CHAPTER 105

STORM INDUCED PERIODICITIES OF SUSPENDED SAND MOVEMENT

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SUMMARY

An array of electronic sensors was installed on Nauset Light Beach, Cape Cod, Massachusetts, U.S.A., in order to provide a description of the sediment movement during storm conditions. These sensors included two sediment concentration indicators (almometers) which monitor sediment movement as a function of elevation and time, one bidirectional electromagnetic current meter, and a resistive wave staff.

Prior field studies performed during "normal" conditions have indicated that surf-zone suspended sediment movement is a low-frequency phenomenon, with the relatively high-frequency component (normal wave period) contributing little to the amount of total sediment transported. Development of a computational technique based upon discrete Fourier analysis and digital filtering called *Spectrally Filtered Integration* (SFI) provides the calculation and filtering of true units of sediment change in grams-per-liter. Moreover, the SFI technique eliminates the possibility spurious sediment information created by the presence of air bubbles in the water column.

Generally, higher-frequency sediment movement is more common during storm conditions than during normal non-storm conditions. This movement is controlled not by the prevailing wave and swell periods, but by a longer period which may be due to water interactions below the surface.

INTRODUCTORY REMARKS

The nature and periodicity of sedimentation during storm conditions

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in the nearshore zone is virtually unknown. At no other time do the processes of erosion, transportation and deposition operate with such a degree of efficaciousness. Therefore, the relationships among storm waves and currents to the movement of sedimentary material is one of the major problems prevalent in the nearshore zone.

A major limitation, however, in understanding these relationships is the lack of reliable storm-garnered quantitative field data. This dearth of data has led workers to rely upon models based on mechanics, hydrodynamics, flume studies and empirically derived non-storm data. Therefore, the ability to make real-time field measurements during storm conditions is essential. The purpose of this report is to present results and interpretations concerning the periodicities of sediment movement based upon a series of five-experiments performed during the rising tide of a coastal storm.

FIELD TECHNIQUES

Instrumentation

To measure nearshore sediment movement and processes, an array consisting of two almometers, a bidirectional electromagnetic current meter and resistance wave-staff was utilized. The almometer (Brenninkmeyer 1973, 1975, 1976) is a series of electro-optical sensors which instantaneously and continuously measure the change in opacity of the lower one meter of water column caused by sediment concentration. A sealed fluorescent bulb at a distance of one meter provides constant illumination. This distance prevents the coalescing of scour pits around each almometer. Each photoresistor was fitted with a 1.5 cm copper tube internally darkened so that its field of "vision" was limited and controlled (see Table 1). The data were recorded on a FM and direct seven-channel analog tape recorder operating at 3.75 ips. The data were gathered between 2400 and 0600 hours so that sunlight could not affect the incident light on the photocells.

Study Area

The instrumentation was emplaced as shown in figure 1 at low tide on Nauset Light Beach in late October of 1975. Nauset Light Beach, located on outer Cape Cod, Massachusetts, U.S.A., trends northerly and faces the open Atlantic Ocean. The major storms are "noreasters" since their principal direction is from the northeast. The tides on the outer Cape are semi-diurnal and have a mean range of 2.3 m and a spring range of 2.7 m. Although the outer Cape has an erosion rate slightly less than 1 m/y (Marindin, 1889; Zeigler, 1964), the beaches are relatively narrow indicating that a large amount of sediment is transported alongshore (Leonard and others, 1976).

Sea State

The original intention of the study was to measure sediment movement during "normal" sea conditions; however, during the latter part of the study a severe storm arose so quickly that the equipment could not

Table 1

Elevation in cm	Vision in liters
0	56.2
5	72.0
10	88.4
15	99.6
20	106.6
25	110.4
30	112.0

Cone of "vision" (in liters of water) for the various almometer photocell elevations (in cm).

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removed from the water. During the storm, the primary breakers were approximately 500 m from shore. Breaker height was estimated to be 4 m, with long-period variations caused by at least two principal swell directions. The array usually stood in the area of secondary and/or tertiary breakers which were considered normal to the beach. These breakers coupled with short-period wind-chop, translational-bores and turbulent-surf defined an extremely confused nearshore hydrodynamic condition. The largest peak in the unusually noisy wave spectra occurred at about 8 seconds.

Zones

Most authors follow the ideas of Shepard and Inman (1951) in dividing the water motion on the foreshore and offshore regions of a beach into three dynamic zones: swash, surf and breaker zones. Schiffman (1965) added another, "the transition zone," between the swash and surf. This zonal concept is valuable in placing a complex environment into a logical reference framework. These dynamic zones, however, are only well-defined during fair-weather conditions. In the conditions extant during a storm, with different period waves arriving at a shore simultaneously from different angles, the boundaries between the zones become indistinct and may even be absent. During this study the breaker zone was relatively far out to sea, and the nearshore was a mass of turbulence caused by the interaction of locally derived wind waves, swell, as well as bore-surf and backwash. In this paper, the operational definition "time zones" will be used. Each zone (Fig. 2) represents a one hour time slice of a rising tide. During this time the array went from partially underwater to completely underwater.

