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# Total Longshore Sediment Transport Rate in the Surf Zone: Field Measurements and Empirical Predictions

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**ABSTRACT**

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The total rate of longshore sediment transport was measured by streamer traps at 29 locations along the southeast coast of the United States and the Gulf Coast of Florida. The rate was also measured concurrently by traps and by short-term impoundment at Indian Rocks Beach, west-central Florida. Data on beach profiles, breaking wave conditions, and sediment properties were taken together with the transport rate. The measured total rates of longshore sediment transport were compared to predictions obtained with published empirical formulas, most of which have been calibrated mainly by sediment tracer measurements made on the (high-wave energy) Pacific coast. Transport rates measured in this study by the streamer sediment traps and the short-term impoundment along low-wave energy coasts were considerably lower than the rates predicted by empirical formulas. The empirical predictions appear to be unrealistically high for the low-wave energy settings investigated in this study. The linear relationship between wave energy flux factor and the total rate of longshore sediment transport contained in the commonly used CERC predictive formula is supported by the streamer trap measurements. However, a lower value of the empirical coefficient, 0.08 instead of the 0.78 recommended by the Shore Protection Manual, was determined by the trap data for low-energy coasts. The total rates of longshore sediment transport predicted by the KAMPHUIS (1991) formula which includes the influences of wave period, beach slope, and sediment grain size were about 3 times lower than the CERC predictions and closer to the measured values.

**ADDITIONAL INDEX WORDS:** *Longshore sediment transport, streamer trap, groins, sediment grain size.*

## INTRODUCTION

Prediction of the total rate of longshore sediment transport is central to most coastal engineering and science studies. Quantitative aspects of longshore sediment transport on beaches have been studied by coastal engineers, geologists, and oceanographers for about five decades. Three standard techniques have been developed for the measurement of the total (suspended load and bed load) longshore sediment transport (TLST) rate in the field: sediment tracer, short-term impoundment, and streamer sediment traps. Sediment tracer has been used to measure the TLST for three decades. Most of the available field data that are used to calibrate empirical prediction formulas were obtained through the tracer technique (principally, from KOMAR and INMAN, 1970; INMAN *et al.*, 1981; DUANE and JAMES, 1981; and KRAUS *et al.*, 1983). Various optical and acoustic techniques have been developed to measure suspended sediment concentration (*e.g.*, DOWNING *et al.*, 1981; STERNBERG *et al.*, 1989; GREENWOOD *et al.*, 1991) from which the suspended sediment flux can be calculated. Some new optical and acoustical techniques were tested during the DUCK94 field campaign (BIRKEMEIER, 1994). Although optical and acoustic techniques are capable of providing measurements with high spatial and temporal resolution, they have not been broadly used for many reasons; among them, high cost, lack of reliable field calibration, and omission of the bedload remain the major obstacles.

Sediment tracer measurements have been conducted at only a few locations, mostly along the Pacific coast, due to their high cost and labor-intensive operation. The majority of the high-quality tracer data were collected from the late 60's to early 80's. Tracer theory and operation have been reviewed by GALVIN (1987), MADSEN (1987, 1989), and DRAPEAU *et al.* (1991). MADSEN (1987, 1989) examined the assumptions behind tracer methodologies and concluded that their use for the determination of TLST is difficult. GALVIN (1987) pointed out operational difficulties in the determination of the two key measurements; mixing depth and center of mass. DRAPEAU *et al.*, (1991), on the other hand, concluded based on their radioactive tracer study that tracers do fulfill the purpose for which they are used and can supply valid sediment transport data if knowledge and care are exercised. Applicable or not, the sediment tracer method is an indirect tech-

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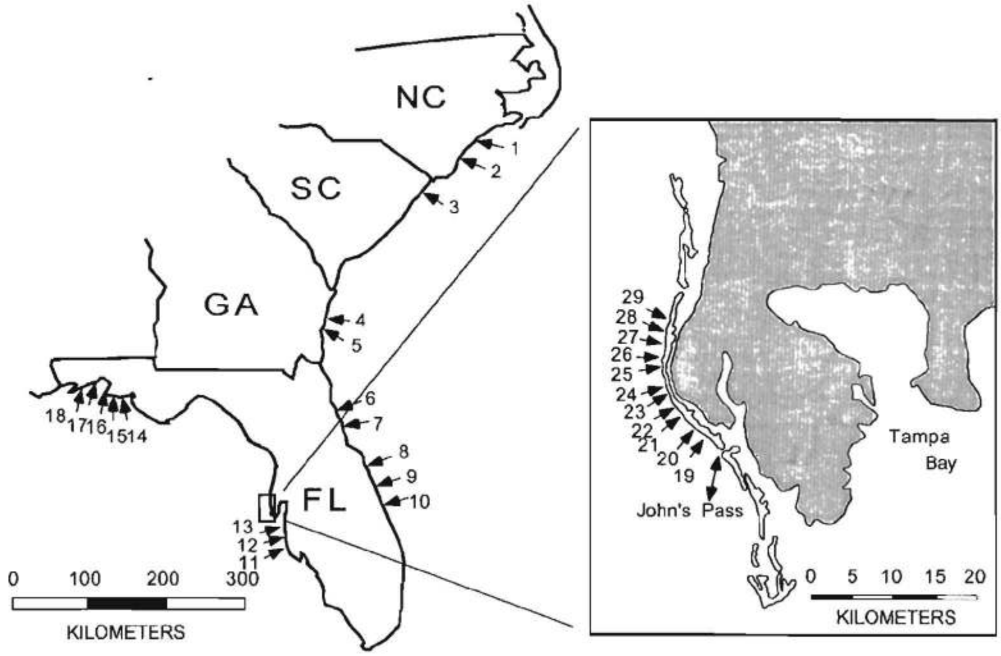


Figure 1. Locations of field sites and site ID.

nique. That is, the sediment flux is inferred by separately quantifying the vertical and horizontal movement of tracers. It is necessary to verify the technique with direct measurements.

The impoundment technique (blocking by structures) has been used to estimate the TLST rate (*e.g.*, JOHNSON, 1957; BRUNO and GABLE, 1977; BRUNO *et al.*, 1981a; BRUNO *et al.*, 1981; DEAN *et al.*, 1983; DEAN *et al.*, 1987; DEAN, 1989). In short-term impoundment, the structure is constructed temporarily only for the purpose of TLST rate measurement and removed after the experiment is completed. A successful example was described by BODGE (1986) and by BODGE and DEAN (1987). The measurement was conducted by quickly constructing a specially designed sand bag groin to intercept the longshore sediment transport. The volume transport rate is obtained by quantifying the morphological change updrift and downdrift of the groin.

In the present study, two techniques, the recently developed streamer sediment traps and short-term impoundment, were applied to measure the TLST rate under low-energy conditions. The trap measurements were conducted at numerous locations along the southeast coast of the United States and the Gulf coast of Florida. One combined streamer trap and short-term impoundment experiment was also performed. The results are compared to the predictions from common empirical formulas. The objective of this study is to examine and evaluate the empirical TLST rate predictions which were calibrated mainly by tracer measurement through use of the more direct streamer trap and short-term impoundment techniques along low-energy coasts.

