

CHAPTER ONE HUNDRED THIRTY ONE

SEDIMENT TRANSPORT ON THE SOUTH-EAST AUSTRALIAN CONTINENTAL SHELF

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ABSTRACT

Engineering projects on the continental shelf off Sydney, Australia, have stimulated investigation into the sediment transport system of the shelf. Investigation activities associated with these projects have included: definition of sea bed morphology, sediment distribution and bedform characteristics; monitoring of steady and wave induced currents; wind data collection; suspended sediment sampling; bottom camera sediment movement investigations and analytical studies of sediment reaction to sea bed forcing functions. Sea bed velocity exceedence relationships for both wave oscillations and steady currents have been determined at depths of 24 m, 60 m and 80 m. Thresholds of sediment movement have been defined. Relative sediment transport computations have been undertaken and studies of suspended sediment concentration profiles are in progress so that absolute transport rates can be determined. The prevailing conditions, which include a mainly south bound current, are seldom sufficient to induce entrainment of shelf sediments. Transport events mainly result from major storms in the Tasman Sea which produce both high energy waves and north bound currents. Although these events are rare and short lived, the combined wave and current shear produced at the sea bed during the events gives rise to entrainment conditions which result in their dominance of the shelf sediment transport system.

1. Introduction

The coincidence of a number of engineering studies on the continental shelf off Sydney, Australia, has provided the opportunity to study shelf bed characteristics and sediment transport under the combined action of currents and the prevailing wave spectra. This paper examines the forcing functions on the sea bed outside the surf zone in water depths from 24 metres to 80 metres. It also documents the response of the sediments to the forcing functions. The location of the study area is shown in Figure 1.

2. Physiographic Setting

The S.E. Australian continental shelf off Sydney varies in width from 20 to 40 kilometres. Its surface comprises a mixture of unconsolidated sediments and bedrock reef (Figure 2). Seaward of the

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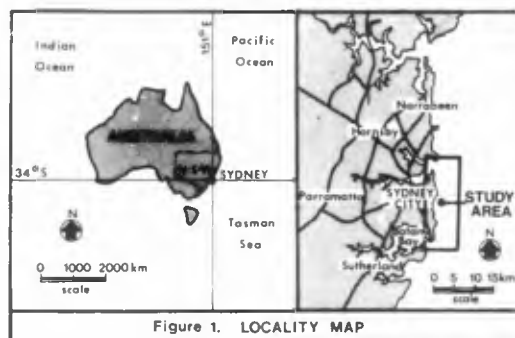


Figure 1. LOCALITY MAP

surf zone, the profile is generally concave up with slopes of 1:50 in 20 metres depth and 1:100 in 80 metres depth. Typically, the 20 metre contour is 1 km and the 80 m contour 10 km offshore. There are locations where the profile is considerably steeper. This occurs where extensive rocky cliff formations are the predominant coastal feature. In these locations the 20 metre contour is often less than 200 metres offshore with the 80 metre contour some 3 km offshore (Figure 2).

Sea bed sediments gradually become finer from medium sands in the surf zone with typical values of d_{50} of 0.35 mm to a d_{50} of 0.18 mm in 14 m depth. These fine sands continue out to depths of 25 to 30 m. From 30 m out to about 60 m, a diverse suite of sediments are found. They range from fine sand to coarse sand and gravel. Deeper than 60 m, fine sands with some silt content predominate. Shell contents are highly variable but are generally highest near areas of exposed reef. Shelf sediment types and their distribution are shown in Table 2 and Figure 2.

Morphological anomalies associated with sediment features occur in certain locations. These features include convex upwards sand lobes, cross shelf sand ridges and mid shelf sand bodies with rhythmic asymmetric morphology (Figure 2).

3. Shelf Data

Data were obtained from an extensive side scan sonar and sediment sampling survey of the Sydney coast (Gordon and Hoffman, in prep, (a)) and from detailed studies at three sites across the shelf (Nielsen, 1984; Gordon and Hoffman, in prep, (b)). Table 1 summarises the instrumentation used and the data collected at the three sites. All instruments were calibrated before and after deployment and cross spectral checks between the electromagnetic current meters and the waverider buoys were also carried out (Nielsen and Gordon, 1984).

