

## CHAPTER 71

### NEARSHORE SUSPENDED SEDIMENT LOAD DURING STORM AND POST-STORM CONDITIONS

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#### ABSTRACT

As part of the DUCK-X experiment at the CERC field research facility at Duck, North Carolina in September, 1978, suspended sediment measurements were made along the CERC pier. *In situ* bulk water samples were collected during a moderate northeast storm and two days later during post-storm wave conditions. Concentrations varied from approximately 0.01 g/l to over 10.0 g/l. Vertical arrays of suspended sediment samples indicated that concentration decreases rapidly up to two meters above the bed, then remains relatively constant, reflecting the nature of the suspension; intermittent suspension of sand near the bed, and continuous washload higher in the water column. Concentrations were at a maximum during storm conditions when measured values were 3 to 5 times higher than during non-storm conditions. The total load of sediment in a pier cross section during sampling periods in storm and post-storm conditions was calculated from arrays of 49 samples each. With  $H_{1/3}$  exceeding 2.3 m and the surf zone width over 300 m during the storm, the total load of sediment in suspension was approximately 10 times higher than during post-storm conditions ( $H_{1/3} = 1.2$  m and surf zone width approximately 100 m). Estimates of the longshore flux of suspended sediment indicate that as much as 60 times more sediment was transported during storm than during post-storm conditions. Longshore transport of sediment measured from 5 cm above the bed to the surface reached the equivalent of 22,330 m<sup>3</sup>/day. This value corresponds very closely to longshore transport predicted from wave energy flux. During post-storm conditions, on the other hand, transport of suspended sediment accounts for less than one-third of the transport predicted from wave energy flux.

#### INTRODUCTION

This report presents results of a field study of nearshore suspended sediment at Duck, North Carolina completed during the August-September 1978 DUCK-X experiment, sponsored by the Coastal Engineering Research Center. The goal of the DUCK-X experiment was to test the capabilities of the SEASAT-A satellite launched in June, 1978. Therefore, several experiments were conducted simultaneously at the CERC Field Research Facility at Duck to obtain ground truth data on waves, currents, suspended sediment and sand transport.

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Numerous agencies were involved in the month-long experiment, including CERC, NASA, CRREL, NOAA, U.S. Navy and university groups from Johns Hopkins (Applied Physics Laboratory) and University of South Carolina (Department of Geology). Field support included the 600 m long CERC research pier and facilities at Duck, two LARC amphibious craft from Ft. Story, Virginia, the CRAB from Wilmington District, Corps of Engineers, and various aircraft for aerial surveys. Instrumentation included pier based and airborne radar, seven pier-mounted Baylor wave gauges, two wave rider buoys, several current meters, and tide gauges and various recording meteorological instruments.

The primary goals of the suspended sediment study, conducted 10-17 September 1978, included:

1. Measurement of the vertical and horizontal distribution of suspended solids from the surf zone to the end of the CERC research pier.
2. Measurement of the weight percent of organic and inorganic solids in suspension.
3. Estimation of the suspended sediment flux transport rate.
4. Correlation of suspended sediment flux transport rates with the longshore component of wave energy flux.

#### STUDY AREA

The CERC Field Research Facility is located on Currituck Bank approximately 2 km north of Duck and 20 km north of Kitty Hawk, North Carolina (Fig. 1). The facility included an approximately 600 m long concrete pier (Fig. 2) with piles spaced 12 m, extending to the 8 m MLW contour. Height of the pier deck is approximately 6 m above MSL.



Figure 1. Study area two kilometers north of Duck, North Carolina, U.S.A.



Figure 2. Oblique aerial photo of the CERC research pier on September 16, 1978. View looking south.

### Beach Profiles

The typical beach and nearshore profile during the study period along the pier included a steep foredune ridge approximately 5-7 m high and a narrow berm with relatively steep beachface slope ( $m = 0.10$ ). At the toe of the beachface was a 30 to 50 cm step dropping abruptly into a runnel 1 to 1.5 m below MSL. Seaward of the runnel was a ridge which sloped gently seaward. Along the beach at Duck, the innermost ridge was broken by numerous rip channels which directed the return flow of water from the runnel. Seaward of the inner ridge, mean nearshore slope was gentler ( $m = 0.015$ ) with local variations due to the presence of low amplitude outer ridges.