## STUDY AREAS

Twenty-nine streamer trap experiments and one short-term impoundment experiment were conducted under low-energy condition along the southeast coast of the United States and the Gulf coast of Florida from September, 1993, to May, 1995 (Figure 1). The field sites were selected so that wide ranges of morphodynamic and hydrodynamic conditions were included. Seven out of the 29 trap experiments were conducted on barred coasts with waves breaking on the longshore bar. Eighteen were on coasts with negligible offshore bar influence on the breaking waves. Four experiments were conducted in the inner surf on barred coasts because of operational difficulties associated with high waves and a deep bottom trough. Twelve field sites had a plunge step at the breaker line or the secondary breaker line for the case of the barred coasts.

Hydrodynamical and morphodynamical conditions of the 29 field sites at the time of measurements are summarized in Table 1. Surf zone width ranged from as narrow as 2 m in one of the Florida Panhandle sites to as wide as 54 m at Redington Beach, Florida, immediately after a winter storm. The average surf zone width was 14 m with a standard deviation of 13 m, indicating a broad distribution. The cross-sectional area of the surf zone was calculated based on the measured water level and beach profile. Wide ranges of the cross-sectional area of the surf zone and average beach slope were measured.

The TLST-measurements were conducted under a variety of hydrodynamic conditions (Table 1). Root-mean-square (RMS) wave height, calculated based on at least 20 measured

Table 1. *Summary of hydrodynamic and morphodynamic conditions at the field sites.*

| Location & Site ID (Fig. 1) | No. of Trap Arrays | Surf Zone Width (m) | Beach Slope# | Avg. Grain Size### (mm) | $H_{rms}$ (m) | Incident Wave Angle (deg.) | Wave Period (s) |
|---|---|---|---|---|---|---|---|
| 1. Emerald Isle, NC | 4 | 35 | 0.028 | 0.35 | 0.79 | 13.5 | 7.5 |
| 2. Onslow Beach, NC | 3 | 7## | 0.094 | 2.25 | 0.61 | 12.0 | 6.0 |
| 3. Myrtle Beach, SC | 5 | 24 | 0.030 | 0.26 | 0.51 | 4.0 | 8.5 |
| 4. Jekyll Island, GA | 2 | 9 | 0.044 | 0.17 | 0.20 | 3.0 | 3.5 |
| 5. Jekyll Island, GA | 3 | 14 | 0.033 | 0.26 | 0.35 | 10.0 | 3.3 |
| 6. Anastasia Beach, FL | 6 | 36 | 0.013 | 0.19 | 0.49 | 5.5 | 10.5 |
| 7. N. Mantazas Beach, FL | 3 | 14 | 0.031 | 0.28 | 0.44 | 7.2 | 7.2 |
| 8. Canaveral Seashore, FL | 3 | 6## | 0.115 | 0.90 | 0.46 | 9.0 | 3.5 |
| 9. Melbourne Beach, FL | 2 | 4## | 0.158 | 1.50 | 0.50 | 2.5 | 3.5 |
| 10. Beverly Beach, FL | 2 | 3## | 0.161 | 0.41 | 0.36 | 11.5 | 3.5 |
| 11. Lido Key Beach, FL | 4 | 38 | 0.105 | 0.68 | 0.38 | 14.0 | 3.7 |
| 12. Lido Key Beach, FL | 5 | 35 | 0.101 | 0.54 | 0.34 | 19.0 | 3.4 |
| 13. Lido Key Beach, FL | 4 | 21 | 0.101 | 0.37 | 0.21 | 2.6 | 3.0 |
| 14. St. George Island, FL | 3 | 3 | 0.123 | 0.29 | 0.29 | 35.3 | 3.0 |
| 15. St. George Island, FL | 4 | 4 | 0.214 | 0.41 | 0.22 | 31.5 | 2.9 |
| 16. St. George Island, FL | 3 | 2 | 0.129 | 0.43 | 0.28 | 23.0 | 3.0 |
| 17. St. Joseph Island, FL | 4 | 10 | 0.062 | 0.24 | 0.53 | 9.3 | 4.2 |
| 18. Grayton Beach, FL | 4 | 29 | 0.042 | 0.28 | 0.56 | 8.5 | 4.5 |
| 19. Redington Beach, FL | 3 | 4 | 0.125 | 0.85 | 0.36 | 8.4 | 4.5 |
| 20. Redington Beach, FL | 3 | 11 | 0.035 | 0.20 | 0.28 | 10.7 | 3.9 |
| 21. Redington Beach, FL | 4 | 19 | 0.026 | 0.90 | 0.32 | 19.2 | 4.5 |
| 22. Redington Beach, FL | 4 | 17 | 0.016 | 0.43 | 0.24 | 15.8 | 4.9 |
| 23. Redington Beach, FL | 4 | 54 | 0.014 | 0.37 | 0.69 | 13.1 | 7.3 |
| 24. Indian Shores, FL | 3 | 12 | 0.039 | 0.32 | 0.36 | 20.0 | 4.5 |
| 25. Indian Shores, FL | 1 | 4 | 0.082 | 0.40 | 0.31 | 1.8 | 3.3 |
| 26. Indian Rocks Beach, FL | 2 | 4 | 0.072 | 0.28 | 0.36 | 7.7 | 2.9 |
| 27. Indian Rocks Beach, FL | 3 | 7 | 0.066 | 0.42 | 0.34 | 7.5 | 4.2 |
| *28. Indian Rocks Beach, FL | 2 | 2 | 0.141 | 1.38 | 0.19 | 10.0 | 2.8 |
| *29. Indian Rocks Beach, FL | 2 | 2 | 0.152 | 1.29 | 0.14 | 8.2 | 3.8 |

*Simultaneous impoundment and sediment trapping
#Determined from the breakerline to the shoreline
##Number indicates width of the inner surf zone, unable to perform trapping in the trough or on the bar due to rough conditions
###Average of the surface samples collected at each trap location (see Methodology for detail)

wave heights from video images, ranged from 0.1 to 0.8 m, representing relatively low wave-energy conditions. The trap measurements were conducted under conditions of plunging, spilling, and collapsing breakers. Incident wave angle ranged from 2 to 35 deg. The extremely oblique wave angle was measured in the Florida Panhandle where the waves were generated by local wind. Wave period ranged from less than 3 sec for locally generated seas in the Gulf of Mexico to more than 10 sec for the swells along the Atlantic coast.

Sediment properties changed from beach to beach as well as from one part of a beach to another. The average bottom sediment grain size of the selected beaches, which was obtained by averaging the three to six bottom sediment samples collected at every trap location, ranged from 0.17 mm (2.55 $\phi$) to 2.25 mm ($-1.17$ $\phi$). Sediment grain size also varied significantly in different parts of the same surf zone at any given time. The difference in mean grain size could be as great as 3.7 mm (3.52 $\phi$, $-2.02$ $\phi$ at breaker line and 1.50 $\phi$ in the trough).

One of the different features of many of the studied beaches, especially along the Florida coast, is the high concentration of platy shell debris from bivalves. The shell content was measured by the percent carbonate concentration in the sediment samples via dissolving in dilute HCl. The platy shell debris behaves differently than the spherical grains during transport. The shape of surf zone sediment, as indicated by the concentrations of platy shell materials in the gravel fractions, varied from beach to beach as well as in different parts of the same surf zone (WANG *et al.*, in press).

