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Sediment Mixing-depths on a Low-energy Reflective Beach

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ABSTRACT

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A field experiment was conducted on a sandy, micro-tidal, estuarine beach at Fire Island, New York, U.S.A. to determine the maximum depth of sediment mixing by waves and currents on a low-energy, reflective beach. Mixing depth was measured during three experiments using fluorescent-tracer sands injected across the upper foreshore at high water. Mean wind speeds at the injection times ranged from 5.3 m sec^{-1} to 11.7 m sec^{-1}; average significant wave heights ranged from 0.09 m to 0.13 m, with peak wave periods from 2.1 sec to 2.2 sec. Measurement of the maximum mixing depth from 192 tube cores revealed average mixing depths of 25 mm, 27 mm, and 28 mm for the three experiments. The average mixing depth for this environment during these experiments was about 22% of significant wave height. Wave-based models for high-energy beaches underestimate the average, maximum mixing-depth by as much as 400%. The cross-shore distribution of mixing depth shows a maximum at the breakpoint associated with breaker-generated turbulence in the swash.

ADDITIONAL INDEX WORDS: *Micro-tidal beach, estuarine beach, fluorescent-tracer sands, high-energy beaches, wave-based model, cross-shore sediment transport, turbulence, swash.*

INTRODUCTION

When sediment transport occurs in the surf zone, there will be an exchange of grains between the immobile bed and the mobile layer above it. This exchange occurs within a vertical length-scale described as the sediment mixing depth, Z (*e.g.*, KRAUS, 1985). The sediment mixing-depth is an important parameter for describing nearshore systems. Maximum mixing depth represents the maximum depth of detectable erosion of the bed (and sediment grain exchange) associated with the passage of waves and currents during a particular transport event. It controls truncation of antecedent sedimentary structures. Sediment mixing-depth is also accepted as representing the thickness of the nearshore sediment-transport layer (SUNAMURA and KRAUS, 1985).

The ability to measure accurately or predict the mixing depth is requisite for using tracer-based models of sediment transport (KOMAR, 1983; KRAUS, 1985; MADSEN, 1987). However, we still have only a rudimentary understanding of this parameter because there have been few field experiments designed specifically to determine spatial and temporal variability of the mixing depth in prototype surf zones. Further, inconsistent definitions of mixing depth have limited the quantitative efficacy of the tracer-derived transport equations (ALLEN, 1988). The purpose of this paper is to describe sediment mixing depths across a low-energy, reflective beach using field measurements of nearshore processes and dyed-sand tracers to determine sedimentary responses. A general distribution of mixing depths is obtained, and the results compared to existing models developed primarily for higher-energy systems.

BACKGROUND

Sediment mixing-depth, as used herein, is a result of the reworking of a surficial layer due to sediment transport by waves and currents over time periods of hours. Mixing depth is therefore considered conceptually distinct from depth-of-activity (or depth-of-disturbance), as the latter is usually assessed over periods associated with tidal cycles or storm events. Depth-of-activity usually includes the results of sediment reworking associated with landform dynamics such as beach profile changes (*e.g.*, ELIOT and CLARKE, 1988;

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STRAHLER, 1966); nearshore bar or bedform migration (DAVIDSON-ARNOTT and GREENWOOD, 1976; GREENWOOD and DAVIDSON-ARNOTT, 1975; SHERMAN *et al.*, 1993; SUNAMURA and TAKEDA, 1984); or beach step migration (NORDSTROM and JACKSON, 1990).

There have been several studies addressing aspects of sediment mixing-depth in the surf zone. The major papers are those of KRAUS (1985) and SUNAMURA and KRAUS (1985). The former presents an empirically derived expression relating mixing depth to breaker height for planar beaches: $\bar{Z} = 0.027H_b$; where $\bar{Z}$ is the average mixing depth in the surf zone and H_b is the height of the waves at breaking. KRAUS (1985) formulated this expression based on field measurements of typical mixing depths developing on test beaches over time-scales of hours. He defined the average mixing depth based on measurements of Z_{80}, the depth through which 80% of the tracer found within an individual core was contained. This relationship seems to correspond to additional field data from the studies of KING (1951), KOMAR and INMAN (1970), GAUGHAN (1979), and INMAN *et al.* (1980).