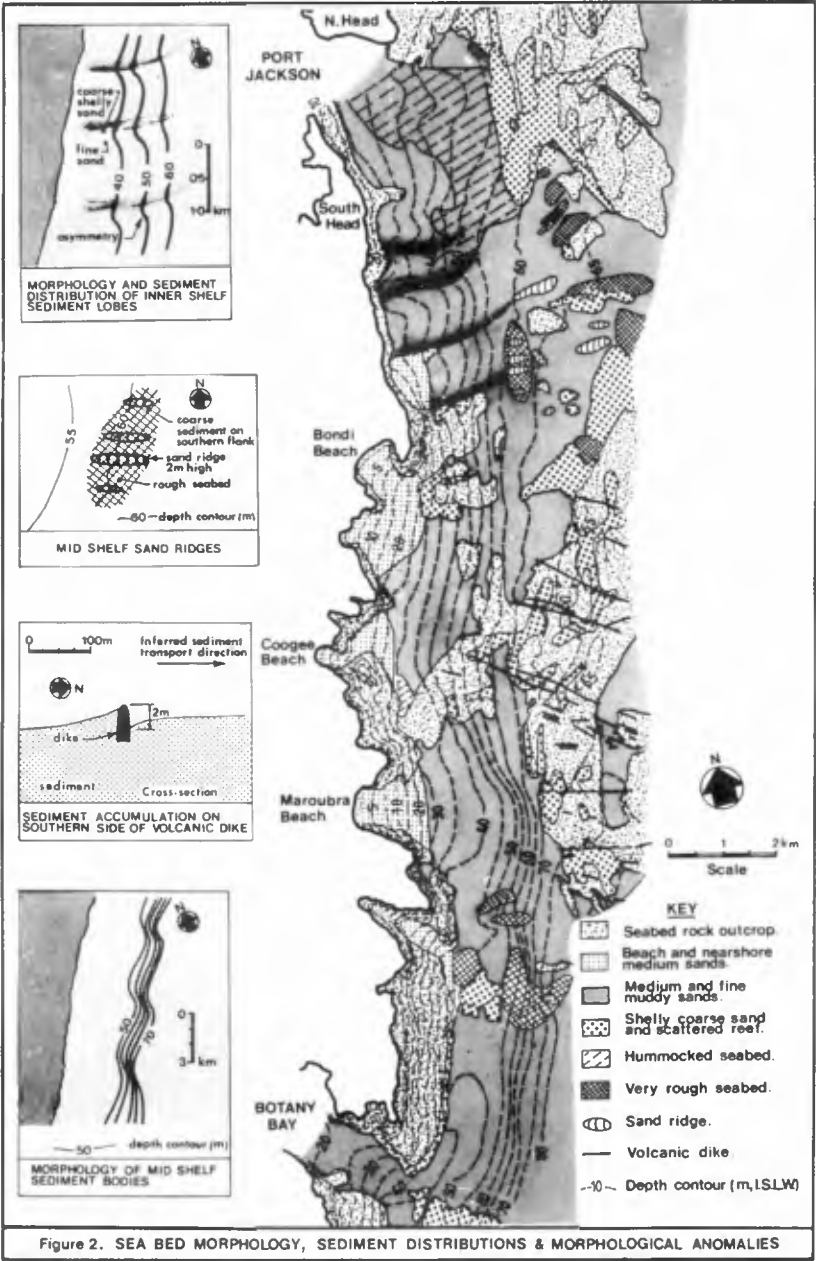


TABLE 1. STUDY SITES, INSTRUMENTATION AND DATA COLLECTED.

Water depth	Period of data collection	Instrumentation and sampling schedules *				
		Waves	Currents	Wind	Sediments	Seabed morphology and bedforms
24m	24 months	Waverider buoy. 1/2 s x 18m x 6h.	Marsh McBirney X-Y current meter. 1s x 10m x 7h.	Dynes anemometer. Continuous.	Surface samples, diver and vibro coring.	Side-scan sonar and diver observations.
60m	6 months	Waverider & dynamic pressure sensor. 1/2 s x 18m x 4h.	Marsh McBirney X-Y current meter. 1s x 8m x 4h.	Lambrecht anemometer. Continuous.	Surface samples, vibra and box coring, suspended sediment samples.	Side-scan sonar, RCV video & time lapse camera. 32s x 8m x 4h.
80m	6 months	Waverider & dynamic pressure sensor. 1/2 s x 18m x 4h.	Marsh McBirney X-Y current meter. 1s x 8m x 4h.	Lambrecht anemometer. Continuous.	Surface samples, vibra and box coring, suspended sediment samples.	Side-scan sonar, RCV video & time lapse camera. 32s x 8m x 4h.