## METHODOLOGY

### TLST Measurement with Streamer Traps

The TLST rate was measured by streamer sediment traps (KATORI, 1983; KRAUS, 1987; ROSATI and KRAUS, 1988, 1989) and by short-term impoundment (BODGE, 1986; BODGE and DEAN, 1987). The streamer traps (Figure 2) used in this study are similar to the original design of KRAUS (1987) except that the racks are made from PVC pipes instead of stainless steel rods. The PVC racks are inexpensive and easier to construct, and they work well in the low-energy settings (WANG and DAVIS, 1994; WANG, 1995). The legs of the rack were shortened for easier operation and more efficient bedload trapping.

The opening of the streamer is 15 × 9 cm with the distance between two adjacent streamer bags being 6 cm. The mesh size of the sieve cloth from which the streamers are made is 63 microns, thereby allowing mud particles to pass through. Mesh size is not considered to introduce measurement error because mud is essentially absent from the surf zone. Mesh

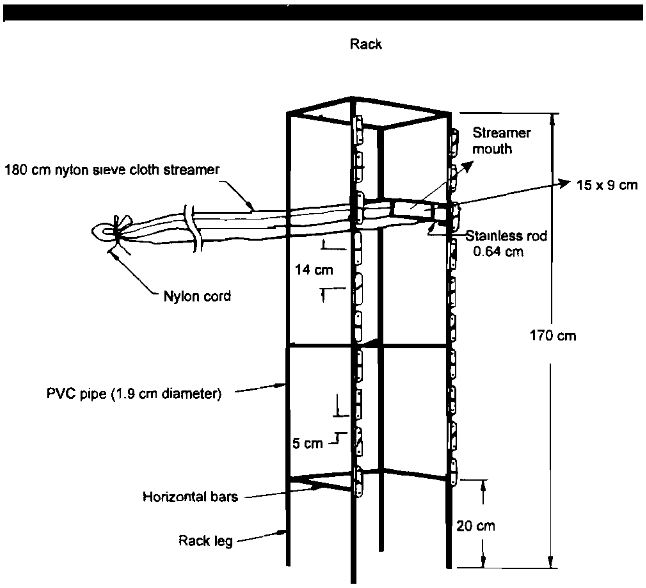


Figure 2. Design of the streamer traps (modified from the original design of Kraus, 1987).

bags of different lengths were mounted at different water depths. Longer bags (~120 cm) were mounted at the bottom three levels and shorter bags (~70 cm) were used at the higher levels. This design allowed good coverage throughout the water column, easy assembly, and efficient sediment sampling.

Four to eight streamer bags were mounted on each rack as determined by the water depth and breaker height. This assemblage is called a one-trap array. Each TLST-measurement experiment was composed of three to six streamer-trap arrays spanning the surf zone.

Beach profiles were surveyed with an electronic total station. Zero water depth at the time of sediment trapping was determined during the survey for the computation of the surf zone cross-sectional area. The locations of the trap arrays and wave poles were surveyed and marked on the beach profile.

Scaled photo poles were used to measure the wave height. For barred-beach locations, three poles were deployed with one at the bar breaker line, one in the trough, and one at the secondary breaker line. For non-barred beaches, one pole was established at the breaker line, one in the swash, and sometimes an additional pole was placed in the bore area between them.

At least twenty wave heights and periods were measured from the video images using the scaled pole as a reference. Five to fifteen incident wave angles were measured in the field with a hand-held compass. RMS wave height was determined as

$$H_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} H_i^2} \qquad (1)$$

where $H_i$ is the measured wave height, and $N$ is the number of measurements. Average wave period and incident angle were calculated to establish the relationship between hydrodynamic conditions and the TLST rate.

A bottom sediment sample was also collected at each trap location. It is assumed that the bottom sediment characteristics can be represented by an 8-cm-long core sample. the bed-load and suspended sediments were sampled simultaneously by the streamer traps. Generally, one bed-load and two to seven suspended sediment samples were collected at each trap location.

The placement of streamer traps in the surf zone was based on morphologic and hydrodynamic conditions. The general placement of trap arrays for a barred coast was one trap array on top of the bar, one in the trough, one at the secondary breaker line, and one in the swash. On a non-barred coast, the commonly used arrangement was one at the breaker line, at least one in the surf bore area, and one in the swash.

The trapping duration was determined based on the general perceived TLST rate and trapping conditions. The duration was typically 5 min. In high wave and/or high-transport situations, the duration was shortened to 3 min. The performance of the streamers was closely monitored to assure that the streamer bags were not tangled. Shorter legs (Figure 2) and slight adjustment of the streamer level were utilized to minimize scour at the bottom streamer, which rested on the bed. A standard set of field procedures was established to ensure that the data were collected in the same manner in all experiments (Wang, 1995).

## TLST Measurement by Short-Term Impoundment

Two short-term impoundment experiments were conducted on Indian Rocks Beach, Florida, under low wave-energy conditions. The first experiment was conducted under normally incident waves and served to test the stability of the impoundment barrier and its influence on the hydrodynamic processes. The second experiment was performed under obliquely incident waves. The TLST rate was obtained through quantifying the volumetric change that occurred between topographic surveys.

The temporary barrier, 10 m long, was composed of a series of plywood sheets (Figure 3) with angle irons attached to one side to act as stakes. The barrier was established by simply pounding the angle irons which carry the board into the sand, causing the plywood to rest directly on the substrate. Topographic surveys were conducted in a closely spaced grid, at 1- to 2-m spacing, both updrift and downdrift of the barrier. A video camera recorded the performance of the barrier.

The surveys were conducted using a SOKKIA Set 4B Electronic Total Station. The pre-installation morphology, both updrift and downdrift, was surveyed as the reference. The barrier installation took less than 30 min. Two topographic surveys were conducted on the same grid at 127 and 217 min after the installation. The survey procedures took about 54 min to complete and actually started 100 min and 190 min after the installation. The mid-points of 127 min and 217 min were used to calculate the rate of volume change.