SUNAMURA and KRAUS (1985) recognize that mixing depth should also be a function of wave period and sediment grain size. They characterize the relationship using a wave-based Shields parameter. Inspection of their Figure 4 (SUNAMURA and KRAUS, 1985, p. 9) shows that for low breaker heights (less than 1 m) with grain sizes between 0.2 mm and 0.4 mm, grain size and wave period are unimportant controls compared to breaker height. Their model and that of KRAUS (1985) both predict that typical, surf-zone averaged, sediment mixing-depths on planar, low-energy beaches should be about 3% of breaker height.

It has also been recognized that the presence of rapidly migrating bedforms can increase the mixing depth substantially. SHERMAN *et al.* (1993) have described mixing due to megaripple migration in rip-current channels over periods of one to three hours. Their results showed local mixing depths of 0.2 m with breaking waves less than 1 m high. The surf-zone averaged mixing-depth was about 400% greater than that predicted with the planar bed, wave-based models of KRAUS (1985) and SUNAMURA and KRAUS (1985).

Several methods have been developed to measure the thickness of the active layer associated with depth of disturbance or depth of sediment mixing in the surf zone and on the foreshore. An early technique was that used by KING (1951). She buried dyed-sand cores of known length at the beginning of her investigation. After an event, the depth of sand over the core, and the length of the remnant core, were measured as indicators of maximum erosion and subsequent accretion. This technique was also successfully employed by WILLIAMS (1971).

GREENWOOD *et al.* (1979) describe the use of depth-of-activity rods and washers to measure patterns of scour and accretion. NORDSTROM and JACKSON (1990) have used small-scale pipe profiling to monitor beach step migration over tidal cycles. KOMAR and INMAN (1970), KRAUS (1985) and SHERMAN *et al.* (1990) used the burial depth of tracer sands as indicators of mixing depth (termed thickness of layer of motion by KOMAR and INMAN, 1970). In these cases, fluorescent sand tracers were released in the surf zone. Tube cores were taken to recover tracer samples, and these cores sliced into several sub-samples representing equal increments of depth. Depth of mixing was associated with the lowest sub-sample containing tracer, rather than with its exact location relative to the surface of the bed. With this method, precision is limited to the thickness of the core slices. INMAN *et al.* (1980) measured directly the depth of tracer occurrence in their samples, although they did not provide an explanation of their method.

None of the data sets used to measure mixing depth have been gathered with a specifically defined measurement of maximum mixing depth using tracers. There has also been a neglect of small-scale, alongshore variability in the mixing process. In order to gather data aimed at addressing these aspects of sediment mixing-depth, three experiments were conducted during a twenty-day field study at Fire Island National Seashore, on an estuarine beach where low energy in the breaking waves and swash enabled tight control on sampling over time, space, and depth.

FIELD SITE AND EXPERIMENTAL DESIGN

The field study was conducted March 17 to April 5, 1992 on a sandy beach located about 400 m west of Sailors Haven, on the backbarrier (northern) shoreline of Fire Island National Seashore, N.Y. (Figure 1). The beach has a steep (8.0°), narrow (7 m) upper foreshore and a flat (< 0.5°) low-tide terrace more than 100 m wide with low-relief (0.2 m high) transverse bars. These characteristics are common for sandy estuarine beaches in micro-