### Sediments

Beach sediments at Duck consist of a range of sizes. Coarse sand with a mean diameter of 0.75 mm and fine sand with a mean diameter of 0.17 mm predominates. A third mode of coarser sediments, including pea-gravel (grain size up to 15 mm diameter), is found as isolated lenses generally along the lower beachface or step. The exact proportion of sediment grain sizes was not determined. In general, the berm is a mixture of the two dominant grain size modes: the step is coarsest, the runnel ranges from pea-gravel to fine sand, and the ridge is well-sorted, fine sand.

### Winds

Winds during the study are summarized in Figure 3 and the wind rose of Figure 4. The dominant wind was from the NNE occurring 13-14 September during the storm. A secondary component during pre- and post-storm periods occurred with winds from the SE. Maximum sustained wind velocity was 12.7 m/s (25 knots) occurring 13 September.

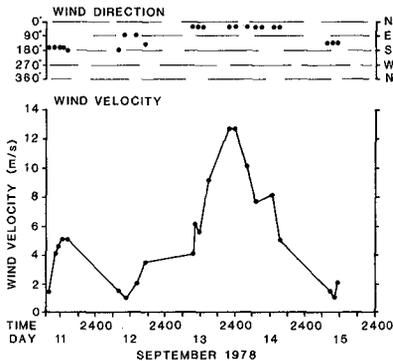


Figure 3. Average wind velocity and direction at the CERC Research Pier, Sept. 11-15, 1978.

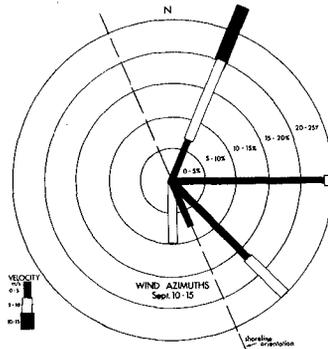


Figure 4. Wind rose for 10-15 September 1978 at the CERC Research Pier.

## Wave Height

The beach at Duck is characterized by moderately high wave energy. During the present study, significant wave heights ranged from 1.0 to 3.5 m, as measured by pier-mounted wave gauges. This range is higher than the yearly average due to the presence of a moderate northeast storm occurring 13 September. Maximum recorded wave height during the study was 6.2 m at the seawardmost Baylor gauge, approximately 400 m offshore (D. Lichy, pers. comm.). Before and after the storm, waves were generally longcrested and smooth in form, characteristic of a swell wave environment. This is reflected in the range of recorded wave periods with shortest periods (6-8 seconds) occurring during the storm and long periods (greater than 10 seconds) during swell conditions. Figure 5 summarizes wave height and wave period as recorded by the innermost Baylor gauge located approximately 100 meters offshore (CERC station 6+20 on pier).

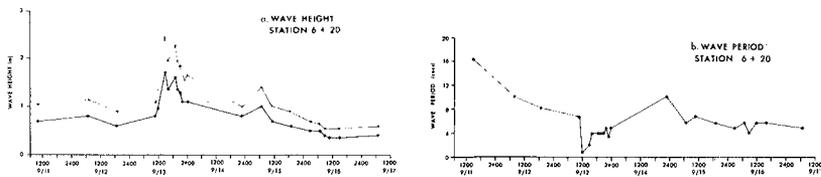


Figure 5. Distribution of wave height (a) and significant wave period (b) for 11-17 September 1978, measured by a pier-mounted Baylor gauge at station 6+20, approximately 100 m from the beach. Bold line in (a) is root mean square wave height; upper line is  $H_{1/3}$ .

## Wave Direction

The distribution of wind velocities and directions caused two sediment transport reversals during the study. From September 10 through 13, waves arrived from the SE, causing sediment transport to the north. During the storm, 13-14 September, waves approaching from the northeast caused a transport reversal to the south. Following the storm, SE swell resumed, and transport was again to the north. Wave direction data was obtained from radar imagery and LEO observations.