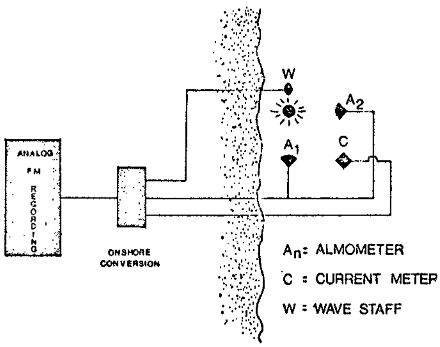


Figure 1. The configuration of the sensor array, onshore conversion station and the recording station (not to scale). W is the wave staff attached to the light source. C is the electromagnetic current meter. A_1 is the onshore/offshore almometer. A_2 is the longshore almometer. The distance of A_1 and A_2 from the light source is one meter.

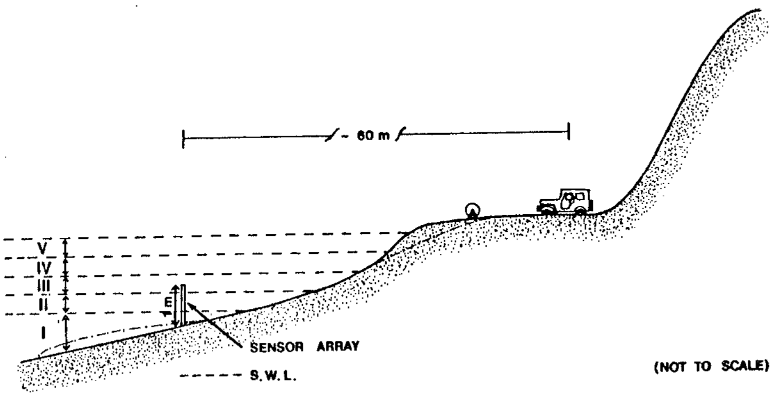


Figure 2. A schematic of the sensor array and its relative position to the time zones described in the text. I-V refer to the approximate still water elevation of each time zone.

ANALYTICAL METHODS

Analog to Digital Conversion

Conversion of the analog data to a digital form was performed subsequent to the field experiments. Each data point of all sensors was twelve-bit resolution at a frequency of 2 kilohertz. Brenninkmeyer (1975) digitized four different key almometer concentrations: 40, 75, 135, and 365 grams-per-liter of sediment at their corresponding elevation in the water column. Each point was sampled at a 5-Hertz interval, thereby showing a time-history of the elevation of a particular sediment concentration. He then Fourier-transformed each concentration's elevation to find its individual spectrum. This method offers information on both the geometry of sand suspension events, and the frequency of particular concentrations of suspension as a function of elevation. A major drawback to this technique is that the mode of digitizing was such that the almometer record was scanned for these key concentrations from the top of the water column to the bottom. If a sediment concentration inversion occurs, the digitizing records only the highest point of this event and indicates a continuous sand fountain.

By contrast, the almometer information for this study was digitized in a different manner. Each discrete elevation above the bottom was recorded with respect to changing sediment concentration, in order that the fluctuations of concentration, not the fluctuations of elevation, could be Fourier-transformed. Although this technique provides little immediate information on the geometry of sand suspension events, it gives an excellent appraisal of the time-history of a discrete elevation. One can, therefore, see the frequency of all sediment concentration as a function of elevation.

A major drawback is inherent in this technique: one must make assumptions as to the location of the dynamic bottom and constantly update these assumptions since the elevations must remain discrete. However, sediment concentration inversion can be found and analyzed.

Time Series Analysis Applied to Experimental Data

The data chosen for Fourier analysis included the wave record and the two current meter records for the five time zones. In addition, 30 elevations above the bottom were selected for the analysis of periodic sediment movement. In all, 2079 points, or 13.86 minutes, of real-time data from each elevation in each time zone were transformed. The Fourier routine used in the analysis was a modification of the FORTRAN program, FILTRAN (Cohn and Robinson, 1975). FILTRAN is based upon the Fast Fourier Transform of the Gentleman and Sande (1966) algorithm as modified from Good (1958) and Cooley and Tukey (1965). This algorithm provides faster and more accurate manipulation of the data arrays and is considered as a significant advancement over the standard Cooly-Tukey techniques.

Digital Filtering and the SFI Technique

Filtering is a process by which a portion of a signal is removed by suppressing amplitudes of certain frequencies. Filtering in the time-domain is defined as convolution (Blackman and Tukey, 1959). In one-dimension this operation can be expressed as:

$$O(x) = \int_{o}^{\infty} I(x-\lambda)S(\lambda)d\lambda \qquad (1)$$

where $I(x)$ is the input function, $S(\lambda)$ is the lagged filter, and $O(x)$ is the filtered output. The Fourier-Transform of the convolution integral is:

$$O(\omega) = I(\omega) \cdot S(\omega) \qquad (2)$$

where $I(\omega)$ is the input function in the frequency-domain, $S(\omega)$ is the filter, and $O(\omega)$ is the filtered output. Filtering in the frequency-domain requires only that the components of the filter be multiplied by those of the input function, whereas filtering in the time-domain is more complicated in that it requires folding, multiplication, shifting and summation (Cohn, 1975).