* Sampling schedule : As x Bm x Ch = burst sampling at intervals of A seconds continuously for B minutes every C hours

4. Forcing Functions

The forcing functions which may influence sediment transport on the Sydney shelf are:

- steady currents due to -
 - (a) the onshelf component of ocean currents;
 - (b) wind induced currents; and
 - (c) wave induced mass transport;
- tidal currents; and
- oscillatory currents induced by surface gravity waves.

4.1 Ocean Currents

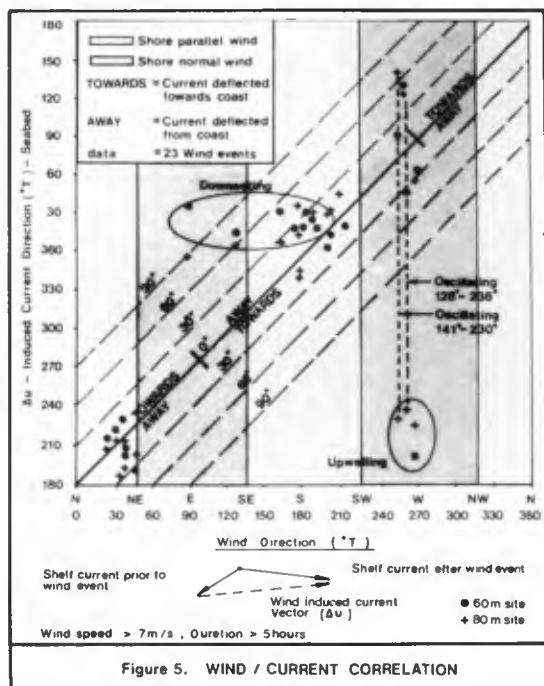
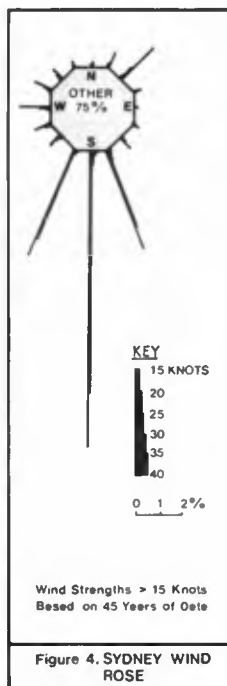
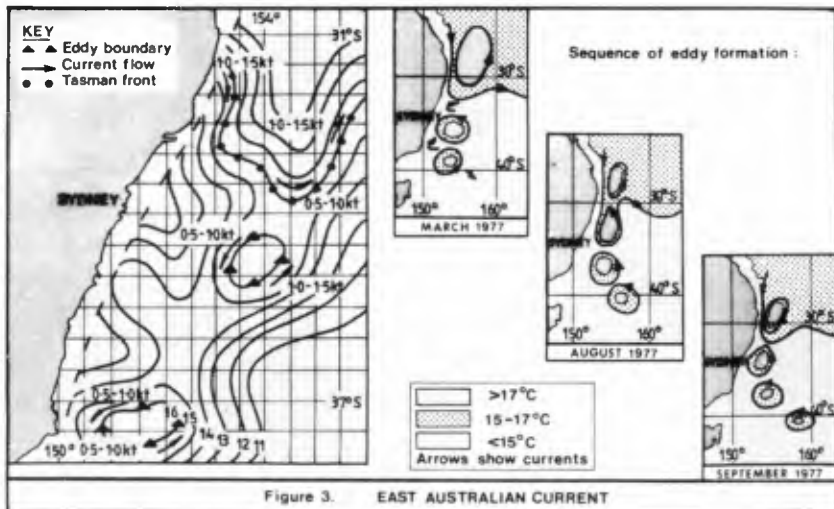
The S.E. Australian shelf is influenced by the offshore East Australian Current. Originally believed to be a southbound flow along the western extremity of the Tasman Sea, it is now known to consist of a complex system of migrating eddies (Nilsson and Cresswell, 1980; see Fig.3).

4.2 Wind Induced Currents

Local winds induce currents which act to modify the prevailing onshelf regime. Rotation of these currents from the prevailing wind direction can occur due to the Ekman effect (to the left in the southern hemisphere). At the shelf bed near the coast, compensating currents in the form of upwellings and downwellings may also be experienced.

Analysis of the study data showed that a direct correlation exists between the anemometer information and the induced change of current behaviour (Figures 4 and 5) for events when the wind speed exceeds 7 m/s for a duration of more than 5 hours. At lesser wind speeds or durations, no clear trend was discernible.