## PREVIOUS WORK

Several techniques have been used to measure suspended sediment concentrations in the surf zone. There are three basic methods: 1) pump systems for obtaining a time-integrated sample of water and sediment (Watts, 1953; Fairchild, 1972, 1977; and Coakley et al., 1978); 2) *in situ* collecting traps for obtaining relatively instantaneous bulk water samples (Kana, 1976; Inman, 1977); and 3) indirect measures which relate turbidity to light attenuation, back scatter of light or gamma absorption (Homma et al., 1965; Hattori, 1969; Kennedy and Locher, 1972; and Brenninkmeyer, 1976). There are certain disadvantages to any of these techniques, most important of which is the influence of the sampling apparatus on the flow field, a universal problem in studies

of suspended sediment.

Of the pump samplers, the most detailed results are reported in Fairchild (1977) in an updated version of an earlier paper (Fairchild, 1972). Working from ocean piers at Ventnor, New Jersey and Nags Head, North Carolina (approximately 35 km south of Duck), he collected over 700 time-averaged water samples seaward and landward of the breaker zone, using a tractor-mounted pump sampler. Sampling in waves from 40 to 120 cm high, Fairchild obtained concentration values ranging over 3 orders of magnitude to a maximum of 4.0 parts per thousand ( $\approx$  g/l). The sampler intake varied between 8 and 75 cm above the bed. Despite a great amount of scatter in the data, Fairchild isolated several trends, including: 1) Suspended sediment increases slightly with breaker height; 2) Concentration decreases away from the breakpoint in both the seaward and landward direction; and 3) Concentration decreases with elevation above the bed.

Leonard and Brenninkmeyer (1978), using the almometer developed by Brenninkmeyer (1973), indirectly monitored sediment suspensions during storm conditions at Nauset Beach, Massachusetts, documenting: 1) An increase in the number of suspension bursts from the bed during storms, and 2) A decrease in frequency of sediment movement with elevation and distance seaward from the shoreline. They also observed concentration inversions, which occur due to the shearing of tabular clouds of sediment moving in the upper layers. This produces a reverse gradient of higher concentration overlying a zone of lower concentration.

Utilizing a portable bulk water sampler (Figure 6), Kana collected over 900 suspended sediment samples primarily in the breaker or outer surf zone along South Carolina beaches. His data for waves up to 1.5 m high (Kana, 1977, 1979) indicate that suspended sediment at a point in the surf zone depends primarily on breaker type, distance from the breakpoint and beach slope. Wave height, wave period, and longshore current velocity during moderate swell conditions, have relatively little influence on mean concentration. A portion of Kana's data (summarized in Figure 7) indicates that plunging waves entrain almost an order of magnitude more sediment than spilling breakers. Typical concentration values range over 3 orders of magnitude with maximum values reaching 10.0 g/l at 10 cm above the bed in plunging waves on fine-grained beaches.

#### METHODOLOGY

##### Suspended Sediment Sampling

Of the previously-mentioned studies, the most comparable to the present experiment is Fairchild's since measurements were made from a pier. However, for the DUCK-X study, Kana's (1976) bulk water sampler was modified for use from the pier. Differences between the sampling techniques include:

- 1) The bulk water sampler obtains multiple instantaneous in situ samples in a vertical array compared to single time-averaged pump samples in Fairchild's apparatus.

2) The volume of water collected by the *in situ* sampler is 2 liters per sample compared to 152 liters per sample from the pump sampler.

3) The entire water sample collected with the *in situ* water bottles was retained to allow analysis of the organic- and fine-grained fractions. With the tractor-mounted sampler, only the sand fraction was retained.

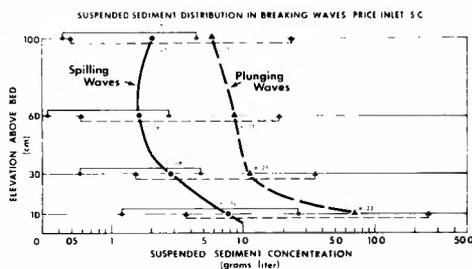


Figure 7. Mean concentration by elevation above bed for approx. 450 suspended sediment samples obtained using the *in situ* bulk water sampler in Fig. 6 (Kana, 1977).

Figure 6. Portable bulkwater sampler used to collect serial arrays of suspended sediment samples in the surf zone (from Kana, 1976).

