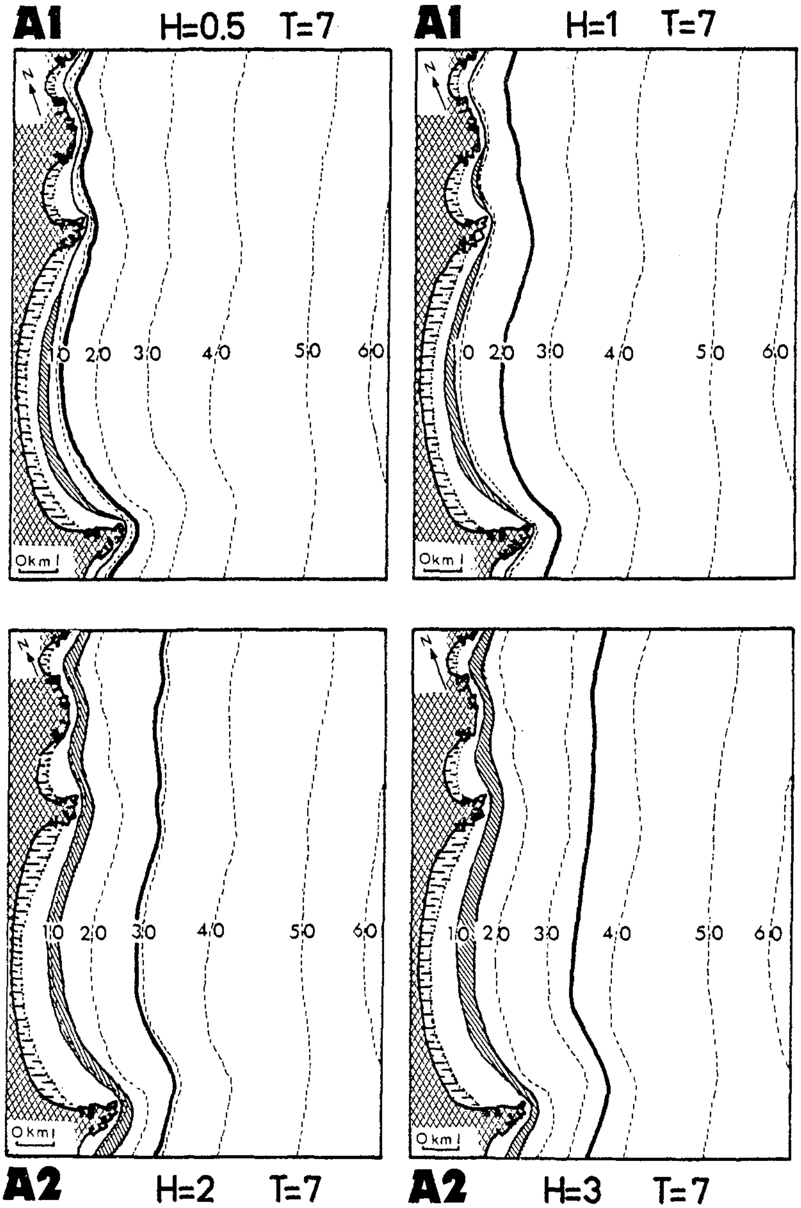
$$V_d = \frac{14.8H^2}{LT \sinh^4 kh} \qquad \text{eqn. 4}$$