The actual filtering process, whether convolution in the time-domain or multiplication in the frequency-domain, simply changes the amplitudes of some of the component sinusoids. Digital filtering enhances the interpretation of a particular waveform by supressing the amplitudes of conflicting sinusoids that fall outside the desired frequency range. This process is analogous to the action of an automobile suspension, where the springs and shock absorbers filter out the short-period undulations while passing long-wavelengths bumps and hills without change (Robinson, 1968).

For digital filtering in the frequency-domain, all that is necessary is to compute the one-dimensional Fourier-Transform, delete undesired frequencies (noise) by multiplying by zero, then return to the time-domain through the inverse-transform (Cohn and Robinson, 1975).

Because filtering in the frequency-domain is achieved with much greater speed and efficiency than its time-domain convolution counterpart, a technique utilizing both numerical integration and digital frequency-domain filtering was developed. This method called the *Spectrally Filtered Integration* technique (SFI) (Leonard, 1977), is used to differentiate the true "unit-valued" amount of sediment moved by various process agents at given frequencies.

Simply, given a function f(t) (in this case, grams-per-liter of sediment movement versus time), the total amount of sedimentation over a particular time span or zone can be expressed as:

$$\int_{a}^{b} f(t)dt \qquad (3)$$

which is step (A) in Fig. 3.

Taking Fourier-Transform of this function and deleting the mean value (Fig. 3, B) produces the function $f(\omega)$ or the frequency-domain spectrum of the original amount of grams-per-liter of movement (Fig. 3, C).

By deleting the amplitudes at various frequencies (Fig. 3, D) and substituting zeros in both the real and imaginary coefficients, one in effect places a filter on the data. Figure 3, D, shows a simple band pass filter that is applied to the frequency spectrum.

Next (Fig. 3, E) one applies the inverse-transform to this data and reassesses the effect of the deleted D.C. component while reordering the data matrix and considering the effects of the imaginary components. This operation results in $f'(t)$, or the filtered reconstruction of the original data (Fig. 3, F).

Since the units are maintained as an end-product, the integration:

$$\int_a^b f'(t)dt \qquad (4)$$

gives the amount of transported material at all frequencies except the ones filtered.

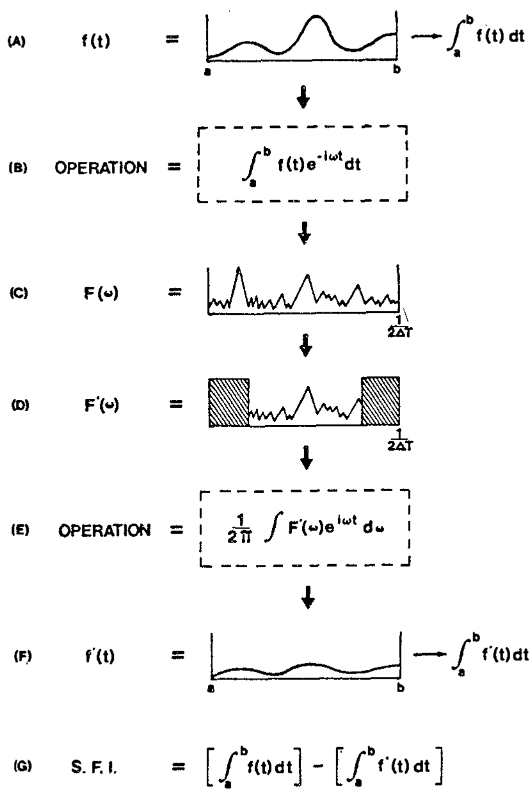
By mere subtraction the residual area of the filtered frequencies is calculated (Fig. 3-G). This is the spectrally filtered integration method. In other words, the contribution of periodic stimuli (i.e., waves, edge waves, and other processes) to the sediment movement can be selectively removed and the resulting sediment concentrations can be calculated.

In this study it was chosen to determine and quantify the amount of sediment moved at low-frequencies (<0.01 Hz. or >100 seconds). The stimulus for this came from Brenninkmeyer (1975) who observed low-frequency movement in his data. The SFI analysis of this data included the application of a bandpass filter. The periodicities greater than 100 seconds were nulled along with the higher-frequency "noise." This "noise" included all frequencies greater than 0.5 Hertz (2 seconds). The variance within this high-frequency band can be attributed to the random variations of air bubbles present in the water column. This effect can be shown through visual observations of the almometer oscilloscope record where bubbles and surface foam exhibit a high-frequency variation. Another cause of high-frequency fluctuations is the vibration of the almometer and the anchoring auger in the presence of waves. We believe the construction of the 0.5 Hertz cutoff will eliminate all but a small portion of the error caused by the presence of air bubbles and vibrations. Therefore, the filtered data should contain only information on sediment movement.

Figure 3. The SFI technique in schematic form (below):

A. The second order integration of the time-domain function F(t).
B. The Fourier Transformation of the function F(t).
C. The transformed function F(t) to F(ω).
D. The frequency-domain filter applied to the function F(ω).
E. The inverse-transform of the function F(ω).
F. The resultant time-domain function F'(t) after frequency-domain filtering and the second-order integration of this function F'(t).
G. The determination of the residual amount of time-domain data, represented by the contribution of the filtered frequencies.