The lag between the commencement of the wind event and the impact on the prevailing current regime is typically between 4 and 24 hours. Prevailing current strength and direction as well as wind strength, direction and duration determine the lag period. Subjective judgement



was required in determining onset of these events. The present data set is considered insufficient to explore the lag question further.

Data for shore parallel wind events with wind speeds greater than 7 m/s and duration greater than 5 hours which produced approximately shore parallel currents were used to compare observed bottom currents with those predicted by Bretschneider's (1967) method:

$$\frac{\bar{V}}{U} = \sqrt{\frac{k}{k^*}} \sin \theta \tanh \left[\frac{Ut}{D} \sqrt{\frac{k k^*}{\sin \theta}} \right]$$

where $\bar{V}$ = depth averaged current

U = sustained wind speed

k = surface stress parameter (3×10^{-6})

$k^* = n^2 g D^{-1/3}$

n = Manning factor (0.025)

D = water depth

t = duration of wind speed

θ = angle between wind and shore normal

The resulting observed and predicted currents, corrected to 1 m above the sea bed, are presented in Figure 6 and show reasonable agreement. Hence, based on the limited data set available, a tentative relationship between wind speed/duration and induced sea bed current magnitude at the 60 m and 80 m sites was determined (Figure 7).

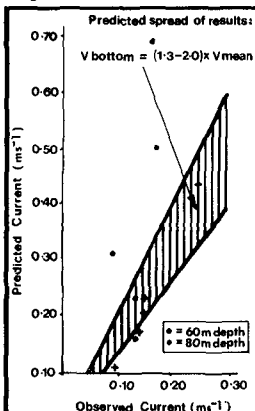


Figure 6. PREDICTED AND OBSERVED BOTTOM CURRENTS

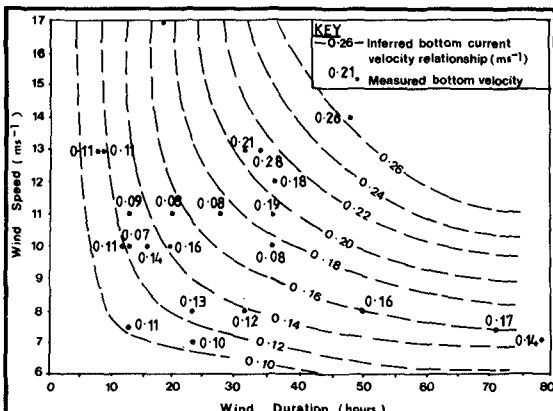


Figure 7. SUGGESTED RELATIONSHIP BETWEEN WIND SPEED / DURATION AND INDUCED SEA BED CURRENT FOR SYDNEY SHELF

4.3 Wave Induced Mass Transport

The depth of water in the study area is such that in general the wave induced mass transport is negligible and was therefore neglected. The time series data from the current meter records supported this approach. That is, changing wave conditions produced no discernible change in steady current direction or strength.

4.4 Tidal Currents

The steep nearshore slopes, the relatively narrow shelf and the small ocean tidal range (mean value 1.2 m) combine to produce weak tidal currents on the shelf. Hamon (1984) carried out a tidal analysis of the study data. He showed that longshore tidal components are in the order of 1 cm/s and offshore components are negligible. Therefore, as with the wave induced mass transport, tidal currents are not considered to be a significant factor in shelf sediment transport in the study area.

4.5 Wave Oscillations

The S.E. Australian continental shelf experiences a moderate to high energy wave environment. Deep water significant wave heights of 1.5 m are exceeded 50% of the time and spectral peak periods are typically between 8 and 12 seconds (Figures 8 and 9). During severe storms however, the significant wave height can reach 10 to 12 metres with peak periods of 14 to 16 seconds. A synoptic chart for a typical storm in the Tasman Sea is shown in Figure 10.

An analysis of the study data and a comparison with 10 years of waverider data at Sydney (Youll, 1981; Figure 8) was undertaken. This showed that the two data sets produced almost identical wave height exceedance curves (Gordon and Hoffman, in prep, (b)), indicating that the study data could be taken to be representative of the long term wave climate.