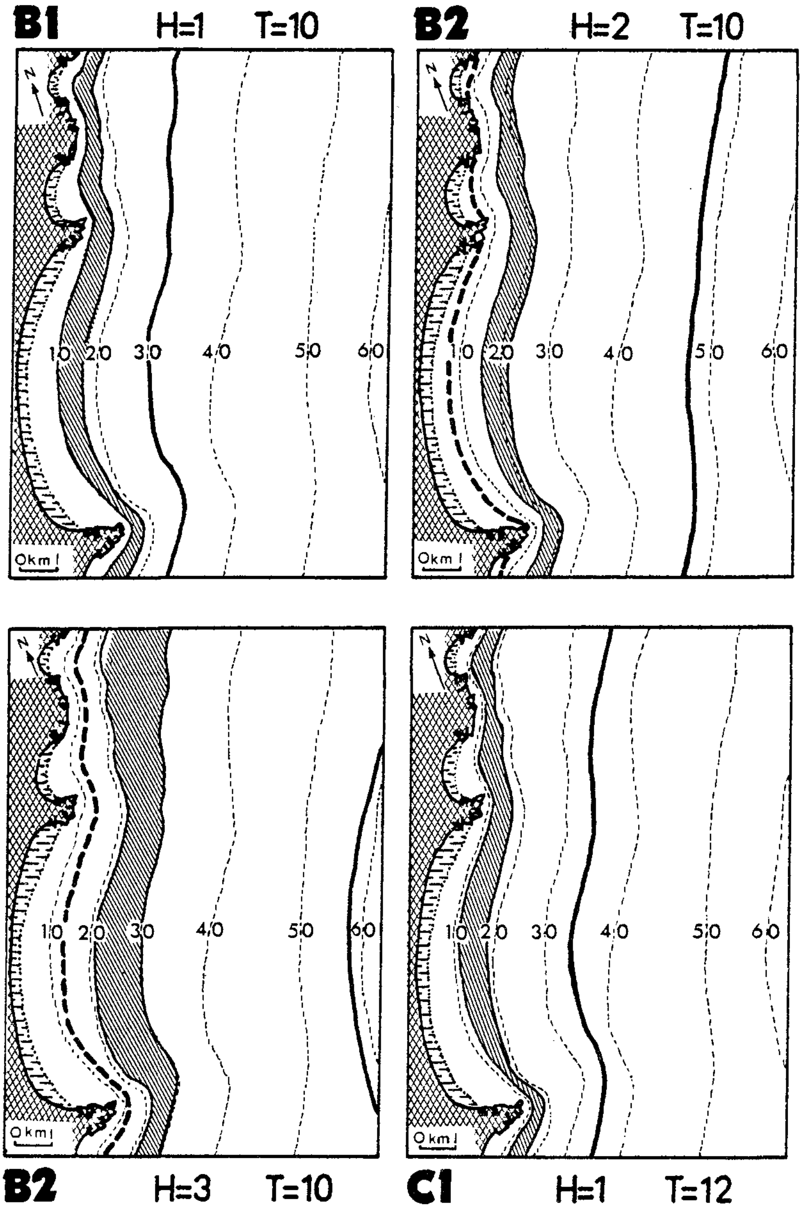
These values were used to construct a further continental shelf fence (for the development of asymmetric bedforms) in each I.S.P.R.M. division. The location of the three sediment transport zones defined by fences for the initiation of sediment motion, development of asymmetric bedforms and onset of sheet flow are shown for each I.S.P.R.M. division in Fig. 5.