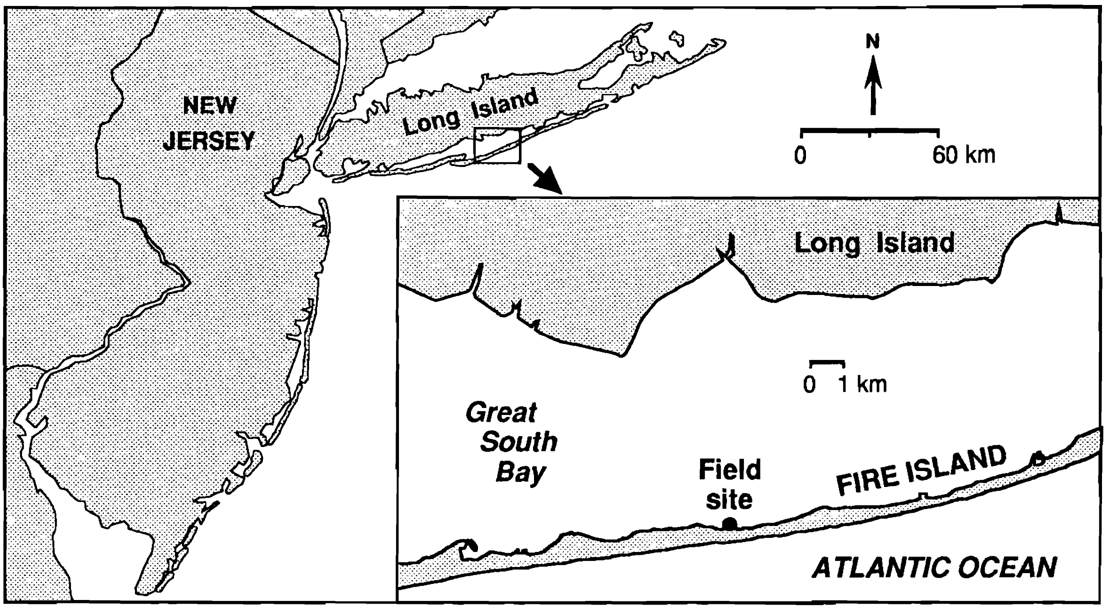

Figure 1. Location of study site.

tidal environments (NORDSTROM, 1992). Dominant waves are locally-generated, short-period wind waves. Despite the short-period waves, this beach tends to be morphodynamically reflective (WRIGHT and SHORT, 1984), because of low wave amplitude and the steepness of the foreshore. Waves breaking on the upper foreshore are converted directly to swash without a transitional surf zone. Dominant winds are from the northwest; strong northeast winds occur during the passage of mid-latitude cyclones. Fetch distances are 12 km to the northwest and 15 km to the northeast. Tides are semi-diurnal with a mean range of 0.2 m (NOAA, 1992). Foreshore sediments have a mean grain size (M_z) of 1.47ϕ (0.37 mm), with a sorting value (σ_I) of 0.31ϕ using inclusive graphic measures (FOLK, 1974). The foreshore is backed by overwash fans two to twenty meters wide. There was no pronounced alongshore variation in foreshore morphology over the 100 m beach length considered through this investigation (Figure 2).

Water surface elevations, for the estimation of wave parameters and mean water depths near the break point, were measured with a pressure transducer installed on the low-tide terrace one meter offshore from the break in slope at the base of the foreshore (Figure 3). Wind characteristics were measured at an elevation of six meters above the backbeach overwash-fan using an R.M. Young Model 12102 Gill-type 3-cup anemometer and a Model 12302 Gill-type microvane. Data were recorded on a Sea Data 1255B-27 data logger at a sampling frequency of 2 Hz. Records contain 2,048 or 1,024 observations (lengths of 17.07 and 8.53 minutes) depending on wave conditions. Data records were obtained at twenty minute intervals. Wave heights, H_b, are reported as 4σ, where σ is the standard deviation of the water surface elevation record (CERC, 1984). Wave periods represent the energy density peak from the spectral estimates. Longshore current velocities were measured using neutral-buoyancy floats and tracer dyes placed in the swash zone.

Sediment mixing-depths were measured using the distribution of fluorescent tracer sands in tube cores. Sampling lines were established at five meter intervals alongshore (Figure 3). Cross-shore sampling increments on these lines were determined by the width of the swash zone with six coring stations established at spacings of 25% of the swash zone width. Care was taken to ensure that sequential coring locations were offset slightly from one another. Morphology of the foreshore sampling area was measured at one meter inter-

Figure 2. Study site at low water. Anemometer tower is at upper left; survey pins extend across foreground. The pressure transducer used to gather the wave data is mounted on the instrument stand visible near center photo.

vals along a shore-normal profile located within the tracer sampling grid (Figure 3). There was little alongshore variation in morphology through the sampling grid.

The cross-shore distances for tracer sampling were made dimensionless using a dimensionless distance X, from the ratio $X = x/x_b$, where x is offshore distance, and x_b is distance to the breaker line. The two offshore stations, at $X = 1.25$ and 1.50 were thus bayward of the surf zone. Four lines were sampled near-simultaneously at one hour intervals by three or four people during each of three experiments. Eight sample sets comprising 192 cores were obtained during the experiments (Table 1).