The bulk water sampler used in the present experiment is designed to collect several closely-spaced simultaneous samples in a vertical array above the bed. It consists of a 2 meter long mounting pole, support brackets, and several 2 liter cast acrylic bottles closed off by hinged doors (Figure 6). A spring loaded trigger similar to that of a Van Dorn type water sampler, which holds each bottle door open, is mounted to the support pole. At the base of the trigger is a footpad which can be pushed up to open the trigger and simultaneously release all bottle doors.

The device has a relatively fast response time of less than one-half second, remaining off the bed until the sampling instant. Tests have shown that the collecting bottles are drawn shut before sediment thrown up by the apparatus reaches each sampling position. The lowermost bottle centered at 10 cm above the bed obtains sediment suspended between 4 and 16 cm off the bottom. The rigid mounting pole allows constant sample positioning with respect to the bed, making it possible to achieve consistency in results.

Minor modifications were made to the bulk water sampler for use from the CERC pier. The apparatus was rigged with rope and counterweights and a trip line for sampling remotely from the deck of the pier. (Note: The sampler is designed to trip as it is lowered onto the sea floor, unlike the standard technique of using a messenger released down a hydrographic wire for a Nisken or Van Dorn sampler).

#### Sampling Procedure from the Pier

A total of 13 pier stations were selected for obtaining vertical arrays of suspended sediment at approximately 1 m intervals above the bed. Each station was located midway between sets of pilings and away from any instrumentation already in place. In the present study, it was not feasible to boom the sampler over the updrift side of the pier, so all sampling had to be done through the center grates located along the pier deck. Approximate distance from sampler to closest piling was 7 m.

The typical array of samples collected were centered 10 cm, 90 cm, 170 cm, 300 cm, 400 cm, 500 cm, and so on above the bed. After each sample array was brought on deck, water volumes were measured and samples transferred into 2 liter Nalgene holding jars for processing in the lab. Thirteen vertical profiles were completed on 13 and 15 September, resulting in 98 usable samples.

#### Filtering and Combustion

Suspended sediment samples were filtered through Millepore filters (0.45 $\mu$  pore diameter) using standard vacuum apparatus and filtering flasks. All samples were rinsed with deionized water to eliminate dissolved salts, then dried for weighing. Suspended sediment concentration was determined as a weight of solids per unit volume of water (g/l) for comparison with other samples.

Approximately 40 samples out of 98 collected were combusted after determination of total concentration in order to calculate the percent organic fraction (assumed to be similar to the percent combustible). The combustion technique involved burning the filter and suspended sediment for 30 minutes at 500°C, then weighing the residual fraction to determine the proportion of noncombustibles and combustibles.

#### Data Contouring and Sediment Load Calculations

Suspended sediment concentrations were plotted for each sample run on a scaled cross-section of the nearshore zone along the pier. Based on previous results, which indicate an exponential decrease in concentration above the bed, a variable contour interval was used to depict the horizontal and vertical distribution of suspended sediment. The contour interval increases with concentration.

Total sediment load under a unit width pier cross-section was calculated by integrating areas between contours and applying a mean concentration to each portion of the cross-section. Contour diagrams were also prepared for the distribution of combustibles.

#### Estimation of Sand Fraction

In order to calculate the proportion of fine-grained material in each sample, the mean concentration of samples devoid of sand-sized particles was determined and assumed to be representative of the weight of sediment continuously in suspension. Particles larger than sand size (0.062 mm) were considered to represent intermittent suspensions origi-

nating from the bed under breaking waves. This procedure was necessary to estimate the effective suspended sediment flux transport rate of coarse bed material.

## RESULTS

### Distribution of Suspended Sediment

Suspended sediment sampling points and corresponding concentration values for 13 September during the northeast storm are plotted on Figure 8. Values ranged over  $3\frac{1}{2}$  orders of magnitude from approximately 0.05 g/l to over 10.0 g/l with highest concentrations in the inner surf zone and near the bed. On 15 September, during post-storm moderate swell conditions, suspended sediment concentrations covered a lower range from 0.01 to over 4.0 g/l. Forty-nine samples were plotted for each date using virtually the same pier stations and sampling position.