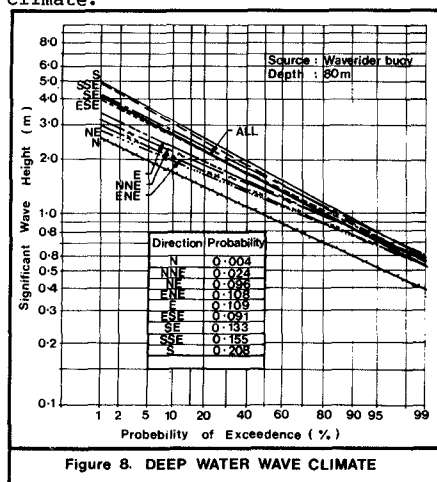


Figure 8. DEEP WATER WAVE CLIMATE

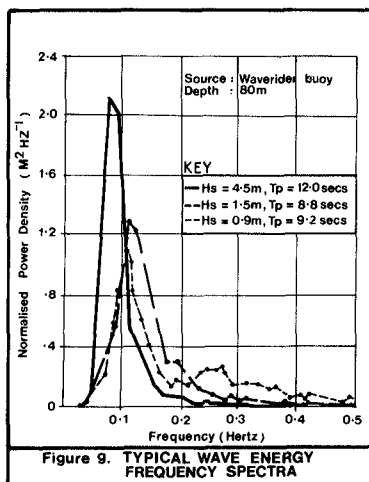
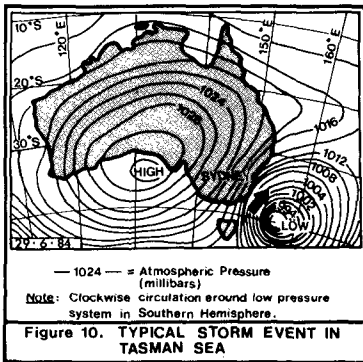


Figure 9. TYPICAL WAVE ENERGY FREQUENCY SPECTRA

Comparison of the directional wave oscillation records from the electromagnetic current meters with the long term directional statistics based on surface observations produced an interesting result. Particularly at the 60 and 80 m sites the depth dependent high frequency filtering showed that the majority of the recorded longer period energy comes from the south-east to south sector; the Lower Tasman Sea generating area. This contrasts with several years of wave directional data obtained at the surface which suggest that there is only a weak bias towards this sector (Fig. 11). It does however explain previously noted anomalies associated with attempts to match surf zone sediment transport calculations on the N.S.W. coast to recorded shoreline changes using the sea surface observations (Gordon et al, 1978).



Exceedence curves of near bed steady and oscillatory currents at depths of 24 m, 60 m and 80 m are shown in Figures 14 to 16. These indicate steady current components (U_c) and the root mean square and 1% values of both the maxima of the oscillatory components (U_w) and of the vector addition of the steady and oscillatory components (U_{c+w}). The latter analysis was undertaken record by record (at one second intervals), taking into account the directions of both the steady and oscillatory components. The wave oscillation velocity parameter $U_{1\%}$ was selected based on the arguments put forward by Nielsen and Gordon (1984) that this parameter is the most appropriate for determining sediment entrainment under natural wave spectra. The ratio $U_{1\%}$ to U_{rms} was investigated over some 70 records. Based on the statistical mean of the results, the relationship adopted was: $U_{1\%} = 1.75 U_{rms}$. This suggests that seabed wave oscillatory velocities in this depth of water do not fit a Rayleigh distribution (Rayleigh gives $U_{1\%} = 2.15 U_{rms}$).

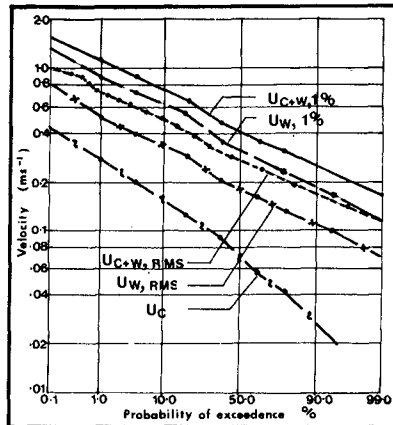


Figure 14. VELOCITY EXCEEDENCE RELATIONSHIPS - 24m SITE

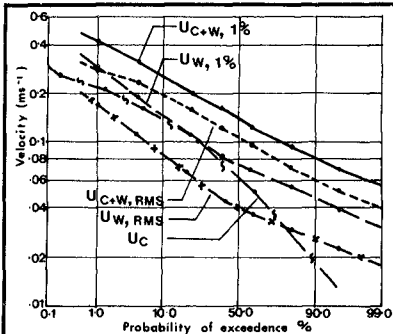


Figure 15. VELOCITY EXCEEDENCE RELATIONSHIPS - 60m SITE

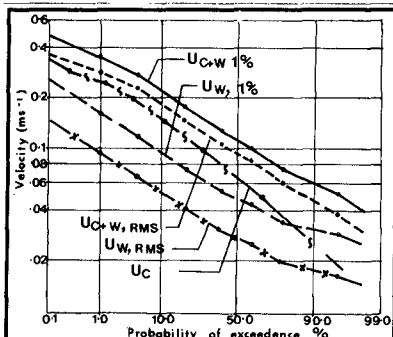


Figure 16. VELOCITY EXCEEDENCE RELATIONSHIPS - 80m SITE

5. Sediment Transport

Sediment transport on the Sydney shelf was analysed by considering the following questions:

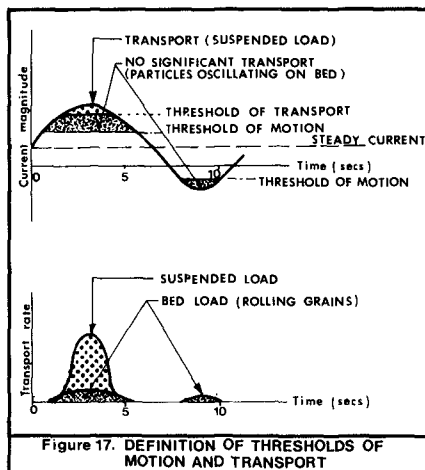
- . What is the availability of sediment, both in terms of areal extent and sediment type?
- . Under what hydraulic conditions do the various sediments move?
- . How often are these conditions exceeded?
- . What is the direction and magnitude of both the gross and net sediment transport?

5.1 Availability

Side scan sonar, fathometer and seismic studies were used to determine the availability of sediments (Figure 2). Surface sediment sampling and R.C.V. video studies provided the detailed surface sediment data. In all, some 650 bottom surface samples and some 41 sub-bottom cores were obtained. Grain size distributions were determined hydraulically in a calibrated fall velocity tube (Gordon and Hoffman, in prep, (a)). Table 2 shows sediment characteristics at various water depths.

5.2 Threshold of Movement

Two thresholds of movement under combined waves and currents are recognised: the threshold of motion and the threshold of transport (Figure 17). The former occurs when the oscillatory shear is sufficient to result in sediment oscillation without net translation, a phenomenon observed in both the R.C.V. and diver studies. The latter (transport) occasionally occurs when the steady currents produce sufficient shear to initiate bed load transport. More commonly on the Sydney shelf however, the threshold of transport is only exceeded when the wave induced motion entrains the sediment. The entrained sediment is then transported by the prevailing steady current.



Entrainment may be caused by boundary layer flow instabilities around bed forms (Nielsen, 1979) or simply result from the combined wave and current shear exceeding that required to lift sediment particles from the bed.

Study site data showed that significant bedforms are present most of the time at the 24 m site (Nielsen and Gordon, 1984); they were also noted from the R.C.V. film and from the side scan survey out to about 40 metres depth. At the 60 metre site, bedforms were only observed on 18 occasions during the 6 months time lapse camera deployment. At the 80 m site no hydraulically induced bedforms were recorded on any of the instruments.

It was noted from the bottom cameras and the samplers that on many occasions fine sediments were in suspension without there being noticeable changes to sea bed conditions. Significant sediment transport events involving major bed changes did, however, occur at all sites. At these times, the current meter data showed that the threshold of motion, as defined by the modified Shields curve (Madsen and Grant, 1976), had been exceeded (Gordon and Hoffman, in prep, (b)). The bed at the deeper sites tended to rapidly progress from a flat bed, pock marked by animal burrows, to a sheet flow condition. During these events, both the coarse and fine fraction of the sediment were captured in the suspended sediment sampler array.

Flume studies under steady flow conditions and mechanical soils tests carried out to examine the progression from no transport to sheet flow indicated that the higher silt content of the sediments at the deeper sites caused them to behave in a semi-cohesive manner until the bed shear was sufficient to directly entrain both the fine and coarse fractions.

It was noted that bedform development and geometry is more marked in the regions where the sediments include significant shell hash (> 5%). This effect appears to be proportional to the coarse shell fragment content of the sediment. It was not, however, a feature of sediments where the shell fraction was medium to fine.

Table 2 presents the results from the threshold of motion studies from flume tests under steady flow and from the bottom camera and diving data. To date, velocity has been used as the parameter for defining thresholds. Although the methods of Madsen and Grant have been used to calculate shear stress, it is recognised that further work is required before meaningful determination of this parameter can be undertaken. In particular, the calculation of both an appropriate friction factor for semi-cohesive flat beds with appreciable biological activity and the determination of the relevant boundary layers and velocity distribution for wave spectra require further research.