Note 1/2 T = the Nyquist frequency.
This diagram implies continuous functions; however, the analyses for this study were performed with discrete functions. Implicitely, the complex conjugant of the Fourier transform must be included in the SFI technique.



RESULTS

In order to determine sediment concentration as a function of elevation, the position of the bottom (datum) must be monitored. Bottom is defined, operationally, as that elevation which attained a time-averaged concentration of greater than 500 grams per liter. Bottom changes not only occur dynamically at high-frequencies, but also may exhibit an established trend. Figure 4 shows the changing absolute position of the bottom as a function of time zones during the increasing tide. At first glance, a disproportionate amount of burial appears in the onshore/offshore almometer at Zone IV. This is interpreted as a sand bar created from the eroding berm.

By performing the Fourier transformation of the autocorrelation function of the time-domain records for the various changing sediment concentrations, information on the frequency or its reciprocal periodicity can be determined at elevations of high concentration variance throughout each time zone. A precise breakdown of contributions appears in Appendix I, A-E, which shows percentage contribution to the total variances (power) of selected bandwidths. The bandwidths chosen include: greater than 120 seconds, 120 to 60 seconds, 60 to 30 seconds, 30 to 15 seconds, 15 to 12 seconds, 12 to 10 seconds, 10 to 8 seconds, 8 to 6 seconds, and 6 to 4 seconds.

The bandwidth of greater than 120 seconds indicates the long periodicities of sediment movement. This change can perhaps be characterized as transient suspension events occurring within the sampling period. Some of these may be due to shelf waves (Munk, 1962). This band may also indicate the long term change of data string (i.e., fluctuations in bottom topography).

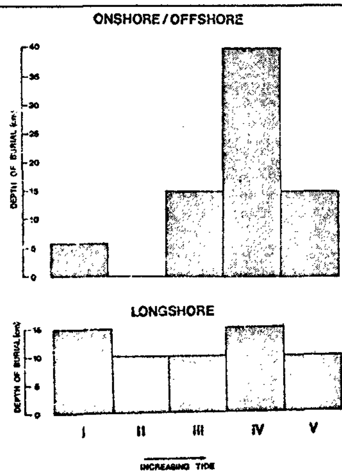


Figure 4. Depth of burial of the bottom of the almometer in both the longshore and onshore/offshore for each zone.

The bandwidth between 60 and 120 seconds represents movement or changes that may be caused by surf beat (Munk, 1949; Tucker, 1950). Surf beat is the systematic low-frequency fluctuation in wave height created when two sets of small waves arrive simultaneously from two different storm sources. The constructive and destructive interference of these wave trains gives the impression of rhythmically varying wave heights on the beach.

The 60-to-30 second bandwidth input during storm conditions is difficult to explain. The processes that contribute to this moderately low-frequency may include the following: (1) The shore face is reflecting surging water. (2) The variations in the components of both standing and progressive edge waves (Bowen and Inman, 1969; and Huntley and Bowen, 1973, 1975). Huntley and Bowen (1973, 1975) measured edge waves in the field and found them to be subharmonic of the incoming waves. In the case of storm conditions, the various wave trains arriving may cause variations in these subharmonic edge waves. (3) Finally, the input process to this bandwidth may include the phase difference or time lag between the incoming bore (swash) and the returning backwash. Emery and Foster (1948) have observed this phenomenon, and suggest that it may be attributed to the interaction with the ground water table. Waddell (1976) also sees this relationship.

The possible causes of the remaining moderate-frequencies which are also the middle-periods of 30 to 4 seconds, may include combinations of the previously mentioned process with the addition of the major swell, breaker, and wave periods. The 10-to-8 and 8-to-6 second bands indicate the periods of the major wave and water velocity variance as indicated by their respective spectra.

Zonal Periodicity

Zone 1. The sediment power spectra for Time Zone 1 show similar characteristics, and generally appear in one form. Appendix I-A indicates a breakdown of percentage contribution of the total power to the various bandwidths. Generally, in the onshore/offshore direction, a majority of the variance of sediment movement occurs within the large band between 60 and 120 seconds. Just (0-5 cm) above the bottom, a major portion of the movements occur every 60 to 30 seconds with the highest peak at 40 seconds. This peak represents a contribution of slightly over 6 percent. As the elevation increases, the frequency of movement also increases with the preponderance of power residing in the 30-to-15 second bandwidth. At 10 centimeters and above, the 15-to-12 second band shows some activity, but not nearly as much as the 30-to-15 second band. Also, from 5 to 25 centimeters (above the bottom), approximately 30 percent of the remaining variances occur between 10 and 4 seconds. Seemingly, the major factor contributing to sand movement in this zone is the interaction of wave surges, which are exhibited as a subharmonic of the wave period.

In the longshore direction, the same trend can be seen with a majority of the power residing in the 30-to-15-second bandwidth. The bottom sediment here also moves at a lower-frequency than the material in the water column.

Little information could have been gained from the wave and current records because of the noisy spectra created by instruments' poor response in alternating wet and dry conditions.

