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Measurement of Longshore Sediment Transport Rates in the Surf Zone on Galveston Island, Texas

Alison L. Rogers and Thomas M. Ravens

Texas A&M University at Galveston
PO Box 1675
Galveston, TX 77553, U.S.A.
ravenst@tamug.edu

ABSTRACT

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Longshore sediment transport in the surf zone on Galveston Island, Texas, was studied to develop a new technique involving optical instruments rapidly calibrated *in situ* and to compare measured transport rates with those predicted by the well-known Coastal Engineering Research Center (CERC) formula. This method used an instrumented sled equipped with a LISST-100 for particle size distribution determination, four optical backscatter sensors (OBSs) for turbidity measurements, and two velocity sensors for longshore current measurements. The sled was pulled across the surf zone, occupying 10 to 15 stations spaced about 10 m apart, for approximately 3 minutes each.

The OBS data were calibrated with the LISST-100 particle size distribution data, thereby overcoming the difficulties associated with the use of these sensors in the presence of a mix of sand and fine particles. Subsequently, these data were fit to a logarithmic profile to determine the average vertical distribution of suspended sand concentration, assuming that the fine particles were vertically well mixed at each station. A logarithmic profile of average longshore current was also computed based on the measured velocity data. The longshore sediment transport rate was calculated as the spatial integral of the product of suspended sand concentration and velocity and related to the wave conditions at the point of breaking. Measured rates ranged from 86,000 to 231,000 m^3/y, and transport was found to be greatest in the vicinity of the sand bars. The popular CERC formula gave sediment transport rates significantly greater than the observed values, with the difference between the two on the order of 100%. The average CERC transport coefficient, K_1, computed from our measurements was determined to be 0.19 ± 0.12.

ADDITIONAL INDEX WORDS: *Optical backscatter sensor, CERC formula.*

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INTRODUCTION

The longshore sediment transport rate is a fundamental parameter in both coastal engineering and coastal science. Reliable field data, obtained under a variety of wind, wave, and beach conditions, are required to calibrate and improve empirical formulas for predicting the total rate of longshore sediment transport (LST), as well as further our understanding of this phenomenon. The majority of field measurements made to date rely on three standard techniques: sediment tracer, impoundment, and sediment traps. The sediment tracer method involves inferring sediment flux through quantification of vertical and horizontal movement of either fluorescent sand tracers (CIAVOLA *et al.*, 1997; INMAN *et al.*, 1981; KNOTH and NUMMEDAL, 1977; KOMAR and INMAN, 1970; KRAUS *et al.*, 1983; NORDSTROM *et al.*, 2003) or radioactive tracers (DUANE and JAMES, 1980). Because of the expenses associated with this costly and labor-intensive technique, its use has been limited to only a few locations, mostly along the Pacific coast. The relatively small number of data sets generated with the tracer method, however, comprises most of the reliable field data on which empirical LST prediction formulas are based (SCHOONEES and THERON, 1993). Known problems associated with sediment tracers include a lack of demonstrated reproducibility (KRAUS *et al.*, 1983) and difficulties in accurately determining the depth of mixing (GREER and MADSEN, 1979; KOMAR and INMAN, 1970) and the center of mass distribution (GALVIN, 1987). Additionally, MADSEN (1989) argues that the assumptions in tracer transport analysis (*e.g.,* both diffusion and dispersion must be dominated by advection, and no tracers may leave or enter the transport system) are difficult to validate. To verify and improve on the results of these previous studies, it is therefore necessary to turn to different measurement techniques.

The other two methods commonly used to estimate total LST rates are impoundment, in which the transport rate is inferred by measuring the volume of material deposited or eroded at a structure or inlet, and sediment streamer traps, in which the transport rate is calculated from point measurements of sediment flux made throughout the water column and across the surf zone. Impoundment has been used to determine both long-term transport rates, typically averaged over several months (*e.g.,* BEREK and DEAN, 1983; BRUNO, DEAN, and GABLE, 1981; DEAN, 1989; DEAN *et al.*, 1983; SEYMOUR, DOMURAT, and PIRIE, 1981), and short-term transport rates, averaged over several hours (BODGE and DEAN, 1987; WANG and KRAUS, 1999; WANG, KRAUS, and

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DAVIS, 1998). Disadvantages of the impoundment technique, on either timescale, include leakage of material from the trap and difficulties isolating the longshore transport signals from those produced by other processes, such as cross-shore transport. In addition, short-term impoundment requires low wave energy conditions. On the other hand, although long-term impoundment can measure LST rates in high wave energy events, the long time interval between surveys often smoothes the influence of extreme events, making it difficult to fully understand the relationship between hydrodynamics and sediment transport. The streamer trap presents an attractive method for quantifying surf zone sediment transport rates because of its low cost and ability to measure both suspended load and bedload (KATORI, 1983; KRAUS, 1987; KUMAR *et al*., 2003; ROSATI and KRAUS, 1988; WANG, KRAUS, and DAVIS, 1998). Problems associated with this technique, however, include questions of trap efficiency and the hydrodynamic disturbance created by the traps. Like short-term impoundment, sediment traps also require low wave energy conditions.

Longshore sediment transport rates obtained with the tracer and long-term impoundment techniques, generally in the range of 100,000–400,000 m^3/y (KOMAR, 1998), are four to 10 times greater than those rates obtained through short-term impoundment and with streamer sediment traps (WANG and KRAUS, 1999). WANG and KRAUS (1999) attribute the lower rates to the relatively short time period over which the latter type of measurements are made. Another important factor is that techniques such as impoundment and tracers measure both bedload and suspended load, whereas others (*e.g.,* streamer traps) quantify only suspended load. Methods that measure the total load can result in significantly higher transport rates (SCHOONES and THERON, 1994). Resolving these disparities would allow for better understanding, and subsequently better prediction, of the phenomenon of LST. This in turn requires more field data obtained under a variety of conditions with different techniques.

Optical instruments, which have substantial potential but have yet to be fully exploited, present another way to measure LST in the surf zone. Optical backscatter sensors (DOWNING, STERNBERG, and LISTER, 1981) detect the portion of emitted infrared light that is backscattered from particles suspended in a small sample volume directly adjacent to the sensor face. Calibration with known sediment concentrations allows the suspended sediment concentration in the test sample to be deduced from the amount of backscattered light. Coupling these measurements with simultaneous measurements of longshore current leads to a determination of longshore sediment flux at a number of points across the surf zone, which can then be used together to infer the LST rate.