It was found that calculations using Jonsson based approaches were sensitive to determination of friction factor and in particular to which velocity parameter was chosen to represent the wave spectra, e.g. U_{rms} or $U_{1\%}$.

TABLE 2. SEDIMENT GRAIN SIZES, THRESHOLDS OF MOTION AND TRANSPORT AND TRANSPORT VELOCITIES

Water depth (m)	Sediment					Threshold of motion (U_{ms}^{-1})		Threshold of transport (U_{ms}^{-1})		Transport velocity (U_{ms}^{-1}) at activity levels			
	grain size (mm)	silt content	shell content	Comment		steady currents	currents* and waves	steady currents	currents* and waves	5	6	7	8
	d_{16} d_{50} d_{84}												
24	0.30 0.24 0.16	1%	31%	medium fine sand		0.20	0.14	0.40	0.22				
40	0.75 0.62 0.35	2%	35%	coarse sand with shell fragments		0.26	0.10	0.35	0.18				
60	0.33 0.20 0.16	14%	26%	med fine sand		0.20	0.13*	0.30	0.14*				
80	0.19 0.17 0.15	32%	33%	silty fine shell fine silty sand, fine shell fraction		0.30	0.10*	0.38	0.13*				

$$* U_c + U_w$$

5.3 Exceedence of Threshold

Diver observations and the time lapse camera data were used to determine the exceedence of threshold. Camera data were subjectively assessed and classed into various activity levels (Figure 18). The hydraulic parameters associated with these levels were then determined. The suspended sediment sampling bottles attached to the current meter frames provided data on the grain size of the sediment being transported at various heights (up to 2.1 m) above the seabed. The camera data and sample bottles indicated that the fine fraction of the sediment tended to be in suspension at activity levels of 4 to 5 whilst activity levels of 6 to 7 were required for the coarser fraction. (Because of the inherent problems of such sampling devices, no attempt was made to use the samples collected in the bottles as a measure of sediment transport or to develop depth/concentration relationships.)

When considered in terms of shear stress, this result contradicts the implications of the Shields curve which suggests that the finer material should be more difficult to entrain. Although the Shields approach was developed for steady flow conditions only, Madsen and Grant (1976) and others have suggested that it can be applied, with suitable choice of parameters, to oscillatory motion.

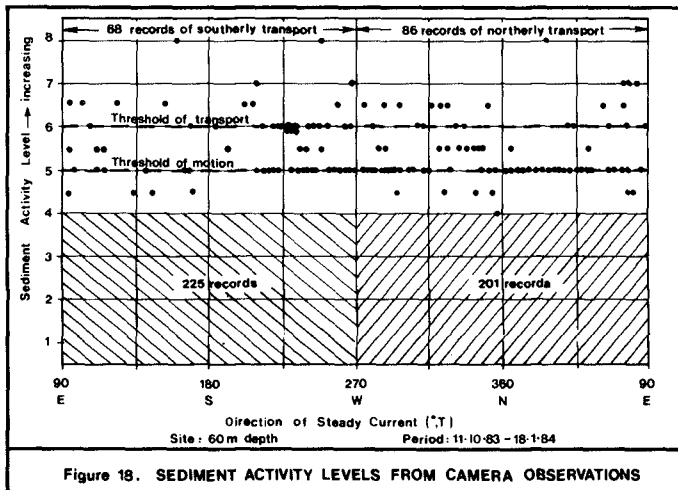


Figure 18. SEDIMENT ACTIVITY LEVELS FROM CAMERA OBSERVATIONS

Two possible explanations for the observed phenomenon are suggested. The first is that fine sediment seen in suspension at low activity levels comes from a remote source; the second is that for the finer fraction, bottom pressure variations associated with wave motion can induce rapid pore pressure fluctuations in this semi-cohesive material. This may result in a bed instability which would effectively lower the shear stress required for entrainment of the finer fraction thus inducing a leaching action. The available data base was insufficient to resolve this matter.

Table 2 presents the threshold data and the estimated velocities associated with the designated activity levels at the 60 m and 80 m sites. The velocity estimates were obtained by taking the statistical mean of $U_{1\frac{1}{2}}$ velocities associated with each event, at each designated activity level. $U_{1\frac{1}{2}}$ was selected as the relevant spectral parameter based on bottom observations that the thresholds of motion and transport are associated with extreme spectral parameters (Gordon and Hoffman, in prep, (b); Nielsen and Gordon, 1984).