Zone II. During Time Zone II, the power spectra (Appendix I-B) reveal a general trend toward low periodic sediment movement. In the onshore/offshore direction, the strongest peaks are all longer than 120 seconds. Above 1 minute, approximately 30 percent of all the variances (power) for all the onshore/offshore elevations can be explained (Appendix I-B). Approximately 40 percent of the remaining variances lie within a band between 15 and 60 seconds, indicating some long-period water interaction creating sediment suspension events. Very little contribution came from the normal wave period (10 to 8 seconds).

The same trend exists for the longshore direction, except that it is more magnified. Approximately 50 percent of the sediment movement is explained at a frequency of greater than 120 seconds. No major contributions occur at a period of less than 15 seconds.

In contrast, the current and wave instruments show their strongest peaks at a band between 8 and 4 seconds. Therefore, the contribution to sediment movement by the normal wave and current activity in this zone is minimal.

Zone III. The spectra of Time Zone III (Appendix I-C) indicate peculiar properties. In the onshore/offshore direction at the 5 centimeter level, more than half the power is located in the greater than 120-second band. This is due to the long-term burial of the lower sensors. The resulting bands at this (5 cm) elevation are virtually undifferentiated. At the 15 centimeter elevation, however, the greatest contribution lies between 30 and 12 seconds, indicating that at this height, movement is still controlled by an interaction of the translational bore with the seaward returning water. At 25 centimeters, the greatest power is in the greater than 120-second band, but a strong peak is present in the 30-to-15 second interval.

In the longshore direction almost 80 percent of the contribution exists in the greater than 120-second band.

Zone IV. In Time Zone IV, the power spectra appear to take on diverse forms. In the onshore/offshore direction less contribution (Appendix I-D) comes from the greater than 120-second band than for the previous time zones. Generally, in upper elevations, more power is concentrated between 8 and 4 seconds, indicating the frequencies of waves and currents. Strong peaks do occur, however, in the water interaction band of 30 to 15 seconds. At 5 and 10 centimeters, the greatest contributions lie in the low-frequencies, with major peaks at greater than 120 seconds. Some sediment movement variance is seen in the 30 to 15 second band, as a response of translational water interaction. A small (10.8 percent) peak is found at the 5 centimeter level, showing that near the bottom normal wave activity contributes to sediment movement.

In the longshore direction, the near bottom elevations of ≥ 0 and 5 centimeters show movement occurring at low-frequencies. A major break exists at 10 centimeters where the frequency of the major contributors occurs in the 8 to 4 second band. Only 5 centimeters above this level however, at 20 centimeters, sediment movement periodicities increased to between 60 and 5 seconds. At present no explanation can be given for this 10 centimeter anomaly.

Zone V. In the onshore/offshore direction of Time Zone V, the sediment power spectra (Appendix I-E) indicate generally low-frequency movement. At all elevations, approximately 20 percent of the contribution can be placed in the wave and current bandwidth. The water interaction band of 30 to 15 seconds shows greater than 10 percent contribution at elevations of 10 and 15 centimeters.

The longshore direction spectrum at 5 centimeters indicates approximately 75 percent of the contribution occurring above 30 seconds. The current and wave sensors spectra indicate that the strongest peaks occur between 10 and 4 seconds.

Amount of Sediment Moved

The integration of the time-domain records of sediment movement provides a reasonable estimate of the total sediment moved during each time zone. Figure 5 illustrates the total amount of sediment moved in the onshore/offshore direction as a function of near bottom elevation for each time zone.

In Time Zone I, the expected pattern of decreasing sediment movement with increasing elevation is present. Total movement on the bottom is over 350 kilograms per 13 minutes of "almometer-sensed" water volume (Table 1), whereas at an elevation of 25 centimeters, only 75 kilograms of sediment move. The decrease from bottom to top is linear, except at 15 centimeters, where the slope steepens, and movement decreases at a lower rate.

Zone II indicates the same trend in movement, although less movement is present at the bottom and at 5 centimeters than in Time Zone I. Interestingly, greater amounts of sediment were moved at the 10 centimeter level in Time Zone II than in Time Zone I, perhaps due to the presence of minor sediment concentration inversions at this level.

Zone III shows a peculiar divergence from the previous zones. At an elevation of 25 centimeters, approximately 250 kilograms of material moved, whereas below this level at 15 centimeters, only 170 kilograms moved. This phenomenon probably occurs because of sediment concentration inversions. Generally, more material was moved in Zone III than in Zones I and II.

In Time Zone IV, the total amount of movement decreases significantly and follows a pattern of decreasing quantity with increasing elevation.

Zone V also indicates less movement than the previous zones, except for a concentration inversion at 10 centimeters. This inversion may be the response of the oceanward flow of water present in a rip-current observed at this time by the array.

In the previous section, it was stated that the low-frequency, long period bands normally contained the most power contribution. It should be mentioned, however, that phase relationships play an extremely important role in determining what the percentage contributions really mean in terms of total material moved. If, for example, a band contains two large power spikes, the percentage contribution would also be large, but if these two peaks were 180 degrees out of phase, the resulting movement would be zero. This reasoning led to the development of the SFI method.