Because of their excellent spatial and temporal resolution, relatively low cost, small size, and ruggedness, optical backscatter sensors (OBSs) have seen moderate use in a variety of field studies conducted in several different environments (*e.g.,* BEACH and STERNBERG, 1996; HANES and HUNTLEY, 1986; JAFFE, STERNBERG, and SALLENGER, 1984; MILLER, 1999; SMITH and MOCKE, 2002). Strong particle size dependency remains the most challenging problem associated with the use of these sensors, despite work to quantify and offset the effect (BLACK and ROSENBERG, 1994; BUNT, LARCOMBE, and JAGO, 1999; CONNER and DEVISSER, 1992; GREEN and BOON, 1993; LUDWIG and HANES, 1990). Although the OBS responds linearly to varying concentrations of homogeneous sediments (LUDWIG and HANES, 1990), its use in an environment containing heterogeneous sediment mixtures has been severely limited because of this dependency. Using pump samples taken concurrently with OBS measurements, BATTISTO *et al.* (1999) found that the lowest 1%–5% of the recorded OBS voltage signal accounted for background turbidity caused by fine particles. Similarly, in measurements of LST during storms, MILLER (1999) offset the measured concentration by the mode of the lowest 5% of the concentration values to correct for the fine matter in suspension. CONNER and DEVISSER (1992) advocated using an *in situ* particle sizing instrument to achieve rapid field calibration of an OBS device; however, this recommendation has yet to be implemented in the field. In this work, we report on an effort to use this novel method to measure longshore sediment rates in a dynamic surf zone characterized by high concentrations of suspended silt and sand.

In this study, suspended sediment concentration is rapidly measured with OBSs calibrated *in situ* via a laser particle size analyzer. Together with simultaneous measurement of longshore velocity, these data are used to determine both the cross-shore distribution of longshore sediment flux and the LST rate under various conditions at a location on Galveston Island, which is situated on the Gulf coast of Texas. The results are then compared with the predictions of the Coastal Engineering Research Center (CERC) formula, a common empirical formula used in the popular GENESIS (generalized model for simulating shoreline change) shoreline change model. The objectives of this study are to further develop the use of optical devices for reliably measuring LST and to test the accuracy of the CERC formula in local conditions, to improve calculations of LST rates and shoreline change along the Texas Gulf coast.

STUDY AREA

The LST measurements reported here were made from May 2003 to August 2004 on Galveston Island, located on the upper Texas Gulf coast (Figure 1). Galveston is a 50-km-long, 3- to 5-km-wide barrier island, well-known among coastal engineers because of the 16-km-long seawall built in response to the devastating hurricane of 1900 and because of the high rates of erosion observed on the island. The precise location of the study site, Jamaica Beach, is situated at the approximate midpoint of the island. This section of the island, about 15 km west of the Galveston seawall and groin field, remains relatively free of the influence of human structures. The beach in this region exhibits a low profile, characterized by several very pronounced bars and troughs that extend along the entire west end of the island.

Field data were collected on approximately 10 days, but because of instrument malfunctions and an initial period of method development, only four deployments resulted in computation of LST rates. The hydrodynamic and morphological conditions at the study site during each of these four mea-

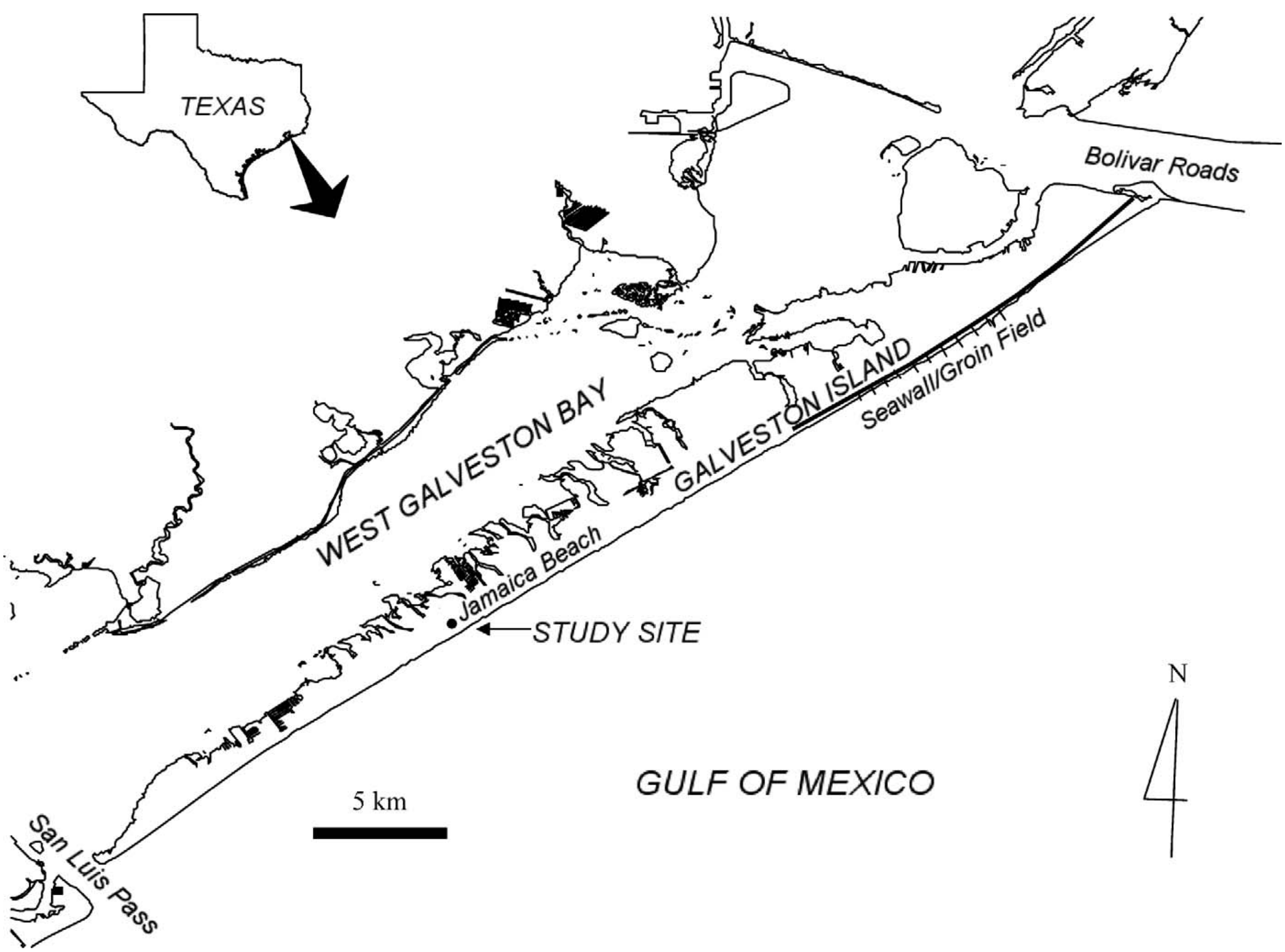

Figure 1. Map of Galveston Island showing the study site.