Streamer sediment traps were deployed 50 and 170 min after the installation. It is assumed that the transport rate between installation and 127 min remained relatively con-

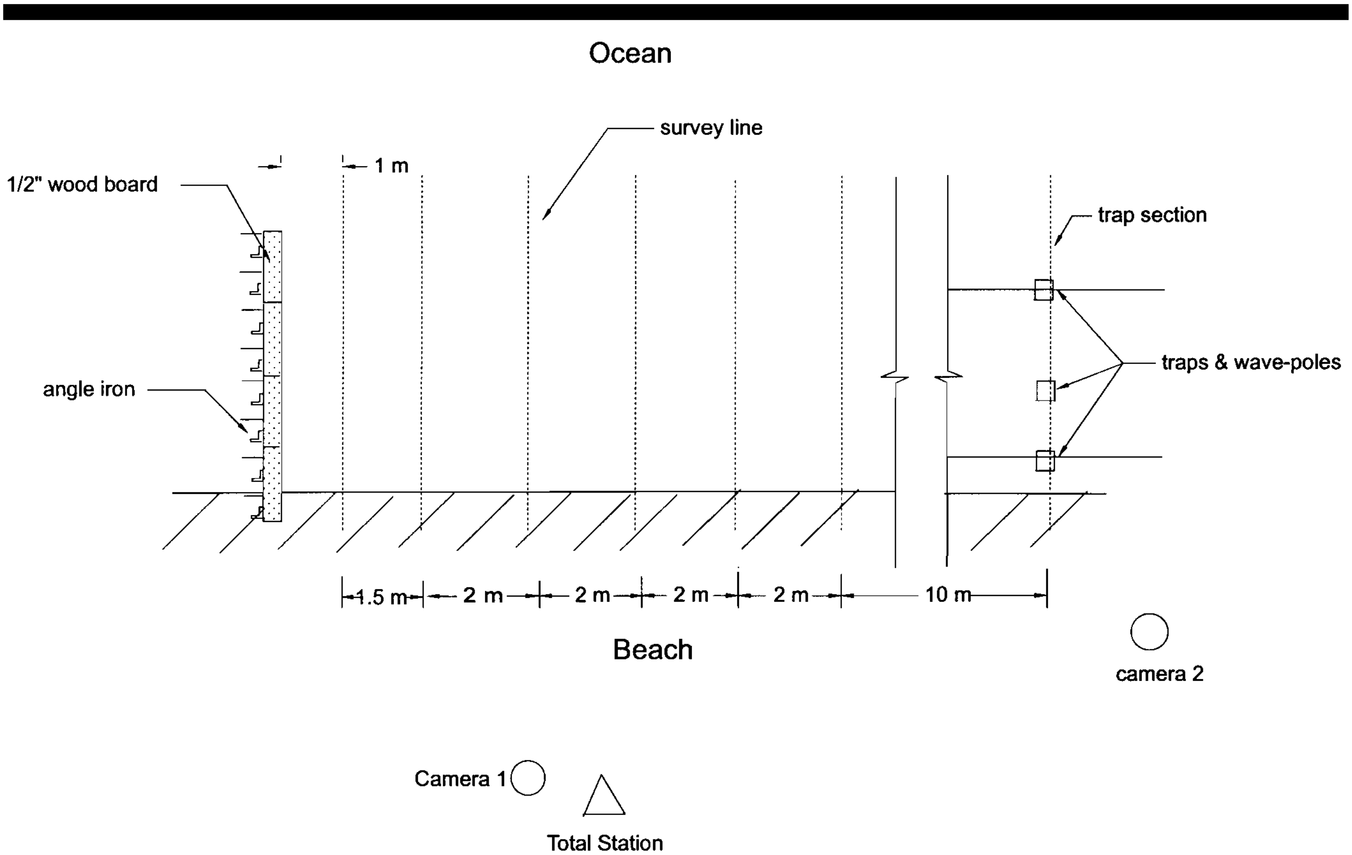


Figure 3. Design and instrument layout for the impoundment experiment. The survey line spacings are modified for the second experiment based on experience from the first one (shown in this figure). This diagram shows the updrift half of the survey grid; the downdrift half is the mirror image except the streamer trap profile.

stant so that it can be represented by the transport rate measured between 50 to 55 min (the trap measurement started at 50 min and stopped at 55 min). The objective was to compare the short-term impoundment and streamer trap measurements.

The experiments were performed on days with minimal tidal influence, a range of less than 30 cm. The updrift and downdrift areas were surveyed with the same grid spacing. Control lines for the monitoring of cross-shore transport were surveyed both updrift and downdrift. In this experiment, it was assumed that the influence of the temporary barrier occurred within 10 m updrift and downdrift of the barrier.

### Calculation of TLST Rate From Streamer Traps

The TLST rate was obtained by integrating the measured sediment flux vertically and horizontally. Sediment flux between two adjacent streamer bags was obtained through linear integration.

$$\Delta F_i = \frac{\left(\frac{F_{i+1}}{z_{i+1}} + \frac{F_{i-1}}{z_{i-1}}\right)\Delta Z_i}{2} \tag{2}$$

where $\Delta F_i$ is the sediment flux between two adjacent streamer bags, $F_{i+1}$ and $F_{i-1}$ are fluxes through the upper and lower bags, respectively; and $z_{i+1}$ and $z_{i-1}$ are the vertical width of the opening of the upper and lower streamers, respectively. The elevations $z$ are both 9 cm for the traps that were used in this study. The distance $\Delta z_i$ between the two adjacent bags equaled 6 cm on these racks. A similar algorithm was used by KRAUS *et al.* (1989) and ROSATI *et al.* (1990, 1991). The sediment flux at one trap array ($I$) is then obtained by summing the sediment flux through each streamer bag and the flux between two adjacent bags as calculated from Equation (2)

$$I = \sum_{i=1}^{N} (F_i) + \sum_{i=1}^{N-1} (\Delta F_i) \tag{3}$$

where $N$ is the number of streamers that are mounted on the rack.

The TLST rate was calculated based on the divisions shown in Figure 4. During the field measurement, the traps were arranged in such a way that the areas with different transport rates were covered by at least one trap array. It is assumed that the transport rate between two adjacent arrays can be represented by the average of the fluxes between the two trap arrays. The TLST rate was then calculated as

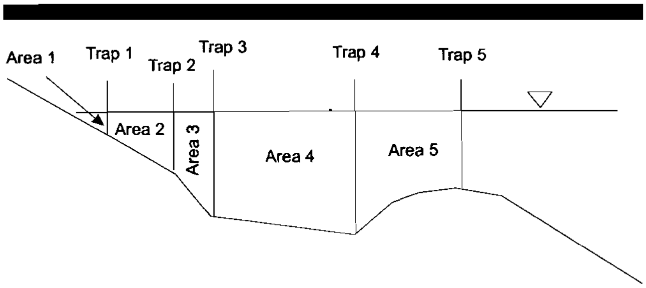


Figure 4. Divisions of the surf zone for the purpose of the total longshore sediment transport rate calculation from the streamer trap measurements.

$$Q_{total} = \sum \frac{I_i + I_{i+1}}{2} A_i \quad (4)$$

where $I_i$ is the sediment flux measured at trap array $i$, and $A_i$ is the surf cross-sectional area between traps $i$ and $i + 1$. The total transport rate was converted to cubic meters per year for comparison of values.