Utilizing the SFI technique, Table 2 presents a summary of the "time-averaged" quantity of sediment moved in each of the respective time zones. The "O" column represents the integrated total quantity (in grams corrected to one liter of water) seen by a photocell in respect to the volume of its particular field of "vision" (Table 1). In other words, these numbers are the grams of sediment per liter of water, one would statistically expect to find in any given second.

TABLE 2

ZONE I	Elevation (cm)	O	F	O-F	F/O
Onshore-Offshore	25	.497	.107	0.39	0.22
	15	.621	.128	0.49	0.21
	10	1.29	.216	1.07	0.17
	5	3.70	.280	3.42	0.08
	≥0	6.36	.310	6.05	0.05
Longshore	20	.200	.038	0.16	0.19
	10	.302	.057	0.24	0.19
	5	.744	.146	0.60	0.20
ZONE II					
	10	1.71	.274	1.44	0.16
Onshore-Offshore	5	2.31	.536	1.77	0.23
	≥0	4.20	.626	3.57	0.15
Longshore	5	.938	.338	0.60	0.36
	≥0	7.05	.311	6.74	0.04
ZONE III					
Onshore-Offshore	25	2.23	.652	1.58	0.29
	15	1.79	.431	1.36	0.24
	5	5.29	.981	4.31	0.18
Longshore	5	1.91	.608	1.30	0.32
ZONE IV					
Onshore-Offshore	20	.315	.146	0.17	0.46
	15	.643	.251	0.39	0.39
	10	1.61	.459	1.15	0.28
	5	1.91	.522	1.39	0.27
Longshore	20	.147	.039	0.11	0.26
	10	.054	.022	0.03	0.41
	5	.595	.182	0.41	0.31
	≥0	4.28	.245	4.04	0.06
ZONE V					
Onshore-Offshore	25	.484	.269	0.22	0.56
	20	.757	.360	0.40	0.48
	15	.390	.205	0.18	0.53
	10	.828	.382	0.45	0.46
	5	1.51	.610	0.90	0.40
Longshore	5	2.25	.385	1.86	0.17

Table 2. Various parameters derived from the SFI technique

A. O equals the "time-averaged" total amount of sediment moved expressed in grams-per-liter per second.

B. F equals the "time-averaged" quantity of material moved at a periodicity greater than 100 seconds.

C. O-F equals the "time-averaged" quantity of sediment moved at periodicities between 2 and 100 seconds.

D. The ratio of F to O.

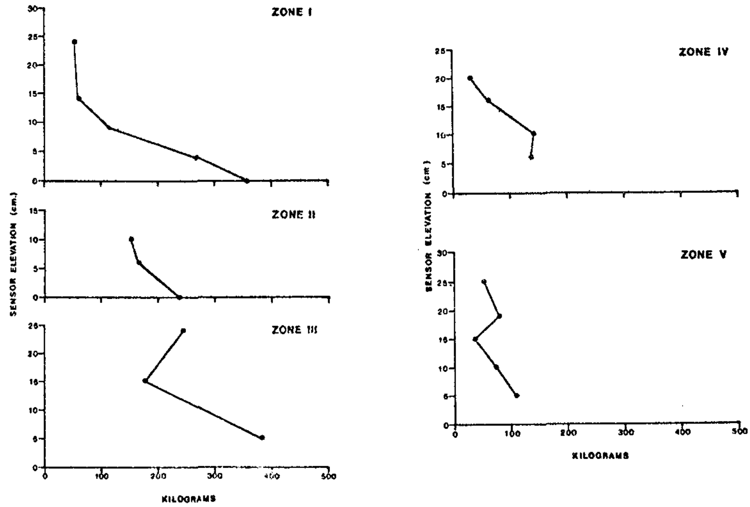


Figure 5. Corrected total amount of sediment movement in the onshore/offshore direction as a function of elevation for each zone.

The data taken from elevations in excess of 10 cm above the bed are in reasonable agreement with values of surf-zone sediment suspension measurements reported by other workers (Komar, 1978, Table 1); utilizing more direct measurement techniques. Those values include .13 g/l at Torrey Pines, California (Thornton, 1977), 0.26 g/l in spilling breakers at Price Inlet, South Carolina (Kana, 1976), 0.39 g/l at Nags Head, North Carolina (Fairchild, 1973), 0.53 g/l at Ventnor, New Jersey (Fairchild, 1973), 0.68 g/l at Pacific Beach, California (Watts, 1953) and 1.09 g/l at Price Inlet in plunging breakers (Kana, 1976).

Below 10 cm, however, the values of sediment concentration increase by several orders of magnitude. This is not surprising, since our data were obtained close to the bed in storm conditions. The "F" value is the amount of sediment moved at a periodicity greater than 100 seconds. Various other derived parameters contained in these tables are explained in the figure captions.

Low Period Contribution to Sediment Movement

Figure 6 illustrates the relationship between the percentage-ratio of the material moved at a periodicity greater than 100 seconds to the total amount of material moved. It can be seen that for the onshore/offshore direction for Zone I, the high-frequency contribution decreases with increasing elevation. This relationship is expected because sediment movement in the higher elevations should be less common than in the lower. In the longshore direction, the low frequency contribution seems to be undifferentiated as a function of depth.