surements are summarized in Table 1. Surf zone width at this location fluctuates with both tidal cycle and wave conditions; for the reported measurements, surf zone widths of 123 and 200 m were observed. Average beach slope as determined from the breaker line to the shoreline varied slightly, ranging from 0.008 to 0.011. Although wave conditions at the study site change considerably on a daily basis, only a fairly small range of conditions corresponding to relatively low wave energies was suitable for measuring LST rates. Root mean square (RMS) wave heights at breaking and wave periods, both derived from pressure data, fell in the range of 0.40–0.49 m and 3.2–4.2 seconds, respectively. Incident wave angles at the main breaker line, computed from the velocity time series following MADSEN *et al.* (1993), were found to be between 10° and 35° relative to shore-normal. Although the reported measurements were being conducted, the surf zone was covered by spilling breakers, with plunging breakers found at the innermost two bars in some cases.

The sediment at the study site exhibits a unimodal distribution, with the mean grain size approximately 0.13 mm. In addition, the strong presence of silt in the water throughout this area, caused by both circulation in the Gulf of Mexico

Table 1. *Summary of hydrodynamic and morphological conditions at the study site.*

Date of Measurement	Surf Zone Width (m)	Beach Slope	RMS H_b (m)	Incident Wave Angle (°)	Wave Period (s)	Water Depth at Breaking (m)
May 30, 2003	200.2	0.008	0.49	34.8	3.7	1.56
June 3, 2003	123.2	0.010	0.47	10.1	4.2	1.29
August 26, 2004	198.1	0.009	0.40	20.9	3.2	1.88
August 27, 2004	123.4	0.011	0.40	21.6	3.4	1.41

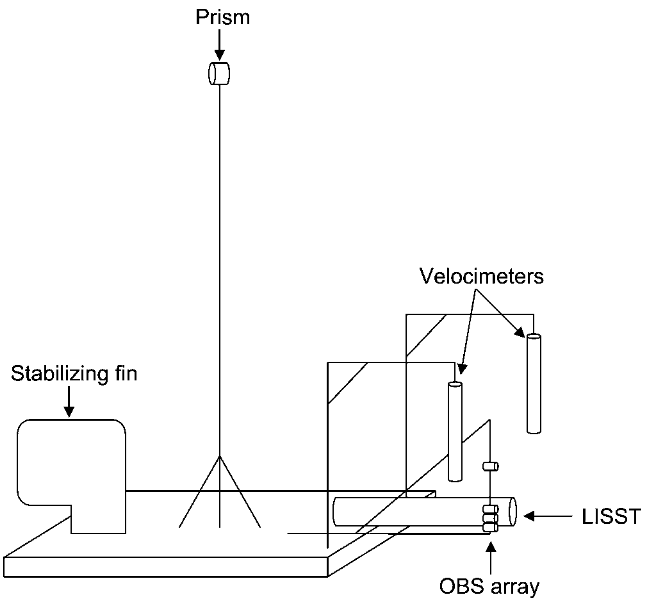

Figure 2. Schematic of instrumented sled.

that brings turbid water from the Mississippi River toward the Texas Gulf Coast and two nearby inlets, leads to typical visibilities of a few inches.

INSTRUMENTATION AND DATA COLLECTION

Longshore sediment transport rates were measured with the use of a sled equipped with various instruments, a schematic of which is shown in Figure 2. The sled, which measured approximately 5 by 3 feet (1.5 by 1 m), consisted of a metal grate with two polyvinyl chloride (PVC) pipes fastened to either side to act as runners. A large wooden fin attached to the rear of the sled helped to align the sled into the waves and provided increased stability in the energetic conditions of the surf zone. A prism affixed to a 4-m mast at the midpoint of the sled allowed for positioning of the sled with a total station during deployment.

At the front of the sled, two velocimeters (Vector, Nortek AS, Oslo, Norway) were cantilevered out from the sled (toward the waves) with metal bars to minimize recording any effects of the hydrodynamic disturbance created by the sled. These instruments measured three-dimensional point velocities to an accuracy of ±0.1 cm/s at a rate of 1 Hz for the two data runs presented here from 2003 and at 4 Hz for the two data runs taken during 2004. With the use of an interior fluxgate compass, flow velocities were recorded in east–north-up coordinates. Additionally, both velocimeters collected pressure data at the same rate as the velocity data. Turbidity in the water column was determined with an array of four OBSs (OBS-3, D&A Instrument Company, Port Townsend, Washington) attached to a 1-inch (2.5-cm)-diameter PVC pipe that protruded beyond the front edge of the sled. These sensors can measure sand concentrations in the range of 0–50 g/L with an accuracy of ±0.1 g/L. Before deployment, all sensors

Table 2. *Measurement locations of each instrument on sled.*

Instrument	Measurement Location (cm above bottom)
OBS1	7.0
OBS2	10.8
OBS3	16.5
OBS4	47.0
LISST	16.5
Velocimeter 1	7.5
Velocimeter 2	15.1

were adjusted in the laboratory to have identical gains, following the procedure detailed in the product manual (DOWNING and ASSOCIATES, 1991). The sensors recorded data via the analog inputs of the velocimeters; thus, the rate of measurement coincided with that of the velocimeters for each data run. A laser particle size analyzer (LISST-100, Sequoia Scientific, Inc., Bellevue, Washington), capable of measuring concentrations of particles ranging in size from 2.5 to 500 μm, was mounted at the front of the sled as far out into the oncoming waves as possible. This device recorded data at a rate of 1 Hz and was factory calibrated to have a resolution of 0.5 μl/L and an accuracy of ±20% over the full range of sizes. Table 2 gives the location of the measurements above bottom (cm) for all instruments on the sled. To resolve the rapid sediment concentration changes in the lower water column, three of the four turbidity sensors were concentrated near the bottom.

To measure LST rates, all devices were synchronized, and the sled was towed with a jet ski past what was visually judged to be the edge of the surf zone. With a winch and a cable attached to the shoreward end of the sled, the sled was pulled toward the shore, crossing the entire surf zone along a line approximately shore-normal. On the way, the sled occupied individual stations for 2–3 minutes each. Although the number of stations depended on the width of the surf zone, an effort was made to keep the stations approximately 10 m apart. The location of each station, measured as a distance offshore and a distance from the shore-normal, was surveyed with a Nikon DTM-522 total station, which was also used to determine a beach profile and the position of the shoreline. One deployment of the sled sampling the whole surf zone typically required 60–90 minutes.