### Calculation of TLST Rate by Impoundment

The TLST rate from the impoundment experiment was calculated from the updrift and downdrift volume changes. No dramatic elevation changes were observed between two survey lines. It is reasonable, therefore, to assume that the change between two survey lines is linear. The volume change between two lines can then be calculated as the volume of a right trapezoidal prism. Profile change measured at the updrift and downdrift control lines are believed to be the result of the cross-shore sediment transport caused by the falling tide. This profile change was subtracted from the updrift accretion and added to the downdrift erosion to eliminate the influence of cross-shore transport caused by water level (tidal) change. The updrift volume change was calculated as

$$V_{U\ total} = \sum \left(\frac{1}{2}[(V_{pi} - V_{pT}) + (V_{p(i+1)} - V_{pT})]L_p\right) \quad (5)$$

and the downdrift volume change was calculated as

$$V_{D-total} = \sum \left(\frac{1}{2}[(V_{pi} + V_{pT}) + (V_{p(i+1)} + V_{pT})]L_p\right) \quad (6)$$

where $V_{pi}$ and $V_{p(i+1)}$ are the profile volume changes (in m$^3$/m) between two surveys, such as those between pre-installation and 127 min or between 127 min and 217 min, at adjacent survey lines $i$ and $i + 1$, respectively. $V_{pT}$ is the correction of cross-shore transport, which was caused by the tidal water level change, obtained from the control lines 20 m from the groin. $L_p$ is the distance between the two adjacent survey lines. The volume transport rate can then be calculated as

$$Q_{updrift} = \frac{V_{U\text{-}total}}{\Delta t} \quad (7)$$

or

$$Q_{downdrift} = \frac{V_{D\text{-}total}}{\Delta t} \quad (8)$$

where $Q_{updrift}$ and $Q_{downdrift}$ are the sediment volume transport rates obtained from updrift accretion ($V_{U\text{-}total}$) and downdrift erosion ($V_{D\text{-}total}$), respectively, and $\Delta t$ is the time interval between two surveys.

## PREDICTIVE FORMULAS FOR THE TLST RATE

A general expression for the time-averaged TLST rate across the surf zone can be written as

$$Q = \frac{1}{T}\int_0^T \int_0^{xb} \int_{-h-b}^{0} U_s(x, z, t)C_s(x, z, t)\, dx\, dz\, dt \quad (9)$$

where $Q$ is the TLST rate across the surf zone, averaged over one wave period or a certain time interval, $T$; $h$ and $b$ are water depth and depth of active sand movement on the bed; $U_s$ denotes the particle velocity; and $C_s$ is the concentration of sediment in the water column and in the bed. Both $U_s$ and $C_s$ are functions of space and time. There have been efforts to model the longshore sediment transport using this approach (*e.g.*, BRIAND and KAMPHUIS, 1993). The above relationship is a complete description of horizontal sediment transport and may be the ultimate goal of transport modeling; however, present predictive capability for $U_s$ and $C_s$ is limited.

Numerous empirical formulas have been developed to predict longshore sediment transport, primarily the total rate. Summaries are provided by HORIKAWA (1988) and FREDSOE and DIEGAARD (1992). Empirical formulas were generally developed from either direct field measurement or from laboratory physical models. Laboratory models have the advantage of controlled accurate measurement but are confined by the small scale and simplified hydrodynamic and morphodynamic conditions. Field measurements are more difficult to control and often less accurate because of the lack of controlled conditions.

One of the simplest yet the most commonly used methods for calculating TLST rate is known as the CERC formula, recommended by the *Shore Protection Manual* (CERC, 1984), one form of which is

$$Q = \frac{K_l}{16\sqrt{\gamma}}\rho g^{3/2} H_{sb}{}^{5/2}\sin(2\theta_b) \quad (10)$$

where $K_l$ is an empirical coefficient, determined from field measurement as 0.32 (KOMAR and INMAN, 1970; BODGE and KRAUS, 1991), $\gamma$ is the breaker index, $\rho$ is the density of the water, $g$ is gravitational acceleration, $H_{sb}$ is significant breaking wave height, and $\theta_b$ is incident wave breaker angle. The CERC formula only requires the input of breaker height and angle which can be obtained from offshore wave observations or by various wave models. The physical foundation of CERC formula is that the rate of sediment transport is proportional to the magnitude of the wave-energy flux. SCHOONEES and THERON (1995) evaluated the determination of the empirical $K_l$ using numerous existing field data obtained mainly from sediment tracer and structural blocking and concluded that significant uncertainties in $K_l$ could be induced by the scatter of the existing data.

KAMPHUIS *et al.* (1986) developed an empirical formula which includes the beach slope and sediment grain size based on their laboratory experiments and existing field data,

$$Q = 1.28\frac{H_{sb}^{3.5}m}{d}\sin(2\theta_b) \quad (11)$$

where $d$ is sediment grain size, and $m$ is beach slope. With additional laboratory study and further data analysis, KAMPHUIS (1991) modified the 1986 formula, adding the influence of wave period,

$$Q = 6.4 \times 10^4 H_{sb}^2 T_p^{1.5} m^{0.75} d^{-0.25} \sin^{0.6}(2\theta_b) \quad (12)$$

where $T_p$ is the peak wave period. It is noted that the dependences on grain size and wave height are greatly reduced as compared to Equation 11. The influence of beach slope and incident wave angle are also decreased.

## RESULTS

The objective of this study is to verify the existing empirical predictive formulas which were mainly calibrated by tracer study on Pacific coasts through field measurements under low-energy conditions along the southeast coast of the United States and the Gulf coast of Florida. The field experiments were designed so that the input parameters for the empirical formulas were measured during the data collection. Comparison of the measured and predicted TLST rates is presented in the following sections.

### TLST Rates Measured by Streamer Traps

The 29 TLST rates measured in this study by the streamer traps and the rates predicted by the above formulas are compared in Table 2. The ACES (Automated Coastal Engineering System; LEENKNECHT *et al.*, 1992) prediction applies the same CERC-formula except that the wave group velocity is calculated by solitary wave theory instead of linear wave theory. The use of solitary approximation results in a prediction that is 25% greater than the CERC prediction and is not considered appropriate by BODGE and KRAUS (1991).

As shown in Table 2, the average CERC prediction (Eq. 10) for the transport rate is 9 times greater than the trap measurements in the present study; the ACES prediction is 11 times greater. The KAMPHUIS formulas (KAMPHUIS *et al.*, 1986; KAMPHUIS, 1991) incorporated the influences of average beach slope and sediment grain size. The average predicted rate of the 1986 formula (Eq. 11) is 8 times greater than that measured in this study. The more recent KAMPHUIS (1991) formulas (Eq. 12) yielded much lower prediction than the earlier KAMPHUIS *et al.* (1986) formula as well as being lower than the CERC and ACES predictions. Compared to the almost one order of magnitude difference between measurement and prediction, the KAMPHUIS (1991) predictions are only 4 times greater than the measured values from the present study.

Although the measured and predicted total rates are significantly different in magnitude, they all follow a similar trend (Figure 5). The exceptionally high predictions of KAMPHUIS *et al.* (1986) for the several Florida Panhandle sites were caused by the combination of fine sediment and fairly steep surf zone caused by the plunge step. The unusually low predictions of KAMPHUIS et al. (1986) for some of the west-central Florida locations were caused by a combination of fairly gentle slope and coarse sediment with high shell concentration. The lower values of the powers of sediment grain size and beach slope in the KAMPHUIS (1991) formula (Eq. 12) are supported by the present field data.