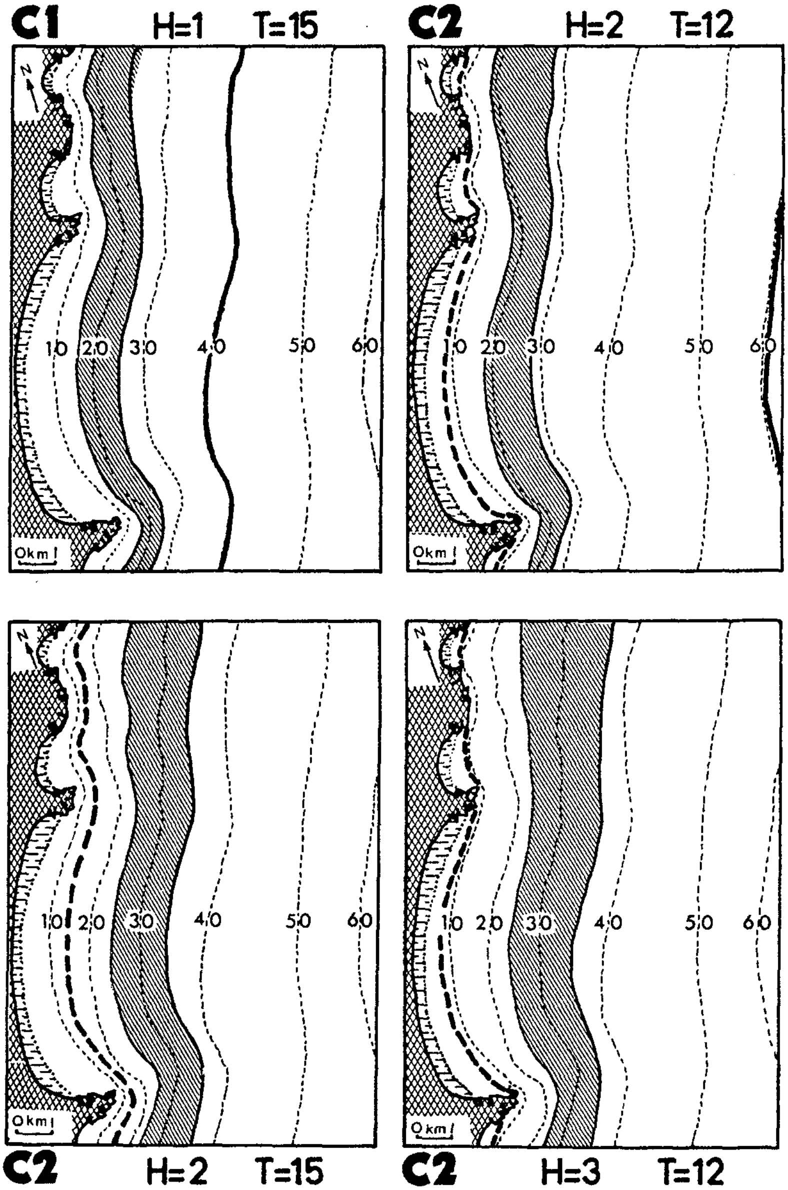
A combination of low θ' values and a seaward increase in grainsize for sand on the inner shelf generally restricts