DATA ANALYSIS AND RESULTS

Longshore Sediment Transport Rate Calculation

A general expression for longshore sediment flux can be written as

$$F_y(x, z, t) = u_y(x, z, t)\cdot c(x, z, t) \qquad (1)$$

where F_y is longshore sediment flux per unit area; u_y is longshore fluid velocity; c is sediment concentration; t is time; and x, y, and z are cross-shore, longshore, and vertical coordinates, respectively. Because of the extremely dynamic nature of longshore current and sediment concentration, longshore flux is typically expressed as a temporally averaged and spatially integrated value. WANG *et al.* (2002) found that a reasonable estimate of the time-averaged longshore sediment flux at a point x can be obtained by integrating over depth the product of the time-averaged profiles of longshore current and sediment concentration. Thus, mean longshore sediment flux can be expressed as

$$\bar{F}_y\ (x) \approx \int_0^h \bar{u}_y(x,\ z)\cdot\bar{c}(x,\ z)\ dz \qquad (2)$$

where an overbar denotes a time-averaged quantity and h is mean water level. Consequently, the time-averaged rate of LST for the entire surf zone, Q, can be estimated as

$$Q = \int_0^X \bar{F}_y(x)\ dx \approx \int_0^X \int_0^h \bar{u}_y(x,\ z)\cdot\bar{c}(x,\ z)\ dz\ dx \qquad (3)$$

where X is width of the surf zone. To approximate LST rates with velocity and sediment concentration data taken at discrete values of x and z, linear integration can be employed, and Equation (3) becomes

$$Q \approx \sum_{j=1}^{M} \sum_{i=1}^{N} \bar{u}_y(x_j,\ z_i)\cdot\bar{c}(x_j,\ z_i)\ \delta z_i\ \delta x_j \qquad (4)$$

where M represents the number of cross-shore positions, x_j; N represents the number of vertical positions in the water column, z_i; and $0 \le x_j \le X$ and $0 \le z_i \le h$. Accordingly, the data collected with the instrumented sled were first used to profile time-averaged longshore velocity and sediment concentration at every station across the surf zone.

Longshore Velocity Profiles

The longshore velocity profile was determined on the basis of the two point measurements of velocity. First, the longshore component of velocity was obtained by projecting the measured east and north velocities in the longshore direction with the use of a dot product and angle of orientation of the shoreline. Mean longshore fluid velocity was then calculated for both velocimeters. GARCEZ FAIRIA *et al.* (1998) and WANG *et al.* (2002) showed that, in the surf zone, the profile of average longshore current is logarithmic in nature. Accordingly, for each station, a logarithmic longshore velocity profile was obtained from the two measured velocities by the linear least-squares method. This time-averaged velocity profile can be written as

$$\bar{u}_y(x_j,\ \mathrm{z}) = \alpha_j \ln(z) + \beta_j \qquad (5)$$

where α_j and β_j are empirical constants determined by the measured longshore velocities at a specific cross-shore location. The velocity profile can also be expressed in terms of a friction velocity, u^*; Von Karmann's constant, $\kappa = 0.4$; and roughness length, z_0.

$$u(z) = (u^*/\kappa)\ \ln(z/z_0) \qquad (6)$$

The logarithmic profile was extended from a depth of 1 cm above bottom to the surface for each station. Because of complicated processes known to exist near the bed, confident extrapolation of the logarithmic profile to elevations less than 1 cm above bottom was prohibited. In rare cases in which the logarithmic profile outlined by Equation (5) predicted negative current values at elevations nearest the bed, β_j was adjusted so as to preclude these negative values. This procedure amounts to a local adjustment of the roughness length and is therefore theoretically justified.

During the data run conducted on August 27, only one velocimeter located at 12.5 cm above bottom recorded flow velocity data. Logarithmic velocity profiles were calculated with the use of that measured data and the average roughness length computed for the August 26 deployment, 0.88 cm ($\pm$0.24 cm). This value was considered approximately valid for the measurements taken on August 27, given the comparable wave conditions and the temporal proximity of the two deployments. The lower velocimeter also failed during the last two stations on May 30. A similar procedure employing the average roughness length calculated for the first 15 stations, 0.4 cm, was used there as well. In addition, in 13% of the current measurements, the velocity at the lower of the two measurement points was greater than that higher in the water column. A constant velocity, computed as the average of the two measured velocities, was used throughout the water column in these cases.

Time-averaged velocities measured during each of the four deployments ranged from 3.6 to 51.8 cm/s. For all reported data sets, Figure 3 gives the longshore velocity at each station as an average of the fitted logarithmic profile, determined every centimeter from 1 cm above bottom to the mean water level, along with surf zone profiles and measured RMS wave heights. For the most part, peaks in average longshore velocity were observed near the innermost two troughs, whereas weaker currents were observed close to the innermost two bars.

Suspended Sand Concentration Profiles

Data from the four OBSs were calibrated with data from the laser particle size analyzer and then used to create profiles of suspended sand concentration at each station in the surf zone. Each OBS time series was first examined for artificial spikes caused by bubbles (SMITH and MOCKE, 2002) and biological interference from fish and kelp (SCHOELLHAMER, 1993). The time series was screened to remove the spurious data points following SATO, HOMMA, and SHIBAYAMA (1990) and SMITH and MOCKE (2002). The mean voltage recorded by each of the four OBSs was then computed for each station. The LISST data were initially filtered for quality by excluding all data points in which the instrument recorded less than 30% computed optical transmission, the level at which multiple scattering effects arise (PENCE, CREED, and RANKIN, 2001). The particle size distribution data were subsequently averaged over each station. The concentrations of all sand-sized particles, taken here to be particles in the range 69–187 μm, were summed, producing a known concentration of sand at the elevation of both the LISST and OBS 3 (16.5 cm above bottom; Table 2).