Table 2. *Summary of measured and predicted total rates of longshore sediment transport across the measured cross-sectional surf zone area for the 29 trap sites.*

| Site ID | Surf Zone Area** (m²) | This Study | CERC Eq. 10 | ACES | Kamphuis-86 Eq. 11 | Kamphuis-91 Eq. 12 |
|---|---|---|---|---|---|---|
| | | | (× 1000 cubic meters per year) | | | |
| 1 | 19.10 | 110 | 1,400 | 1,744 | 1,315 | 502 |
| 2* | 8.80 | 42 | 655 | 816 | 253 | 317 |
| 3 | 10.58 | 6 | 146 | 183 | 132 | 143 |
| 4 | 3.57 | 2 | 10 | 13 | 8 | 7 |
| 5 | 5.00 | 52 | 136 | 170 | 90 | 30 |
| 6 | 13.95 | 8 | 175 | 218 | 92 | 126 |
| 7 | 3.24 | 12 | 178 | 221 | 134 | 120 |
| 8* | 1.77 | 19 | 249 | 310 | 223 | 100 |
| 9* | 1.30 | 6 | 86 | 108 | 69 | 62 |
| 10* | 5.25 | 10 | 170 | 212 | 367 | 110 |
| 11 | 1.63 | 39 | 234 | 292 | 209 | 96 |
| 12 | 1.79 | 37 | 233 | 290 | 225 | 83 |
| 13 | 0.58 | 1 | 11 | 13 | 10 | 9 |
| 14 | 0.78 | 45 | 240 | 299 | 443 | 84 |
| 15 | 0.16 | 3 | 113 | 141 | 199 | 62 |
| 16 | 0.24 | 6 | 167 | 209 | 212 | 63 |
| 17 | 2.28 | 56 | 367 | 458 | 771 | 157 |
| 18 | 3.04 | 60 | 385 | 480 | 481 | 128 |
| 19 | 1.00 | 15 | 126 | 157 | 102 | 92 |
| 20 | 2.16 | 6 | 85 | 106 | 64 | 29 |
| 21 | 11.35 | 8 | 171 | 213 | 24 | 31 |
| 22 | 7.48 | 5 | 83 | 103 | 11 | 17 |
| 23 | 35.32 | 145 | 961 | 1,197 | 385 | 215 |
| 24 | 2.54 | 34 | 280 | 349 | 187 | 80 |
| 25 | 0.71 | 1 | 18 | 23 | 18 | 15 |
| 26 | 1.12 | 19 | 116 | 144 | 164 | 41 |
| 27 | 1.55 | 23 | 98 | 122 | 79 | 52 |
| 28 | 0.92 | 3 | 30 | 38 | 9 | 14 |
| 29 | 0.76 | 2 | 12 | 15 | 3 | 12 |
| AVG. | | 27 | 239 | 298 | 217 | 96 |

*The transport rate is based on the measurement and calculation from the inner surf zone

**The cross-sectional area with major sediment transport as measured by the traps; area, e.g. deep trough, with less than 5% transport is excluded

### TLST Rates Measured by Short-Term Impoundment

One of the objectives of conducting the short-term impoundment experiment was to compare the impoundment rate with that obtained from the streamer traps. The comparison between measured and predicted rates is summarized in Table 3. The impoundment rates are 2 to 3 times larger than the trap rates, and the CERC predictions are 2 to 5 times larger than the impoundment rates. Similar results relative to the CERC prediction were obtained by BODGE (1986). Again, the unusually low predictions of the KAMPHUIS *et al.* (1986) formula (Eq. 11) were caused by gentle slope and coarse sediment.

During the second 90-min interval of the impoundment experiment, the afternoon sea breeze began developing. Inci-

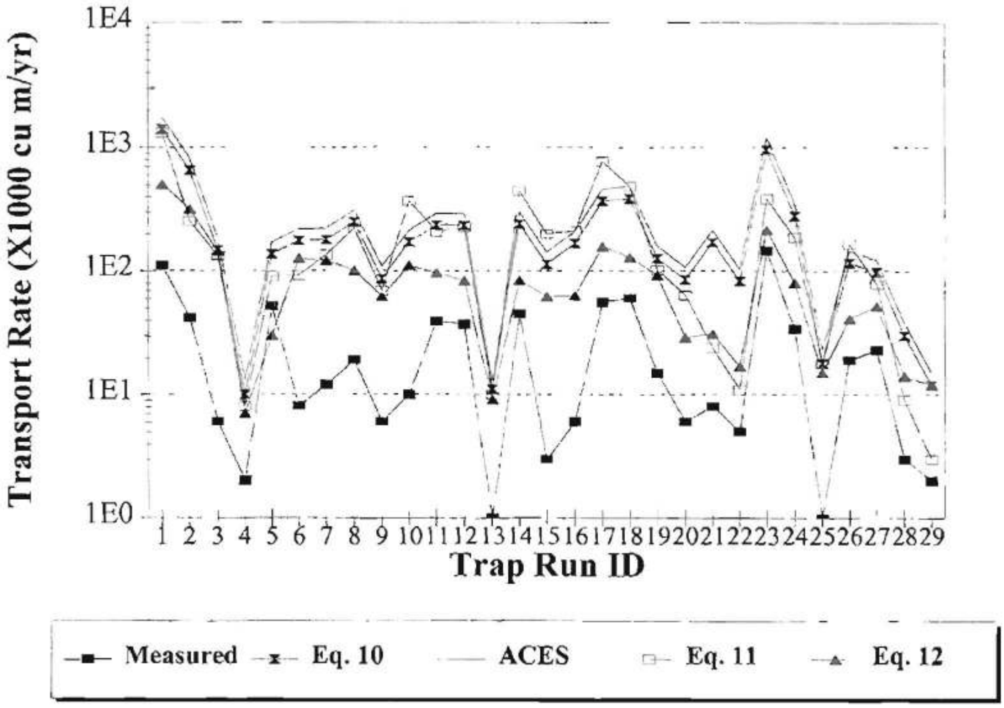


Figure 5. Comparison between the 29 measured and predicted total rates of longshore sediment transport, notice the similar trend of changing but different magnitude.

dent wave angle increased, and breaker height increased. A corresponding increase of the streamer-trap rate and the predicted rate was observed (Table 3); however, a slight decrease from 6,300 to 5,800 $m^3$/yr was measured by the short-term impoundment. The decrease was suspected to be the result of shoreline change at the temporary groin. Development of rip cells and beach cusps was observed shortly after the installation of the groin. The rip cells were also observed both in the field and laboratory by the short-term impoundment study of Bodge (1986).