5.4 Transport

Whilst some bed load transport was observed at the 24 m site, suspended transport was observed to be the dominant mechanism at all sites. For the purposes of this study, the oscillatory motion of sediment without net movement taking place was not considered to constitute sediment transport.

Shelf sediment transport was estimated by considering the time averaged flux of suspended sediment:

$$\bar{Q} \approx \int_0^h U_0(z) \bar{C}(z) dz$$

where $\bar{Q}$ = time averaged transport

$U_0(z)$ = average velocity at height z above the bed

$\bar{C}(z)$ = time averaged concentration at height z above the bed

h = bottom zone thickness

This was applied to each individual record for which it had been determined that threshold had been exceeded (Table 2 and camera data).

Nielsen et al (1982) suggested the relationship:

$$\ln \bar{C} = \ln C_0 - \frac{\bar{w}h}{\sqrt{E_B} E_S} \tan^{-1} \sqrt{\frac{E_S}{E_B}} \frac{z}{h}$$

where $\bar{C}(z)$ = time averaged suspended sediment concentration at elevation z .

C_0 = $\bar{C}(0)$

$\bar{w}$ = average settling velocity of sediment

h = water depth

E_B = diffusivity due to boundary layer turbulence

E_S = diffusivity due to non boundary layer turbulence

and showed that:

$$C_o \approx 0.008 \left(\frac{\tau'}{\rho g (s-1)d} \right)^{2.5} \quad \text{for } r = 2.5d$$

Although Nielsen's (1979) work was confined to flume tests and the later work (Nielsen et al, 1982) to prototype measurements in the vicinity of the surf zone, some deep water data exist (Glenn, 1983) which was useful in scaling Nielsen's approach to the deeper shelf sites. This was necessary due to the lack of concentration profile data at these sites.

Absolute values of sediment transport have not been determined; further studies of the concentration profiles are being undertaken. This work is initially being carried out at the 24 m site. At the deeper sites, the six months data show that sediment transport events are rare. For example, at 60 metres, twelve events ranging in duration from 4 to 56 hours occurred where transport is considered to have taken place. At the 80 metre site, only six events of duration 8 to 16 hours were recorded. It should be noted that Figure 18 presents the number of recordings obtained, not the number of continuous events. For each event, a record was taken each four hours.

A significant finding of the study was that resultant net transport on the shelf is to the north and is determined by storms in the Tasman Sea. It had been generally believed that net transport was to the south since the net movement of water on the shelf is in that direction. During Tasman Sea storms, the wave induced seabed shear dominates and results in the entrainment of bed material which is then transported by the prevailing currents. As a majority of storms which impact on the shelf are a product of low pressure systems in the Lower to Central Tasman Sea (Figure 10), a strong coast parallel wind shear to the north is generated. This wind field gives rise not only to the waves which induce entrainment but also a short lived north bound shelf current (see Section 4.2). Near the coast, the Ekman effect rotates this current to produce a set up which is balanced by a downwelling. Hence, whilst the midshelf current during the storms is directly to the north, nearshore there is an additional offshore component at the sea bed due to the downwelling phenomenon. Overall, the net movement of sediment is therefore to the north and offshore near the coast but swings more towards the north further offshore.

The side scan sonar records include features consistent with net northerly sediment transport and with the modifying near-coast downwelling effect (Gordon and Hoffman, in prep (b) and Figure 2).

Sedimentological studies carried out by Roy (1984) suggest that average annual sediment transport is small; his estimates of accretion rates on identified depositional features on the shelf are in the order of 2 to 5 mm/year.

6. Conclusions

- . Transport on the shelf off Sydney mainly occurs during storm events in which wave activity produces sufficient seabed shear to cause entrainment. The dominant southerly steady current on the shelf seldom induces sufficient seabed shear to entrain sediment. On the occasions when wave induced shear results in entrainment, the mechanism producing the waves also tends to give rise to a short duration north bound current and hence the net movement of sand sized material is to the north. Near the coast, modification to the current pattern due to downwelling results in movement which is to the north and offshore.
- . Side scan sonar data have identified a number of sediment features which are believed to be related to this movement; the implied stability of these features suggests that transport rates on the shelf are small. This is supported by the sedimentological evidence and by the sediment transport calculations.
- . Estimates of absolute values of sediment transport on the Sydney shelf require further studies on concentration profiles and improved estimates of bottom shear stress.
- . Extreme wave spectral parameters are considered the most appropriate for examination of threshold of movement in these environments.

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