LUDWIG and HANES (1990) demonstrated that in the presence of a constant concentration of mud, the output voltage of the OBS, V, can be related to a varying concentration of suspended sand, c_{sand}, via a simple calibration equation,

$$c_{\mathrm{sand}} = \frac{1}{g_{\mathrm{sand}}}\cdot V + c_{\mathrm{mud,0}} \qquad (7)$$

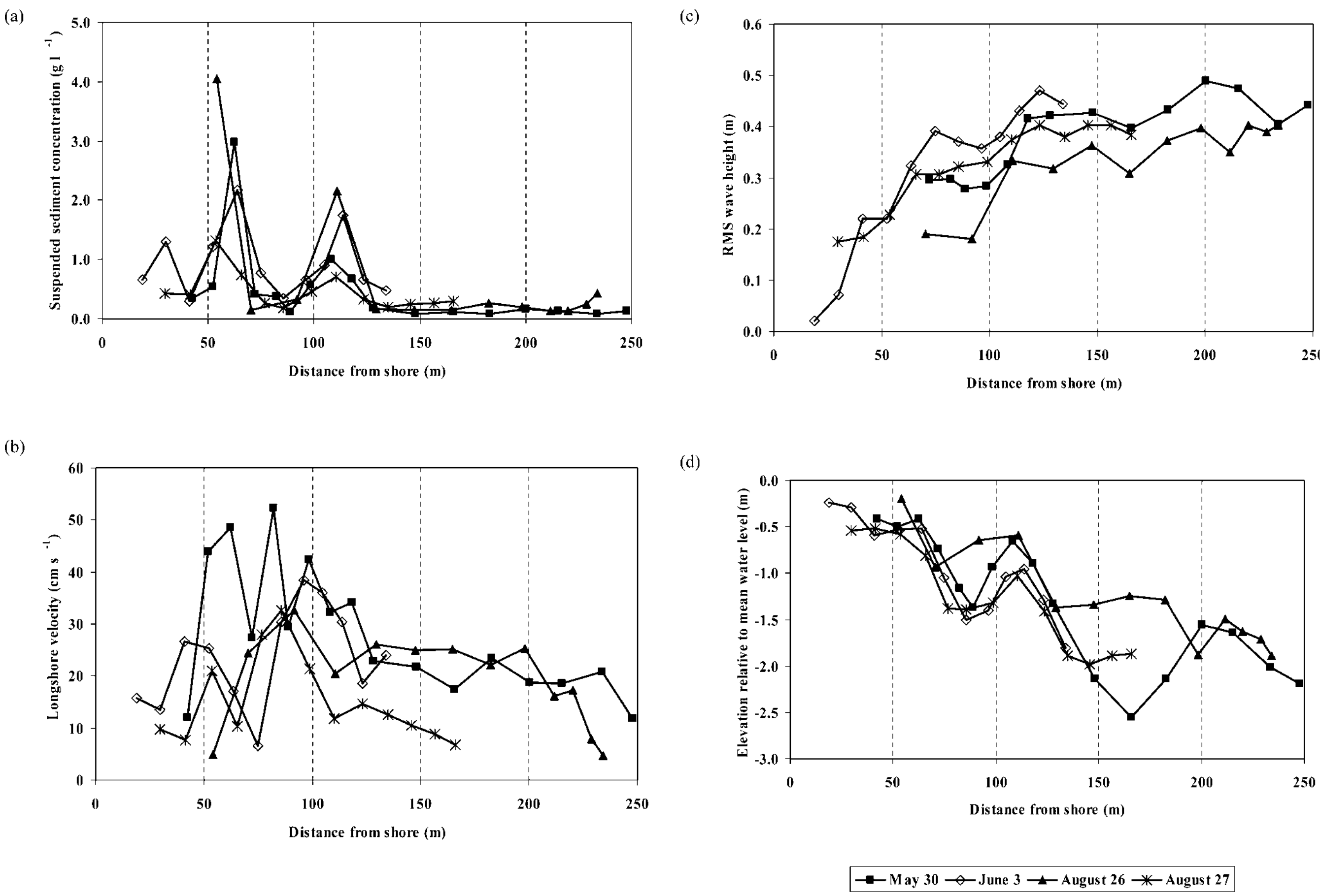

Figure 3. Measured data: (a) depth-averaged suspended sediment concentration, (b) depth-averaged longshore velocity, (c) RMS wave height, and (d) elevation relative to mean water level.

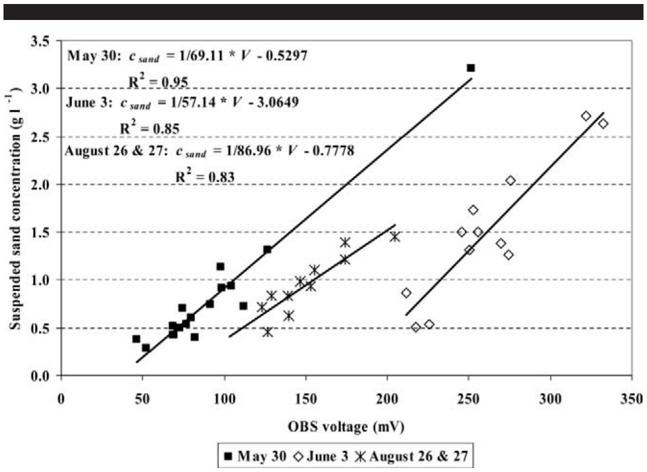

Figure 4. Mean LISST data plotted against OBS 3 voltages with computed OBS calibration curves.

where g_{sand} is OBS gain for sand-sized particles and $c_{\text{mud},0}$ represents the offset from both the background turbidity from suspended mud and the bias in the calibration procedure. In the present case, both the suspended sand concentration and the OBS output voltage were known at one particular depth for numerous locations in the surf zone. Through linear regression, these data sets were used to determine g_{sand} in Equation (7). During the August 26 measurement, the LISST unfortunately became obscured by kelp or other debris, and calibration was not possible. Instead the gain, g_{sand}, and average offset, $c_{\text{mud},0}$, found for August 27 were assumed to be reasonably close to those for August 26 given the short time between the two deployments and the similar wave conditions. Accordingly, these values were used to calibrate the August 26 OBS data.

The linear relationship between suspended sand concentration and OBS voltage for the data sets is documented in Figure 4. As shown on the graph, the calculated gain for sand-sized particles was determined to be about 69 g L^{-1} mV^{-1} on May 30 and 57 g L^{-1} mV^{-1} on June 3. These values were fairly close, as expected, because of the temporal proximity of the two measurements. The gain determined for August 26 and 27, 87 g L^{-1} mV^{-1}, is significantly higher than the gains found for the 2003 deployments. This difference is consistent with the minor adjustments that were made to the OBSs during laboratory calibrations; it might also reflect changes in the particle size distribution of suspended sediment at the study site from 2003 to 2004. The values of the correlation constant R^2 associated with the linear fits for the reported data sets range from 0.83 on August 26 and 27 to 0.95 on May 30.