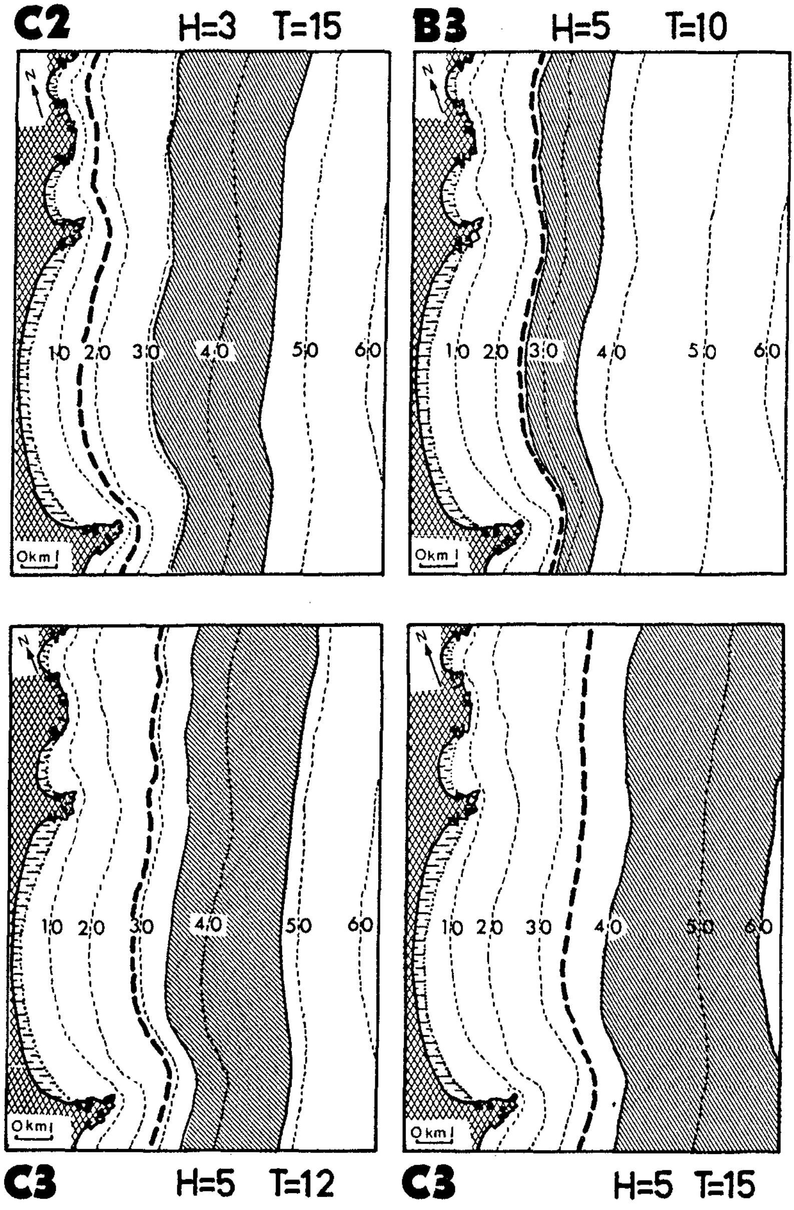
FIGURE 5
SHELF ZONATION FOR SEDIMENT DYNAMICS




A1 H=0.5 T=7
N
1.0 2.0 3.0 4.0 5.0 6.0
0 km 1
A1 H=1 T=7
N
1.0 2.0 3.0 4.0 5.0 6.0
0 km 1
N
1.0 2.0 3.0 4.0 5.0 6.0
0 km 1
A2 H=2 T=7
N
1.0 2.0 3.0 4.0 5.0 6.0
0 km 1
A2 H=3 T=7


B1 H=1 T=10
B2 H=2 T=10
B2 H=3 T=10
C1 H=1 T=12
1.0 2.0 3.0 4.0 5.0 6.0
0 km 1
N


C1 H=1 T=15
1.0 2.0 3.0 4.0 5.0 6.0
0 km 1
C2 H=2 T=12
1.0 2.0 3.0 4.0 5.0 6.0
0 km 1
1.0 2.0 3.0 4.0 5.0 6.0
0 km 1
C2 H=2 T=15
1.0 2.0 3.0 4.0 5.0 6.0
0 km 1
C2 H=3 T=12
N


C2 H=3 T=15
B3 H=5 T=10
1.0 2.0 3.0 4.0 5.0 6.0
N
0 km 1
C3 H=5 T=12
C3 H=5 T=15

active bedform development to the shoreface, above the 30m isobath, for I.S.P.R.M. divisions A1, B1 and C1. Bedform activity in Divisions A2, B2 and C2 may extend onto the inner shelf while Divisions C3 and C4 create active sediment motion in all areas of the inner shelf and extend into the midshelf zone, below the 60m isobath. Fine sand modes (less than 0.5mm grainsize) in inner shelf sands are entrained at significantly deeper depths and under lower energy conditions than the coarser sand and gravel modes. Asymmetric bedforms are virtually restricted to the shoreface except for Divisions C2, C3 and C4. Sheet flow under flat bed conditions is entirely restricted to the shoreface except for extreme events in Division C4. In Divisions A1, B1 and C1 sheet flow is restricted to the vicinity of the surf zone.

DISCUSSION

The model which has been presented above contains several important implications for sediment dispersal on the central NSW continental shelf.

1. The dominant parameters identified as controlling near-bottom current asymmetry on this shelf are wind speed and direction, wave height and frequency distribution of near-bottom currents.

2. The active zone of sediment exchange, as defined in the fence diagrams, extends further offshore than is usually acknowledged on this coast. This is because the active zone limit has been previously correlated with a sharp sediment textural discontinuity at depths of 20-25m. Theoretical predictions for initiation of sediment motion, distribution of the asymmetric bedform zone (which contains migratory bedforms) together with corroborative data derived from bottom photographs and sediment volume measurements (Boyd, 1980) all indicate onshore/offshore sediment exchange may occur between the surf zone, the shoreface and the inner shelf on this coast.

3. The relative frequency of constructive versus destructive conditions (as defined in figure 4) is the primary determinant of both the short-term and long-term exchange budgets.

CONCLUSION

In its present form, the above model may be used to indicate direction and relative magnitude of near-bottom currents. For a wave-induced flow field, the model also indicates the modes of sediment transport and their areal distribution on the inner shelf. It thus represents a conceptual framework with which to interpret the general nature of sediment dispersal on the central NSW continental shelf.

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