Three batches of fluorescent tracer sands were made using the Polyvinyl Chloride Acetate Resin recipe described in MCARTHUR (1980) and SHERMAN *et al.* (1990). Different colors were used for each batch so that grains from each deployment could be recognized. Tracer was injected using a cut-away tube long enough to span the swash zone. Cores were obtained using clear plastic tubes 100 mm long and 50 mm in diameter. Each core was carefully sliced from the top down until the last fluorescent grains from the appropriate tracer injection were encountered. There was occasional distortion of the sediment lamination within the cores as a result of water draining from the sample. This distortion was usually plainly visible through the clear plastic of the cores. If it were clear that the tracer grain was not a contaminant due to water drainage, then the remaining length of sample is recorded as the mixing depth. Multiple observation of individual cores showed that this method yielded results reproducible to the nearest 2 mm.

For Experiment 1, March 31, 1992, tracer was injected along Line 2 (Figure 3), and Lines 3, 4, 5, and 6 were sampled at 0840 and 0940 hr. Experiments 2 and 3 took place April 2 and 3, 1992, respectively, with tracer injected along line 7 in both instances. Lines 3, 4, 5, and 6 were sampled at 1000, 1100, and 1200 hr during Experiment 2. Lines 1, 3, 5, and 6 were sampled at 1010, 1110, and 1210 hr during Experiment 3.

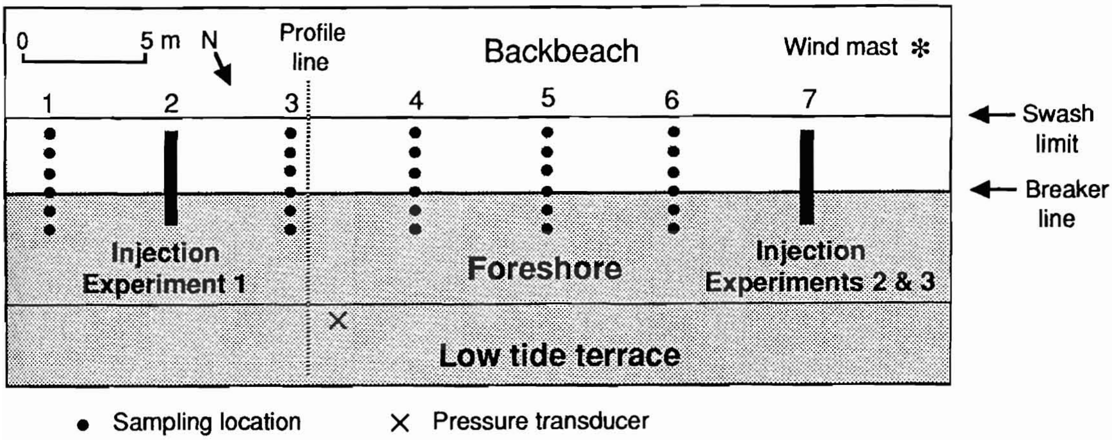

Figure 3. Details of experimental design across the study site, March 31 to April 4, 1992.

RESULTS

Wind direction during Experiment 1 (March 31) was from azimuth 017 (03 degrees east of shore-normal), driving waves almost directly onshore. Wind speed at the time of tracer injection was 6.3 m sec $^{-1}$. Average significant wave height, H_s, was 0.10 m; longshore current velocity averaged 0.10 m sec $^{-1}$; peak average wave period was 2.1 sec; and average water depth at the pressure transducer was 0.38 m. Average mixing depth for the 48 cores obtained during this trial was 25 mm, with a standard deviation of 12 mm.

Wind direction during Experiment 2 (April 2) was from azimuth 339, (41 degrees west of shore-normal), driving waves from the northwest. Wind speed at the beginning of this experiment averaged 5.3 m sec $^{-1}$. Average H_s was 0.09 m; longshore current velocity averaged 0.16 m sec $^{-1}$; peak wave period was 2.1 sec, and average water depth was 0.48 m. The average mixing-depth for the 72 cores obtained in this experiment was 28 mm, with a standard deviation of 14 mm.