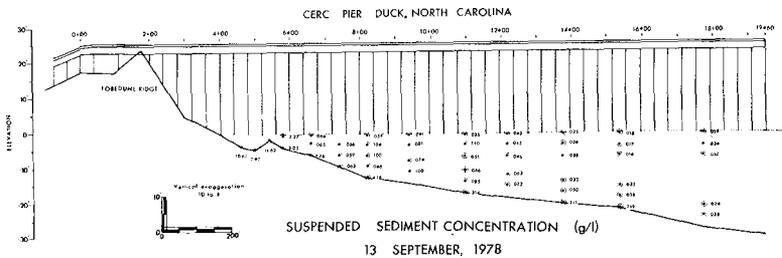


Figure 8. Suspended sediment sample positions and concentration values for 13 September 1979 during storm conditions.

To show the difference in suspended sediment between storm and post-storm surf conditions, mean concentration by elevation above the bed for each sample run is given in Figure 9. Note that, during the storm, suspended sediment concentrations, at a given elevation, were approximately 3 to 5 times higher than during post-storm conditions. As shown in Figure 9, there is an exponential decrease in concentration up to 170 cm above the bed, then concentration remains relatively constant to the surface. This distribution reflects an intermittent type of suspension: Coarse sediment originating from the bed in the lower elevations; and a continuous suspension: Washload of fine-grained sediments in the upper layers. The washload concentration on 13 September was approximately 2 times higher than the washload during post-storm conditions.

The horizontal and vertical distributions of suspended sediment for 13 and 15 September are given in the contoured pier cross-sections of Figure 10. Highest concentrations are found on the inner ridge and wash zone (lower beachface) and near the bed. On both sampling days, concentration decreased seaward from the inner ridge and with elevation above the bed.

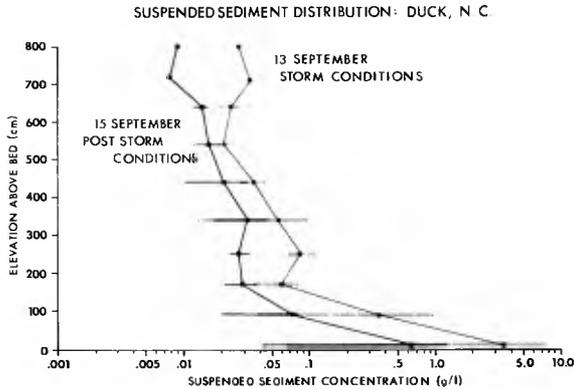


Figure 9. Mean suspended concentration vs. elevation above the bed for storm vs. calm conditions, 13 and 15 Sept., 1978, respectively. Note concentrations were three to five times higher, on average, during the storm.

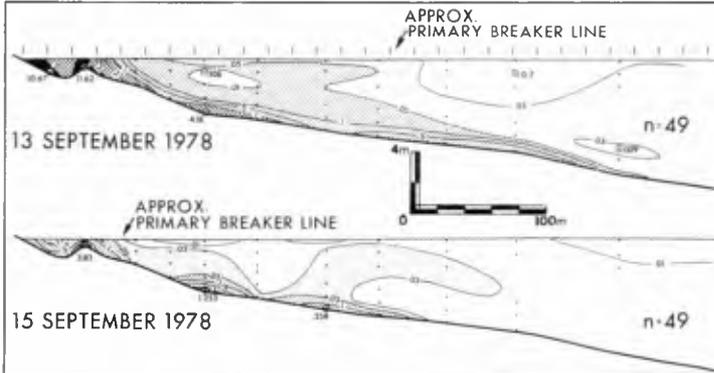


Figure 10. Suspended sediment contour diagrams along the CERC pier on 13 Sept. (upper) and 15 Sept. (lower) 1978. Total load of sediment in suspension was approximately ten times higher during storm conditions on 13 Sept. than during non-storm conditions on 15 Sept.

The primary difference between sample runs was, of course, the height of the waves and width of the surf zone. Figures 11 and 12 offer a comparison of wave conditions on the 13th and 15th. Significant wave heights during each sample run calculated from  $H_{rms}$  measured by the inshore Baylor gauge were 3.5 m on 13 September and 1.2 m on 15 September. As indicated on Figure 10, the seawardmost primary breakers were approximately 3 times farther offshore during the storm. Width of the surf zone was over 300 m on the 13th compared to less than 100 m on the 15th.