Onshore/offshore sediment movement in Time Zone II indicates high- to mid-frequency motion on the bottom, with increasingly low-frequency contribution to an elevation of 5 centimeters. This trend then reverses, and the contribution of lower-frequency decreases to an elevation of 10 centimeters. The longshore direction shows that low-frequency increases with increasing elevation.

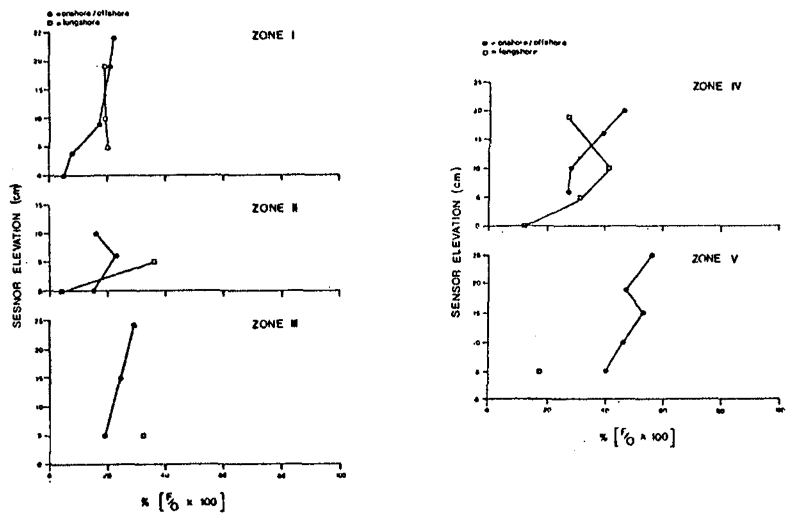


Figure 6. The ratio between the sediment moved at periodicities greater than 100 seconds (F) and the total sediment moved (O) for the five zones, as a function of elevation (in cm), in both the onshore/offshore and longshore directions. Note: Dark circles indicate onshore/offshore.

Zone III (onshore/offshore) also shows the expected relationship with 20 percentof sediment movement accounted for by the greater than 100-second periods at 5 centimeters above the bottom. This figure then increases to 30 percent at 25 centimeters.

As the water deepens, the low-frequency contributions tend to become more important. In Time Zone IV, the onshore/offshore direction reflects this expected relationship, but the total curve shifts to the right, indicating a generally more significant contribution by the low-frequencies. An anomalous trend occurs, however. In the longshore direction of Zone IV, at above the 10 centimeter elevation, the lower-frequencies become approximately a factor of 2 less significant. This reduction may be explained by sediment shedding off a sand bar, which buried the onshore/offshore sensors, but not those of the longshore.

In Zone V, the curve shifts further to the right, indicating a greater lower-frequency contribution in deeper water. A small shift to the left (higher-frequency contribution) can be seen at the 20 centimeter elevation, and is probably due to sediment "jetting" from the higher bar elevation bounding the throat of a rip current.

In contrasting the five time zones for the onshore/offshore direction with the contribution of low-frequency movement, Figure 7 illustrates the relationship between the total sediment moved (expressed in decibels) and the ratio of sediment moved at low-frequencies (expressed in decibels). The decibel scale [10 log (ratio)] was chosen since it compacts both data sets to the same scales of the same order of magnitude. For the total sediment movement (TdB), the ratio was determined by contrasting the total amount moved in kilograms to a nominal movement of 1 kilogram, hence eliminating division by zero.

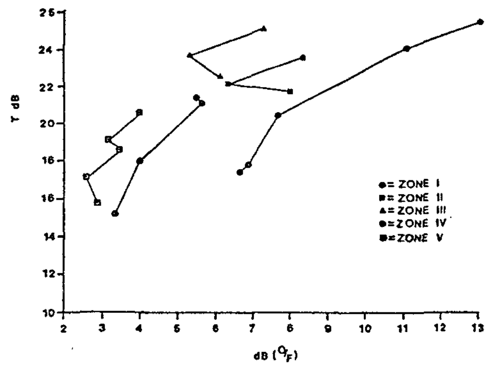


Figure 7. Relationship between the ratio of the total sediment moved (TdB) and the ratio of the total amount moved at low frequencies (dB O/F) for the onshore/offshore direction.

The zonal grouping shown indicates that, during storm conditions, high-frequency sediment movement decreases as the tide rises. This diagram also indicates that as time progresses, this relationship is virtually constant, i.e., it shows little if any differentiation due to the traditional dynamic zones.

CONCLUSIONS

Some general impressions can be extracted from the analysis of data concerning the nature and periodicity of sediment movement in the nearshore zone during storm conditions. A summary of the more salient conclusions follow:

(1) Standard time series analysis is insensitive to the study of quantitative periodic sediment transport in the nearshore zone. A technique has therefore been developed (the SFI method) which will isolate certain sediment movement frequencies caused by explained and inferred stimuli; wave period, edge waves, surf beat, shelf waves and interference of uprush and backwash. This method allows an analysis of the absolute amount of material moved by each of these inputs.

(2) During severe storm conditions sediment suspension and resuspension is more prevalent through the five time zones than during times

of milder wave conditions.