During Experiment 3, the wind direction was azimuth 309 (71 degrees west of shore-normal). Waves were again from the northwest. Wind speed at the beginning of this experiment averaged 11.7 m sec $^{-1}$. The average H_s was 0.13 m; longshore current velocity averaged 0.24 m sec $^{-1}$; peak wave period was 2.2 sec, and average water depth was 0.41 m. The average mixing depth from 72 cores was 27 mm with a standard deviation of 16 mm.

The short duration of the wind events limited the growth of waves in all of the experiments. Some offshore wave breaking in the form of white caps also occurred in each experiment. However, in all cases, dominant breaking of incident waves was forced by shoaling across the foreshore.

Data from the three experiments reveal that sediment mixing-depth varies considerably both across the beach face (Table 1) and alongshore (unsystematically, so we do not address this further). The greatest mixing depths generally occur at or near the breakpoint, $X = 1.0$, and decrease onshore and offshore from that location. Maximum measured mixing depth was 66 mm, a value that occurred twice at the breakpoint during Experiment 2. Minimum mixing depth was 3 mm. This value occurred twice near the upper limit of swash, $X = 0.25$.

The twelve across-shore profiles of sediment mixing-depth from samples collected during Experiment 3 are presented in Figure 4. This series displayed the greatest instantaneous variation through a sampling sequence.

Summary data for the three experiments (Table 2) reveal that nearshore conditions were similar for all eight sampling runs. Calculations for the mean sediment mixing-depth across the beach face, Z_{sz}, and the standard deviation of mixing depth for each profile, Z_{sd}, do not include samples from locations outside the swash zone ($X > 1.0$). This is to make the results comparable to earlier studies (*e.g.*, KRAUS, 1985 and SUNAMURA and

Table 1. *Measured mixing depth from 192 tube cores obtained during the Fire Island experiments. All depths are in mm.*

Date/Time/Line	X − 0.25	X 0.50	X 0.75	X 1.00	X 1.25	X 1.50
March 31/08:30/3	17	32	48	27	26	34
08:30/4	9	31	33	31	26	31
08:30/5	10	18	35	14	11	27
08:30/6	8	17	23	6	20	19
09:30/3	24	18	26	8	10	40
09:30/4	13	33	18	15	35	32
09:30/5	12	16	35	36	38	48
09:30/6	8	44	43	47	13	16
April 2/09:50/6	12	27	56	39	49	25
09:50/5	21	21	36	30	14	15
09:50/4	3	20	31	12	11	15
09:50/3	5	21	15	34	8	4
10:50/6	19	42	38	47	18	18
10:50/5	22	48	44	66	24	32
10:50/4	10	31	38	41	22	22
10:50/3	10	35	29	24	13	21
11:50/6	39	49	36	66	33	19
11:50/5	37	53	26	45	33	35
11:50/4	22	23	25	43	19	17
11:50/3	9	23	33	25	31	10
April 3/10:00/6	3	4	41	21	16	16
10:00/5	7	21	42	26	8	20
10:00/3	9	11	57	48	13	14
10:00/1	29	27	33	36	10	16
11:00/6	4	16	58	21	14	7
11:00/5	5	32	58	50	22	9
11:00/3	22	23	42	52	20	40
11:00/1	5	19	30	40	22	12
12:00/6	47	24	25	45	35	35
12:00/5	27	40	15	55	38	29
12:00/3	12	38	17	59	4	46
12:00/1	33	51	20	61	19	18

Table 2. *Summary statistics for the sample periods during the three experiments. Values of Z_s and Z_{sd} include only data obtained where $X \leq 1.00$.*

Date/Time	Z_s (mm)	Z_{sd} (mm)	h (m)	H_s (m)	ϵ	Z_s/H_s
March 31, 08:30	18	14	0.37	0.09	2.3	0.20
March 31, 09:30	20	16	0.39	0.11	2.5	0.18
April 2, 09:50	19	16	0.49	0.09	2.1	0.21
April 2, 10:50	27	19	0.49	0.09	2.1	0.30
April 2, 11:50	28	19	0.45	0.10	2.3	0.28
April 3, 10:00	21	18	0.42	0.13	2.7	0.16
April 3, 11:00	24	20	0.43	0.10	1.9	0.24
April 3, 12:00	28	21	0.37	0.15	2.9	0.19

KRAUS, 1985). Each mixing depth number in Table 2 is obtained from five across-shore, swash/breaker zone locations, including X = 0.