Figure 11. Wave conditions at approximately 1600, 13 Sept., 1978 at the CERC pier, Duck, N. C. View looking east.  $H_{1/3}$  was approximately 3.5 m at the seaward end of the pier and 1.8 m in the inner surf zone.



Figure 12. Wave conditions at approximately 1430, 15 Sept., 1978. View looking north from the CERC research pier.

#### Percent Combustibles

The weight percent of combustibles in each sample was plotted on a pier cross-section and contoured as shown in Figure 13. In general, the proportion of combustibles was very low (less than 5%) with a slight increase in the seaward direction and vertically in the water column. This correlates well with the concentration data indicating the expected trend of increasing percentage of combustibles with decreasing total suspended solids. As indicated on the contour diagrams, the overall combustible fraction was slightly higher on the 15th during post-storm conditions. The percent combustibles ranged from less than 1% in the inner surf zone to a high of 15% at a seaward mid-depth station.

#### Suspended Load per Unit Width Cross-Section

Using the pier cross-section for reference frame, the total load of suspended solids per unit width ( $S$ ) was calculated for each sample run by:

$$S = \rho \sum_{j=1}^m \int_{i=1}^n a_{ij} C_{ij} \quad (1)$$

where  $\rho$  = sediment density  
 m = number of subsections normal to beach  
 l = representative distance normal to beach  
 n = numbers of samples over the depth  
 a = the portion of the depth over which C was made  
 C = concentration in subsection ij.

The total suspended load per meter width was 657.4 kg on 13 September and 118.5 kg on 15 September. Of these totals, an estimated 84.1 kg and 67.0 kg was washload (fine-grained sediment in continuous suspension) on the 13th and 15th, respectively (based on reference washload concentration of 0.03 and 0.022 g/l). Thus, the effective load of coarse-grained suspended sediment ( $S_e$ ) was 573.3 kg during the storm and 51.5 kg two days later, an order of magnitude difference.

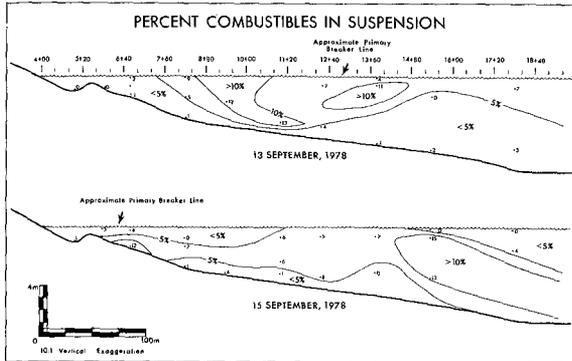


Figure 13. Distribution of combustible fraction in suspended sediment samples. In general, percent combustibles increases with distance from shore and elevation above the bed in contrast to a corresponding decrease in concentration.

#### ESTIMATION OF TRANSPORT RATES

Any estimation of suspended sediment transport rates in the longshore direction during the DUCK-X experiment must be an approximation, since the velocity field under the pier was not measured. However, to better appreciate the relative magnitude of storm vs. post-storm transport, two methods for estimating transport were performed. One was based on the suspended sediment load and an empirically determined longshore current velocity; the other on wave energy flux.

#### Suspended Sediment Flux Transport Rates

The total effective longshore transport rate ( $Q_s$ ) of suspended sediment moving under the CERC pier during each sample run was estimated according to:

$$Q_s = 8.64 \times 10^4 S_e V \quad (2)$$

where  $Se$  is the total effective sediment load,  $V$  is mean longshore current velocity, and the coefficient is a factor to convert an instantaneous transport rate to a daily rate giving  $Q_s$  in  $m^3/day$ .

Longshore current velocity,  $V$ , was calculated using the modified Longuet-Higgins (1970) equation as given by C.E.R.C. (1973, p. 4-48):

$$V = 20.7 m (gH_b)^{1/2} \sin 2\alpha_b \quad (3)$$

where  $m$  is slope,  $H_b$  is breaker height,  $\alpha_b$  is the angle between breaker crest and shoreline,  $g$  is acceleration of gravity, and the coefficient is empirically determined using english units for all variables. The predicted longshore current speed in ft/s was then converted to m/s. Variables  $H_b$  and  $\alpha_b$  were determined from the innermost Baylor gauge and pier-mounted radar imagery, respectively. The root mean square wave heights given by the gauges were converted to significant wave height ( $H_{1/3}$ ) for use in the equation by:

$$H_{1/3} = 1.416 H_{rms} \quad (4)$$

which is based on the Rayleigh distribution function (see CERC, 1973, p. 3-5 to 3-10).