The LISST data showed that the concentration of fine particles (<69 μm) varied a little across the surf zone. The $c_{\text{mud},0}$ therefore was adjusted slightly for each individual station so that Equation (7) was satisfied precisely. Because all OBSs were set at the same gain in the laboratory, the g_{sand} determined for OBS 3 was considered to be valid for the other OBSs. Similarly, the constant $c_{\text{mud},0}$ determined for OBS 3 was also extended to the other OBSs, assuming that the fine particles were evenly distributed vertically (*i.e.,* $c_{\text{mud},0}$ was not a function of depth). This assumption, formed on the basis of the slow settling velocities of mud particles, as well as the high turbulence in the surf zone, was substantiated by two different sets of secondary LISST measurements made at three elevations spanning the water column. With the use of the determined gain for sand-sized particles and the offset constant computed for each individual station, the mean OBS output voltage for every station was converted to a mean suspended sand concentration via Equation (7).

Many studies have measured suspended sediment concentration under waves and have established a logarithmically
?2 decreasing upward trend (*e.g.,* BOSMAN, VAN DER VELDEN, and HULSBERGEN, 1987; NIELSEN, 1984, 1986). On the basis of these results, a profile of average suspended sand concentration at each station was constructed according to the general form

$$C(x, z) = C_0 \exp\left[-L\frac{z}{h(x)}\right] \qquad (8)$$

where C_0 is sand concentration at the bed, L is a dimensionless constant, and $h(x)$ is water depth. Like the longshore velocity profile, suspended sediment concentration was also extrapolated from a depth of 1 cm above bottom to mean water level.

Time-averaged suspended sand concentrations were found to exist over a wide range of values, from 0.015 g/L at the uppermost OBS to 4.45 g/L at the OBS nearest the bottom. Figure 5 provides suspended sediment concentration data for one representative deployment on August 26. This graph shows that, at most stations, the concentrations at the three sensors near the bottom of the water column were around 1 g/L, significantly greater than the approximately 0.1 g/L concentrations found at the OBS closest to the top. At about 54 and 111 m from shore, however, greater suspended sand concentrations were found throughout the water column. These locations correspond to the two inner sand bars, which were covered by plunging breakers. For the most part, the measured suspended sand concentrations at each station were consistent with the expected logarithmic profile. Concentrations measured at the innermost bar were somewhat more homogeneous than those observed in the troughs; however, a sharp upward decrease in suspended sand concentration was usually only observed seaward of the main breaker line. The slow settling speed of the fine sand at the study site and the multiple breaker lines can perhaps account for this data, which correspond with visual observations of high sand concentrations throughout the surf zone. Additionally, at a few stations, the sediment concentration measured by OBS 3 was slightly higher than the concentrations measured by OBS 2, located lower in the water column. OBS 3, which was attached to the LISST, was located several centimeters behind the other OBSs. This phenomenon was perhaps a consequence of the hydrodynamic disturbance created by the LISST or the sled. Given the relatively minor differences between the two values and the overall logarithmic nature of the data, such effects are believed to be minimal.

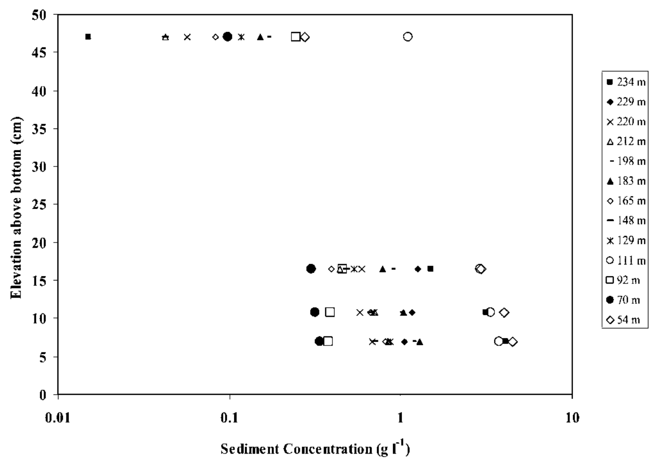

Figure 5. Time-averaged suspended sediment concentration at each station on August 26. Legend specifies distance from shoreline.

Figure 3 shows the suspended sand concentration for each deployment, given as an average over depth of the fitted logarithmic profile from 1 cm above bottom to mean water level. For all deployments, peaks in the measured suspended sediment concentration correspond extremely well with the location of the innermost two bars, where breaking waves were observed. Conversely, low levels of suspended sand are found in the troughs. Average sediment concentrations were generally well below 1 g/L, except in the vicinity of the two sand bars, where average concentrations measured as high as 4 g/L.

Determination of LST Rates on the Basis of Measured Data

The product of the longshore velocity and suspended sand concentration was integrated over depth for each station, yielding the mean longshore sediment flux at that point. Although the percentage of LST flux obtained from extrapolating above the highest sensor varied with cross-shore location, it was generally less than 20%, except near the sand bars where it comprised 30%–40% of the total flux. With the distance between stations, as determined from the total station survey, a cross-shore profile of sediment flux was constructed