(3) The power spectra of sediment movement throughout various elevations, various zones and different directions exhibit diverse forms. Typically, however, during severe storm conditions, throughout all time zones, the power contained in the lower-frequencies is not as strong as that during normal (non-storm) conditions. If one were to characterize the most common process based upon the spectra, it would be the frequency of the water collision and interaction of two opposing velocity distributions. This is substantiated by current meter measurements. However, this relatively higher-frequency movement decreases as water deepens and lower frequency contributions tend to become more important to sediment transport. Nevertheless, contrasted to non-storm conditions sediment movement during storms is at a much higher-frequency.

Because these experiments represent only conditions which occurred during one storm event, much more data of this type must be acquired in order to characterize the processes interacting with the dynamic beach environment. This study is, therefore, more of a starting point than an end in itself.

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APPENDIX I

(SECTION A-E)

Percent Contribution of Total Sediment Variance (Power) from the Spectra for Zones I-V at Selected Bandwidths

APPENDIX 1-A
Zone I

ELEVATION	Bandwidth in Seconds >120	120-60	60-30	30-15	15-12	12-10	10-8	8-6	6-4
Onshore/Offshore									
25 cm	4.4	3.8	9.3	21.3	12.7	6.7	10.1	10.7	13.5
15 cm	5.1	5.1	8.5	23.3	12.3	5.7	8.9	11.1	13.7
10 cm	6.9	5.4	7.9	18.6	16.7	7.6	10.9	10.7	9.7
5 cm	7.1	8.5	11.2	18.2	8.7	7.3	12.1	9.9	9.4
≥0 cm	4.3	11.8	20.2	16.3	8.8	7.4	8.2	7.3	9.9
Longshore									
20 cm	4.7	5.3	10.0	24.0	12.9	5.3	11.9	10.6	11.0
10 cm	15.1	4.7	12.7	25.5	11.4	6.2	11.1	8.6	11.0
5 cm	11.1	5.3	18.1	23.6	12.2	4.6	8.8	6.8	7.0

APPENDIX 1-B
Zone II

ELEVATION	Bandwidth in Seconds >120	120-60	60-30	30-15	15-12	12-10	10-8	8-6	6-4
Onshore/Offshore									
10 cm	15.2	14.0	18.3	18.7	7.6	4.2	4.3	6.7	2.9
5 cm	22.0	13.9	19.2	19.1	6.3	2.6	3.3	5.6	5.1
≥0 cm	21.0	16.0	19.1	17.1	5.7	2.1	4.2	6.0	5.1
Longshore									
5 cm	48.6	16.5	11.3	13.5	2.7	1.8	2.6	1.8	2.1
≥0 cm	50.9	11.1	8.0	11.9	1.8	3.1	2.9	2.6	3.7

APPENDIX 1-C
Zone III

ELEVATION	>120	120-60	60-30	30-15	15-12	12-10	10-8	8-6	6-4
	Bandwidth in Seconds								
Onshore/Offshore									
25 cm	47.9	8.4	6.7	11.3	6.8	3.5	4.3	4.4	4.1
15 cm	23.2	12.0	7.3	14.2	11.6	6.4	8.1	8.6	5.3
5 cm	59.1	6.2	2.3	7.3	6.6	3.4	3.6	4.2	4.0
Longshore									
5 cm	79.7	4.8	3.7	4.7	1.8	0.7	1.0	1.7	1.0

APPENDIX 1-D
Zone IV

ELEVATION	>120	120-60	60-30	30-15	15-12	12-10	10-8	8-6	6-4
	Bandwidth in Seconds								
Onshore/Offshore									
20 cm	7.7	6.3	5.3	17.2	7.2	8.8	8.0	18.8	14.0
15 cm	10.0	5.7	11.2	15.2	13.3	6.0	5.7	16.4	10.4
10 cm	23.0	18.9	13.6	12.7	5.3	3.2	4.5	8.9	5.3
5 cm	21.9	12.9	15.5	11.3	7.3	4.4	5.5	10.8	5.4
Longshore									
20 cm	12.9	11.6	16.6	10.4	6.1	6.1	9.0	9.1	9.6
10 cm	8.4	11.6	2.9	13.6	9.8	5.0	11.8	17.1	10.6
5 cm	42.8	12.6	11.6	9.6	2.6	3.0	3.6	7.8	4.0
≥0 cm	53.4	10.1	11.4	7.9	1.7	1.9	1.9	2.9	2.3

APPENDIX 1-E
Zone V

ELEVATION	>120	120-60	60-30	30-15	15-12	12-10	10-8	8-6	6-4
	Bandwidth in Seconds								
Onshore/Offshore									
25 cm	33.7	18.4	11.4	8.3	5.3	1.9	3.9	5.8	7.1
20 cm	41.5	7.7	8.1	8.2	4.2	2.4	4.9	8.4	9.2
15 cm	19.9	11.9	8.4	14.2	9.5	1.7	7.6	10.4	11.5
10 cm	26.1	7.3	10.8	13.7	8.0	2.0	5.4	11.0	9.8
5 cm	39.8	5.6	9.3	8.6	6.1	2.9	5.5	10.8	7.2
Longshore									
5 cm	56.1	8.9	9.5	9.9	3.7	2.1	3.9	2.7	2.0