Based on the results summarized in Table 1, average velocities of 0.74 m/s and 0.15 m/s were used in equation (3) for 13 September and 15 September, respectively. Then solving equation (2), the effective transport rate,  $Q_s$ , was calculated to be approximately 22,300  $m^3/day$  on the 13th and 383  $m^3/day$  on the 15th. Thus, the effective transport rate of sand through the pier cross-section was as much as 60 times greater during the storm than on September 15.

Table 1. Calculation of Mean Longshore Current Velocity ( $V$ ) given in Equation (3).

Date	Time	$H_{1/3}$ (ft)	$\alpha_b$	$V(ft/s)$	$V(m/s)$
13 Sept	1200	4.5	2	0.26	0.08
	1400	8.1	20	3.21	0.98
	1600	6.5	28	3.71	1.13
	1900	7.5	21	3.21	0.98
	2000	6.5	14	2.10	0.64
	2200	6.0	14	2.02	0.62
15 Sept	1300	3.1	5	0.54	0.16
	1700	2.7	5	0.50	0.15

Note:  $m = 0.015$ ;  $g = 32.2 \text{ ft/s}^2$

#### Wave Energy Flux Transport Rates

It can be shown that daily longshore transport rate ( $Q$ ) is related to the longshore component of wave energy flux by (metric equivalent of C.E.R.C., 1973, equation 4-40):

$$Q = 3.51 \times 10^{-7} P_{1s}, \quad (5)$$

where  $P_{1s}$  is an empirically determined factor of the longshore component of wave energy flux in ergs/m.s.  $Q$  is given in  $m^3/day$ .  $P_{1s}$  is given by the metric equivalent of CERC (1973) equation 4-35:

$$P_{1s} = 2.84 \times 10^{10} H_b^{5/2} \sin 2\alpha_b \quad (6)$$

where  $H_b$  is in meters.

Using recorded wave measurements for  $H_b$  and determining  $\alpha_b$  graphically from radar imagery, values  $P_{1s}$  during each suspended sediment sampling period were calculated. On 13 September,  $P_{1s}$  averaged  $6.89 \times 10^{10}$  ergs/m.s; whereas, on 15 September  $P_{1s}$  was an order of magnitude less, averaging  $3.54 \times 10^9$  ergs/m.s. The corresponding longshore transport rates, based on equation (5), were 23,400  $m^3/day$  and 1,250  $m^3/day$ , respectively. The transport rate during the storm is in surprisingly close agreement with  $Q_s$  calculated from suspended sediment flux (Table 2).

Table 2. Longshore Transport Rates from Suspended Sediment and Wave Energy Flux.

Date	$H_{1/3}$ (avg.) (m)	$P_{1s}$ (ergs/m.s)	$Q$ (from $P_{1s}$ ) ( $m^3/day$ )	$Q_s$ (fm. sus. sed) ( $m^3/day$ )	Dir.
13 Sept.	1.99	$6.89 \times 10^{10}$	23,400	22,300	S
15 Sept.	.88	$3.54 \times 10^9$	1,250	385	N

#### DISCUSSION

Perhaps the most interesting aspect of the suspended sediment data is the comparison of suspended load during two greatly different surf conditions. In this case, scheduling of the sample runs was fortuitous. This may have been the first direct documentation of nearshore suspended sediment concentration during storm conditions.<sup>1</sup> Therefore, it is worthwhile to examine possible sources of error in these data.