The impoundment rate obtained from updrift accretion, used in Table 3, is believed to be more reliable than that obtained from downdrift erosion. The development of beach cusps was more severe downdrift than updrift. The rate of downdrift erosion decreased dramatically through time despite the increase in incident wave angle and breaker height (Figure 6). In fact, minor sediment accumulation was measured immediately downdrift of the groin. The accumulation is attributed to further development of beach cusps. The de-

Table 3. *Comparison of the total rate of longshore sediment transport obtained from impoundment and streamer traps, Indian Rocks Beach, Florida.*

| Test Period | Trap | Im-pound.* | CERC Eq. 10 (×1000 m³/yr) | Kam-phuis-86 Eq. 11 (×1000 m³/yr) | Kam-phuis-91 Eq. 12 |
|---|---|---|---|---|---|
| First 127 min. | 2 | 6 | 12 | 3 | 12 |
| Second 90 min. | 3 | 6 | 30 | 9 | 14 |
| First 217 min. | 2 | 6 | 21 | 6 | 13 |

*: The transport rates from the impoundment are obtained from the updrift accumulation

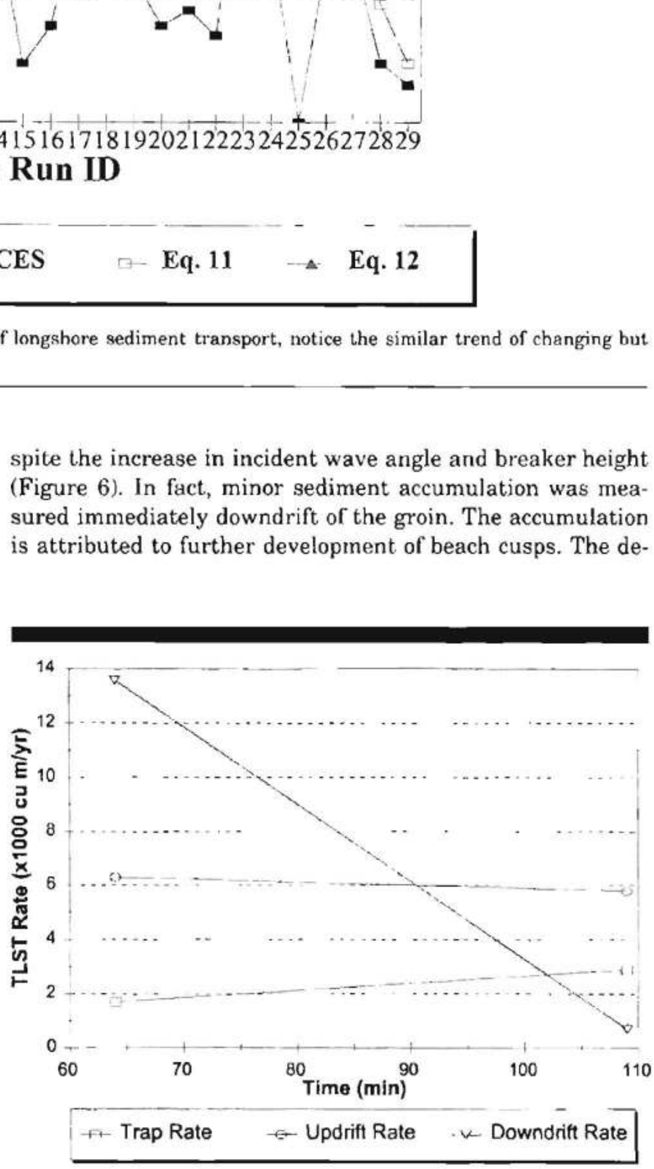


Figure 6. Changes of updrift accretion and downdrift erosion with respect to impounding period (mid-point of the impounding duration is used). Notice the dramatic decrease of downdrift erosion, Indian Rocks Beach, Florida.

crease of both the updrift accretion and downdrift erosion rates (or impounding efficiency) may be explained by a combination of bypassing at the end of the groin, smaller changes in the profile over wider areas not being detected with adequate accuracy, and growth of three-dimensional features (cusps) not accounted for in the surveying.

## Dependence of the TLST Rate on Individual Hydrodynamic and Beach Parameters

Dependence of the TLST rate on the individual factors of wave height, wave period, incident angle, sediment grain size, beach slope, surf zone width, and cross-sectional area of surf zone was examined. The TLST rate was not directly related to the wave period and incident wave angle (Figure 7A and B) by itself for our measurements. No direct relationship was found between the TLST rate and beach slope, surf zone width, and cross-sectional area of the surf zone (Figure 8).

The indistinct relationship between the TLST rate and incident wave angle (Figure 7) is attributable to the large variation in wave height during the field experiments (Table 1), that is, wave height could not be held fixed for variable wave angle. No relationship is found between the measured wave height and wave angle (Figure 7C). A clear relationship is found if the TLST rate is normalized by the wave height to the 2.5 power ($H_b^{2.5}$). Detailed discussion is presented in the following section on the relationship between the TLST rate and the wave-energy flux.

A linear relationship was also found between both measured and CERC-predicted TLST rates with the square of the wave height (Figure 9). The correlation coefficient, $R$, is 0.62 for the streamer-trap rates (Figure 9A) and 0.81 for the CERC predictions (Figure 9B). The streamer-trap data therefore support the simple relationship proposed by GALVIN (1973) for estimation of the gross longshore sediment transport rate, $Q_g$

$$Q_g \propto H_b^2 \qquad (13)$$

The above relationship indicates that among the many factors that control the longshore sediment transport rate, wave height is most significant.

## Relationship Between TLST Rate and Wave-Energy Flux

One of the most commonly used assumptions in the TLST rate prediction, which is also the assumption used by CERC formula, is that TLST rate $Q$ is proportional to the energy flux factor $P_l$ expressed as

$$Q = P_l = EC_g\sin(2\theta_b) = \frac{1}{8}\rho g H_b^2\sqrt{gh_b}\sin(2\theta_b) \qquad (14)$$

where $E$ is wave energy, $C_g$ is group velocity, and $h_b$ is water depth at breaking.

The field data collected in this study show that this proportionality is acceptable under a variety of hydrodynamic and morphodynamic conditions (Figure 10). The predictions from KAMPHUIS *et al.* (1986, Eq. 11) and KAMPHUIS (1991, Eq. 12) also have good correlation with the energy flux factor (Table 4). The magnitude of coefficients vary significantly