The morphodynamic state of the beach is quantified using the surf-scaling parameter, ϵ (GUZA and INMAN, 1975), $\epsilon = (a\omega^2)/(g \tan^2 \beta)$ where a is wave amplitude, ω is wave radian frequency (2π/T, where T is wave period), g is gravitational acceleration, and β is beach slope in degrees. Although there are theoretical constraints concerning the use of the surf-scaling parameter with shallow water waves (*e.g.*, BAUER and GREENWOOD, 1988), these constraints are only mildly relaxed for our data. Beaches are considered to be reflective when ϵ is less than about 2.5 (GUZA and INMAN, 1975). For most of the measurements described in Table 2, estimates of ϵ predict substantial wave energy reflection. The modal morphodynamic state for the series of experiments is reflective, with average $\epsilon = 2.4$.

DISCUSSION AND CONCLUSIONS

Our data indicate the ratios of mixing depth to significant wave height, averaged across the swash zone, vary from 0.16 to 0.30. The average mixing depth for this low-energy environment is about 22% of significant wave height. KRAUS (1985) used significant breaker height, rather than significant wave height. However, as waves shoaled between our pressure transducer and the break point, a distance of about 2 m, their height would have increased only slightly. Thus differences in wave-height parameterization do not appear to account for differences between our results and those of KRAUS (1985). Kraus also calculated average mixing depth based on his measures of Z_{80}. Average, maximum mixing-depths measured by Kraus, comparable to our measurements, were two to three times the average values for Z_{80}. If his ratio of mixing depth to wave height is adjusted to be based on maximum mixing depths, his relationship becomes $0.054H_b < \bar{Z} < 0.081H_b$. Our comparable mixing depth to wave height relationship, $\bar{Z} = 0.22H_b$, is thus about 250% to 400% larger than the values reported for higher-energy beaches.

Although individual mixing-depth profiles are irregular (Table 1, Figure 4), there is a characteristic profile around which variation occurs. Figure 5 is a dimensionless, cross-shore mixing-depth profile based on our measurements. Mixing depth at each cross-shore sampling location is standardized against the mean mixing depth obtained from all the measurements we made. The nonlinear shape of this profile does not conform with cross-shore distributions of wave processes such as wave height and radiation stress, which are