#### Sources of Error

As with any sampling device used in the surf zone, there is always some effect of the apparatus on the flow field. This is undoubtedly true of the apparatus used in the present study. More recently, Inman and Hanes (1980) have used a portable bulk water sampler which "cores" the water column and may have less effect on the flow field than devices with hinged doors. Whatever effect the apparatus used in the present experiment has on the surf zone flow field is probably less important than the consistency of sampling technique. Departures of the apparatus from the vertical plane during sampling may possibly pro-

<sup>1</sup>Leonard and Brenninkmeyer (1978) used the alcometer to obtain indirect measurements of suspended sediment in the surf zone at Nauset Beach, Massachusetts during a storm. Kana (1977) obtained single vertical arrays of direct samples during minor storm conditions ( $H_{1/3} = 1.5$  m) on South Carolina beaches.

duce more anomalous values than any resulting from triggering and closure of the device. Given the wide range of concentrations occurring under breaking waves, it is extremely difficult to evaluate the performance of any sampler under prototype conditions. The extensive use of the present apparatus on South Carolina beaches (Kana, 1977, 1979) indicates that the sampler produces relatively consistent results and responds immediately upon contact with the bed minimizing the influence of sampler-induced suspensions. Furthermore, the concentration values obtained during the DUCK-X experiment are not abnormally high, suggesting the sampler did not bias the data on the high side. The range of concentration values obtained during storm conditions on the 13th are the same order as Fairchild's (1977) and those obtained on 15 September in the present study. The unusually high suspended sediment load on the 13th is due to the higher concentrations occurring throughout the water column and further offshore.

Another probable source of error is the scouring effect of the pier pilings. There is evidence that scour pits developed between pilings during the storm, and wakes of high concentrations were observed trailing from pilings in the inner surf zone on both sampling days. Some of the "plumes" at the foot of the inshore pilings sampled on 15 September were found to have concentrations approximately 50% higher than at a position 7 m from the pilings. Due to more intense wave action at the pilings on 13 September, no samples could be obtained for comparison.

With regard to the estimation of longshore transport from wave energy flux, there are three primary sources of error: 1) the longshore current velocity distribution was not directly measured and could only be estimated using presently existing theoretical models; 2) wave measurements were made under the pier possibly resulting in slight attenuation of the actual wave profile; and 3) wave approach directions, whether from radar or LEO observations, are imprecise at best.

#### Storm vs. Post-Storm Sediment Transport

Despite the possible sources of error listed above, the present data offer unique evidence that there is a great increase in suspended sediment transport during storm conditions. Measured point source concentrations ranging up to just 5 times higher during the storm, but extending significantly seaward and higher in the water column, produced an effective sediment load over 10 times higher. Estimated longshore current velocities 5 times higher during the storm resulted in a predicted transport rate over 60 times higher on the 13th than on the 15th. The close agreement on 13 September between suspended sediment transport and transport predicted from  $P_{1S}$  is probably fortuitous, but it is not unreasonable to believe these rates are of the right order.

#### The Importance of Suspended Sediment on Total Transport

An interesting result of these data is that during the storm, transport predicted from wave energy flux is totally accounted for by sediment 5 cm or higher in the water column. During post-storm swell conditions, however, suspended sediment flux only accounted for 30% of the transport predicted from  $P_{1S}$ . This may indicate that transport by sediment suspension is more important during storms, but may be secondary to bedload transport during post-storm swell conditions.

The data contained herein by no means resolve the controversy over the relative importance of suspended vs. bedload transport on beaches (Komar, 1978). However, they add an interesting twist. These results indicate that suspensions extend higher in the water column and farther offshore during storms. And, as Leonard and Brenninkmeyer (1978) reported, the frequency of suspensions may also be higher.

On the other hand, surf zone suspensions of sand during post-storm swell conditions appear to be lower in concentration, of lesser extent through the water column, and, perhaps, of lower frequency. This is analogous to the case for plunging vs. spilling waves reported by Kana (1979), where plunging waves suspend much greater quantities of sand. The present data, therefore, suggest that the suspension mode of transport is much more important during storms than during post-storm average conditions.

#### CONCLUSIONS

The present study at Duck, North Carolina provides some unique information on the relative quantities of sediment in suspension during storm and post-storm conditions. The following conclusions are offered:

1. Suspended sediment load in the surf zone is significantly higher during storms than post-storm swell conditions due to greater vertical and horizontal extent of the suspensions.
2. Sediment suspensions are relatively more important during storms in terms of their role in sediment transport.
3. Intermittent suspensions of sand from the bed are a less important component of longshore transport during post-storm recovery periods dominated by a swell wave environment.

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