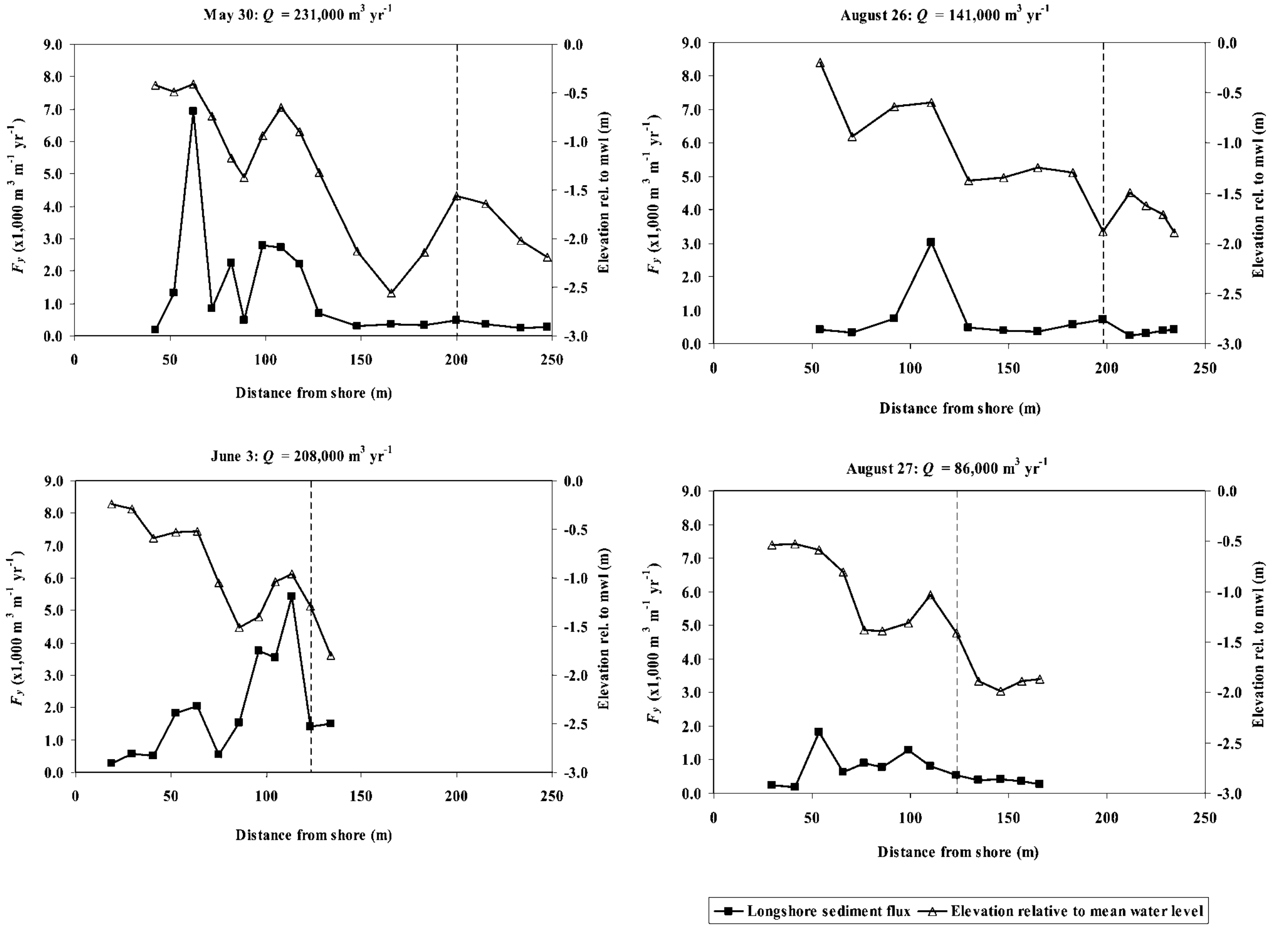

Figure 6. Cross-shore distribution of longshore sediment flux for all reported deployments. Dashed lines indicate the locations of main breaker lines.

(Figure 6). The data show that the peaks in transport flux were consistently at the tops of the sand bars, whereas the lower levels were found in the troughs. Following WANG *et al.* (2002), the location of the main breaker line was estimated to be at the station landward of which a considerable decay in wave height was measured. A second integration, from the shoreline to the main breaker line, as per Equation (4), produced the total LST rate. In this calculation, the sediment flux in the region extending from the station farthest onshore to the shoreline itself was considered to remain constant at the level measured at that station. The measured longshore transport rates for each deployment are given in Table 3, ranging from about 86,000 m³/y on August 27 to 231,000 m³/y on May 30.

Table 3. *Measured and predicted LST rates.*

Date of Measurement	$Q_{MEASURED}$ (×1,000 m³/y)	Q_{CERC} (K_1 = 0.78) (×1,000 m³/y)	% Difference	K_1
May 30, 2003	231	1414	144	0.13
June 3, 2003	208	440	72	0.37
August 26, 2004	141	728	135	0.15
August 27, 2004[1]	86	666	154	0.10
			Average K_1:	0.19

[1] Longshore current estimated with one measurement only.

Comparison with the CERC Formula Calculation

The measured LST rate was compared with that calculated from the CERC formula. The CERC formula, recommended by the *Shore Protection Manual* (CERC, 1984), is a widely used empirical expression relating the LST rate to the energy flux at breaking, given in terms of the wave conditions at breaking. One formulation can be written as

$$Q = \frac{K_1}{16(\rho_s/\rho - 1)(1 - p)} H_b^2 C_{gb} \sin(2\theta)_b \qquad (9)$$

where K_1 is an empirical coefficient; H_b is RMS wave height at breaking; C_{gb} is wave celerity at breaking; θ_b is incident wave breaker angle, relative to shore-normal; ρ_s and ρ are sediment and water densities, respectively; and p is sediment porosity, nominally 0.4 (HANSON and KRAUS, 1991). Assuming shallow water wave conditions, the wave celerity, C_{gb}, is taken to be $\sqrt{gh_b}$, where g is acceleration of gravity and h_b

is water depth at breaking. The *Shore Protection Manual* suggests the coefficient K_1 be set at 0.78, although several authors have found a better fit to field data by deviating from that coefficient (*e.g.,* BODGE and KRAUS, 1991; SCHOONESS and THERON, 1993; WANG, KRAUS, and DAVIS, 1998). In this study, the LST rate predicted by the CERC formula was calculated via Equation (9) with 0.78 as the coefficient. Wave height at breaking, H_b, and water depth at breaking, h_b, were computed according to linear wave theory from pressure data at the station determined to be the location of the main breaker line. Incident wave angles were derived by first calculating the difference between the velocity signal at each station and the time-averaged velocity at that station. The resulting wave signal was then analyzed to determine the dominant direction following the procedure described by MADSEN *et al.* (1993). The incident wave breaker angle, θ_b, was taken as the average of the wave angles at and preceding the main breaker line.

Table 3 presents the LST rates predicted by the CERC formula for each deployment, which range from approximately 440,000 m^3/y to 1,414,000 m^3/y, and the percent difference between the measured and predicted rates. The CERC formula transport rates were consistently higher than the corresponding measured rates, with the difference between the two on the order of 100%. For each deployment, the measured LST rate was fit to the CERC formula by adjusting the empirical constant K_1, the results of which are also shown in Table 3. The average calculated K_1 was then determined to be 0.19 ± 0.12 on the basis of the four sets of LST and wave measurements.

DISCUSSION

Uncertainty and Error in LST Measurements

The LST measurements and K_1 calculation reported in this study carry significant associated uncertainties, primarily because of the unsteadiness of wave conditions and sand transport in the surf zone. Wave trains arrive every several minutes, leading to significant variation in wave height over that time period. Wave conditions at each station, however, were determined with only 2–3 minutes of data. Therefore, the measured wave conditions could be high or low relative to the "average" transport conditions measured throughout the surf zone during the 60–90-minute sampling period. Given that the goal of this research was to obtain a snapshot of the sediment transport from breaking waves, such a sampling window was the maximum allowable because tidal effects become more significant if field data are collected over 2–3 hours. In addition, memory limitations of the LISST mandated a shorter sampling time at each station and, as such, could be improved upon in future studies. Most likely, this source of uncertainty is more significant than other sources, including the sampling of longshore transport at a discrete number of locations (as opposed to continuous sampling) and the uncertainties in sand concentration and longshore current.