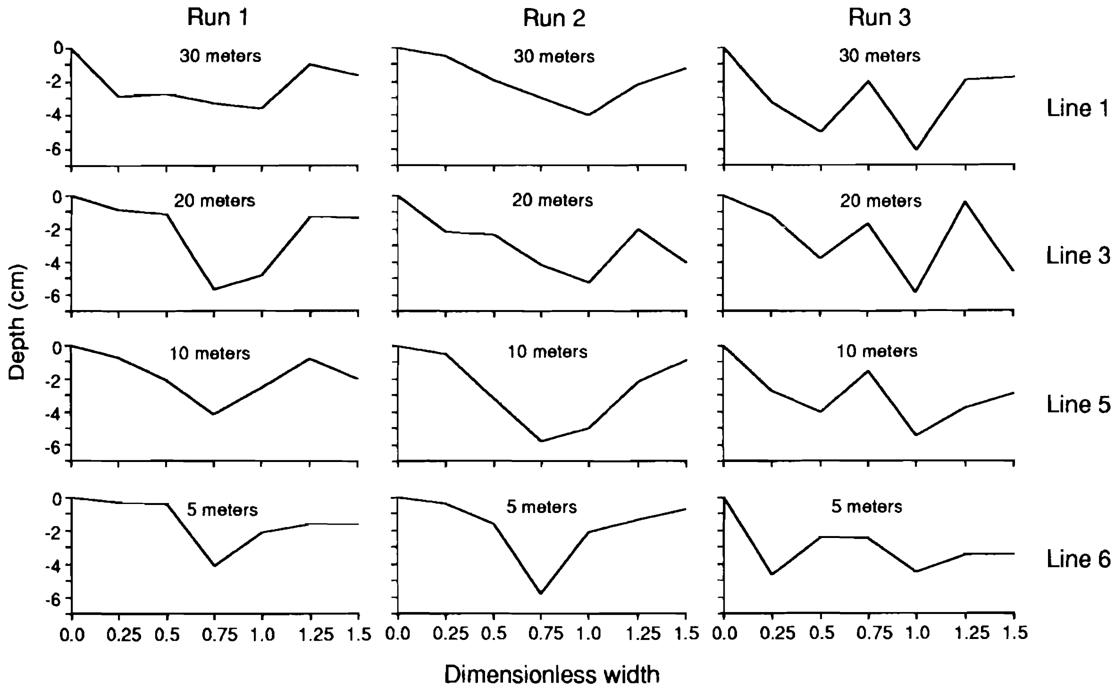

Figure 4. Cross-shore mixing-depth profiles for Experiment 3, April 3, 1992. Runs 1, 2, and 3 occurred at 1010, 1110, and 1210 hr, respectively. Distances in meters refer to distance from the tracer injection line.

linearly related to water depth (a simple rectilinear form in our study), or to wave-induced sediment transport rates derived from linear or first-order non-linear equations (*e.g.*, Hughes, 1992).

The dimensionless distribution of mixing depths across the nearshore (Figure 5) is similar to that described by Longuet-Higgins (1972) for longshore currents in the surf zone when there is little lateral mixing (*i.e.*, Longuet-Higgins' mixing parameter, $P, \simeq 0.01$), as well as by Thornton (1971) for alongshore sediment transport. The chief difference between the latter distributions and ours is that mixing depth is at a maximum at the breaker line ($P \simeq 0.0$), and longshore currents and alongshore sediment transport should typically peak landward of that line, between about $0.60 < X < 0.80$ (*i.e.*, $0.1 > P > 0.01$). Such an observation is consistent, theoretically, with processes in a narrowly confined breaker/swash zone. There should be a steep radiation stress gradient just onshore of the step due to wave breaking, and a concomitant increase in local alongshore current velocity. We believe that these elements are fundamentally distinctive of steep, low-energy beaches where pronounced steps are present.

The distribution of mixing depth across the beach face is also affected by alongshore transport

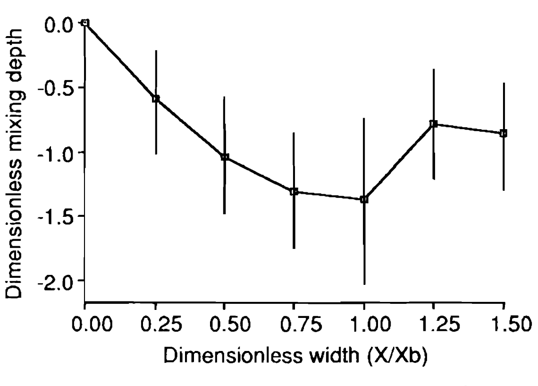

Figure 5. Average dimensionless profile of mixing depths across the beachface. Lengths of vertical bars represent ± one standard deviation of sample measurements for each location.

processes, which disperse tracer grains rapidly, and by the local cross-shore accumulation of tracer within beach step deposits at the lower foreshore. Our process measurements do not allow confirmation of the exact mechanism responsible for the mixing depth pattern. However, the distribution is similar to mixing depths on high energy beaches where swash dominates across the full width of the surf zone (KRAUS, 1985), that is, when bores and spilling breakers are absent.

Estuarine beaches tend to be morphodynamically reflective (HUGHES and COWELL, 1987; JACKSON, 1992; NORDSTROM and JACKSON, 1992), and our results confirm this state for the study site. For the case of reflective and intermediate beaches ($2.5 < \epsilon < 20$), HUGHES (1992) noted that the beach face tends to be dominated by swash processes rather than bores. Therefore, energy dissipation occurs over a short distance, in conjunction with relatively high alongshore sediment transport rates. We speculate that these processes combine to produce (1) a mixing-depth distribution that is characteristic of beaches without a well-developed surf zone and (2) mixing depths that are greater than those expected due to waves breaking in a high-energy environment.

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