The magnitude of the uncertainty in the LST measurements presented here is consistent with that reported elsewhere. In a large-scale laboratory study of transport rates, WANG *et al.* (2002) estimated that LST rates calculated from the product of time-averaged longshore current and suspended sand concentrations carry substantial uncertainties of up to 30%–40%. Furthermore, uncertainties associated with estimates of longshore sediment flux at a single cross-shore location were predicted to be as great as 200%. The uncertainty in the calculated K_1 empirical constant could also indicate that other terms besides wave height at breaking and incident wave angle—for example wave period, beach slope, grain size, and breaker type—need to be included in a formulation for estimating transport rates. Reaching the same conclusion, KAMPHUIS *et al.* (1986) developed an empirical formula that included beach slope and sediment grain size, which was later modified by KAMPHUIS (1991) to incorporate wave period as well. Future work should compare the results of the technique developed here with the LST rates predicted by these and other empirical formulas.

In addition to these uncertainties, two probable sources of bias exist. The omission of measurement of bedload transport could lead to an underestimation of total transport. Several conflicting views have been put forth regarding the importance of the bedload to total transport rates (*e.g.,* INMAN *et al.*, 1981; KANA and WARD, 1981; KOMAR, 1978; KRAUS and DEAN, 1987; STERNBERG, SHI, and DOWNING, 1984). At present, the question of the significance of bedload transport relative to suspended load transport on beaches does not have a definitive answer. When measuring LST during storms, MILLER (1999) neglected the contribution of the bedload and assumed that the transport was well approximated through measurements of suspended sediment concentration and fluid velocity at elevations of 3 cm and greater above the bed. Considering the high suspension rates at the current study site, bedload was tacitly assumed to be small compared with the suspended load, allowing the transport rate to be reasonably well estimated *via* water column measurements alone. Although this assumption might in fact lead to slightly underestimated total transport rates, the error introduced is thought to be acceptably small compared with the total LST rate, given that the sand was fairly fine. Further work is necessary to precisely quantify the role that bedload transport plays in controlling total LST rates.

The second possible source of bias in the technique used here concerns the calculation of the wave height at breaking. This method computed average wave height at each station and then specified wave height at breaking as the wave height at the station determined to be the main breaker line. This probably leads to an underestimation of the true breaking wave height, given that the main breaker line is not likely to be located exactly at any particular station. In addition, breaking waves tend to rise to their greatest height immediately before breaking, which would not be accurately represented by the current calculation of wave height. This potential underestimation of breaking wave height implies that the transport rates calculated here with the CERC formula might in fact be reduced and that a greater disagreement between measured and predicted rates could exist. In future work, the spacing between stations could be reduced in the vicinity of wave breaking to minimize this bias.

Measured Transport Rates and Flux Distribution

Overall, the LST rates measured in this study appear quite reasonable. Taking into account the uncertainties associated with these values, the transport rates measured on May 30, August 26, and August 27 correlate fairly well with the observed wave conditions, as demonstrated by the similar K_1 values calculated from those data sets. The LST rate determined on June 3 is much greater than would be expected if transport was solely a function of the wave environment at the breaker line. Wind data and other factors might help better explain the variance in the observed rates than the wave data alone do. Measurement uncertainties, in particular variability in the wave conditions at breaking, undoubtedly also contribute to these disparities.

The LST rates determined in this investigation are the first measurements of LST made along the Texas Gulf Coast, and as such, comparisons with previous local results are not possible. In the most similar study, WANG, KRAUS, and DAVIS (1998) made measurements of surf zone LST rates in low–wave energy environments along the Florida Gulf Coast with streamer traps and short-term impoundment. They found total LST rates that varied between 1000 and 145,000 m^3/y. The breaking wave heights of this study ranged from 0.14 to 0.79 m; incident wave angles from 1.8 to 35.5 degrees; and wave periods from 2.8 to 10.5 s. On the basis of their measurements, WANG, KRAUS, and DAVIS (1998) calculated the CERC formula K_1 to be 0.08 and argued that K_1 is small for low wave conditions. The results of this study support that conclusion, insofar as K_1 was estimated to be about 0.19 for measurements taken in fairly weak wave environments. However, these values are significantly less than those determined in other studies (*e.g.,* BODGE and KRAUS, 1991; KOMAR and INMAN, 1970; MILLER, 1999). Additional study is needed to more accurately assess the effects of sediment grain size and beach profile on sediment transport and to further investigate the differences between measurement techniques.

Also instructive is a comparison of the cross-shore distribution of longshore sediment flux found in this study with that determined by others. During storms, MILLER (1999) observed a bimodal distribution of LST with one peak at the seaward side of the bar and one peak between the midsurf location and the beach. These results are similar to the cross-shore distribution measured in this study. In the controlled environment at the U.S. Army Engineer Research and Development Center's Large-Scale Sediment Transport Facility, WANG *et al.* (2002) found that the cross-shore distribution depended on breaker type. For plunging breakers, a large increase in flux was observed at the breaker line and another in the swash zone. For spilling breakers, a significant peak was observed only in the swash zone. Although the hydrodynamic conditions at the study site of this investigation were considerably more complicated than those in the laboratory, the distributions measured here agree fairly well with these results, given that plunging breakers were observed at the tops of the sand bars. Examination of the data collected here also shows that peaks in longshore sediment flux seem to be more strongly related to peaks in suspended sand concentration, as opposed to peaks in longshore velocity, a finding also reported by MILLER (1999).

CONCLUSIONS

The objectives of this study, to explore the use of optical sensors calibrated *in situ* via a particle size analyzer and to measure LST rates for Galveston Island along the Texas Gulf Coast, were achieved. The use of a laser particle size analyzer to quickly calibrate OBSs *in situ* provided an excellent means for measuring suspended sand concentration with these sensors in a mixed sand-mud environment. Difficulties experienced with this method were primarily due to instrument malfunctions and can therefore be easily rectified for future studies. An effort should be made to more firmly establish the accuracy of this technique and to continue its development, including adding more sensors at adjustable elevations.

Longshore sediment transport rates determined in this study were found to be significantly less than the rates predicted by the widespread CERC formula with the coefficient recommended by the *Shore Protection Manual* (CERC, 1984). Differences between the measured rates and those calculated by the CERC formula were on the order of 100%. The measured cross-shore distribution of longshore sediment flux varied considerably, although peaks generally occurred at the tops of the sand bars. Given the highly contradictory views regarding the accuracy and applicability of the CERC formula, future work should compare measured LST rates with those predicted by various other empirical formulas in existence. To resolve these issues and develop a more complete understanding of the processes involved in LST, it is essential to continue conducting field measurements over a wide range of hydrodynamic and morphological conditions.

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