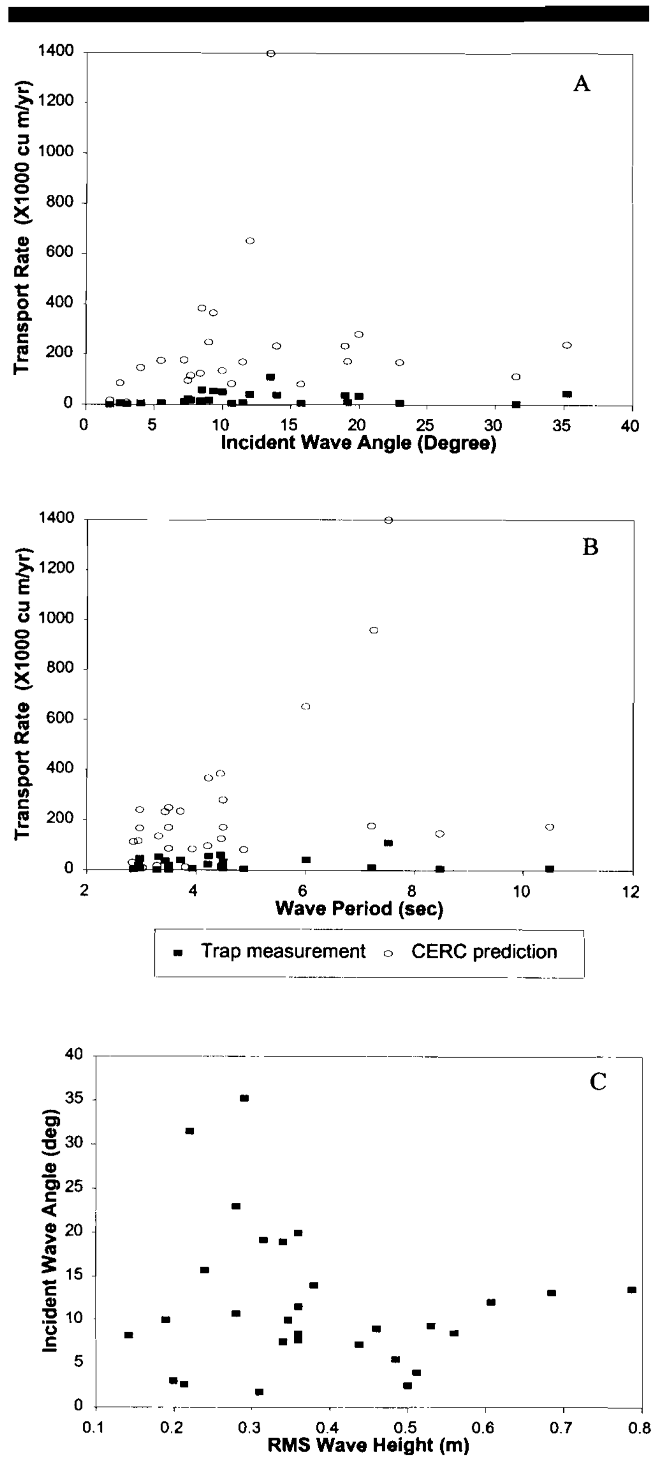


Figure 7. Relationship between transport rates and individual factors; (A) transport rate vs. incident wave angle, and (B) transport rate vs. wave period. (C) Random distribution of wave height vs. wave angle.

(Table 4). The best-fit coefficient for the 29 trap rates is 0.08, almost one order of magnitude lower than the coefficient recommended by the SPM (CERC, 1984). Similar low TLST rates were obtained by the streamer-trap study of KRAUS *et*

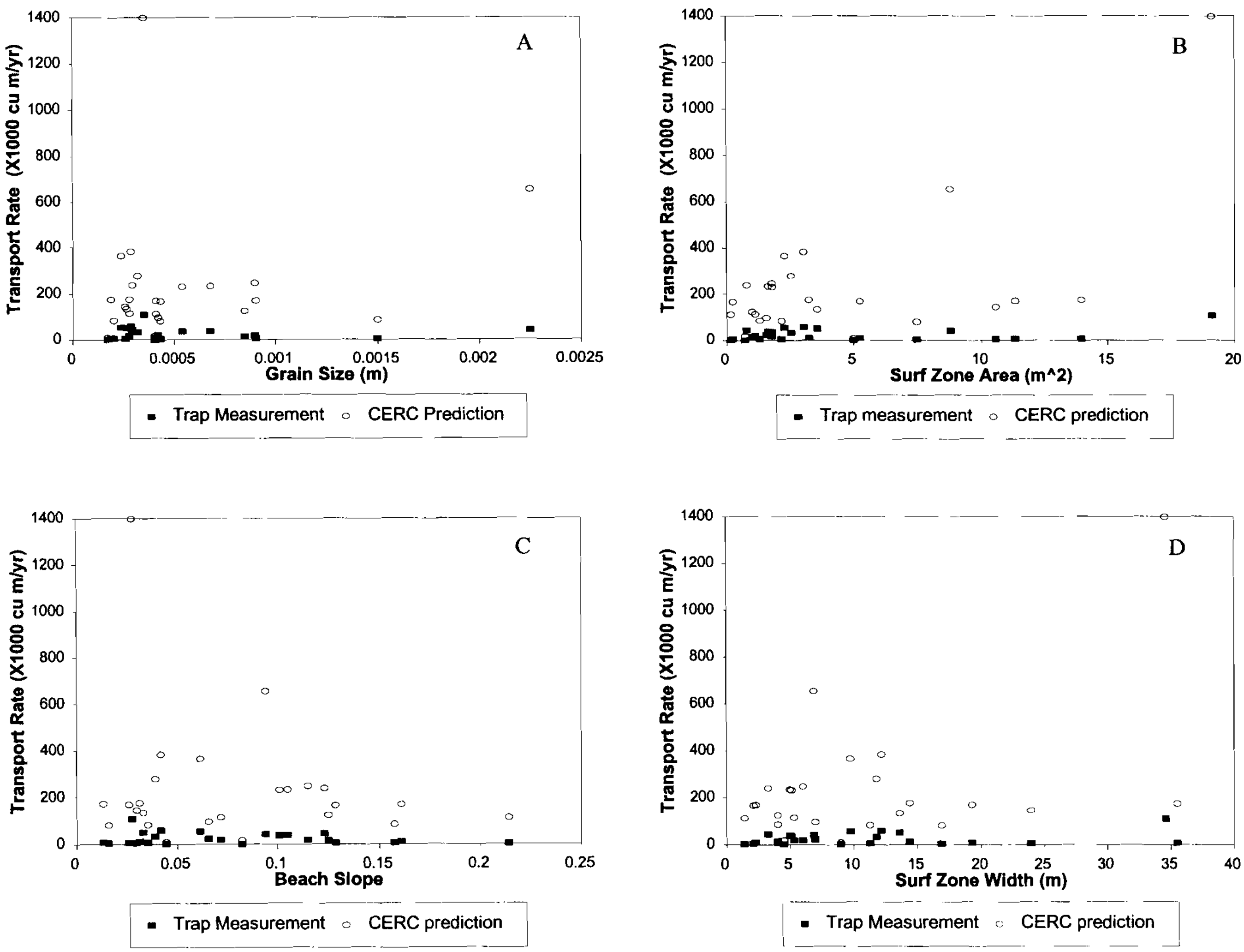


Figure 8. Relationship between transport rates and individual factors; (A) transport rate vs. grain size, (B) transport rate vs. surf zone area, (C) transport rate vs. beach slope, and (D) transport rate vs. surf zone width.

*al.* (1989), ROSATI *et al.* (1990, 1991), and LEVOY *et al.* (1995). The predictions by the KAMPHUIS (1991) formula are generally two to four times lower than the CERC predictions as indicated by the lower coefficients but still greater than field data from this study. The highest rates are predicted by the ACES version of the CERC formula. BODGE and KRAUS (1991) have discussed similar discrepancies between trap measurements, tracer measurement, and predictive formulas.

## Reasonability Check

As stated in the Introduction, empirical predictions of the TLST rate are strongly influenced by sediment tracer measurements conducted on the Pacific coast. How much sand needs to be trapped under a typical situation in the study areas to meet such predicted values? A series of average values is used here to perform hypothetical streamer trap and sediment tracer thought experiments. The objectives are two-fold to investigate if 1) something significant is missing from the streamer trap measurement, or 2) the predicted value from empirical formulas is unrealistically high.

The average properties of the 29 field sites are used for the hypothetical experiments. The hydrodynamic and beach conditions are listed in Table 5. It is believed that these conditions represent a typical situation in the studied low wave-energy settings. Under these conditions, the TLST rate predicted by the CERC formula is 231,000 $m^3$/yr. Assuming homogenous transport throughout the surf zone, then each streamer with a 15 $\times$ 9 $cm^2$ opening needs to trap 9,249 g of sand for a typical 5-min trapping duration. The maximum amount obtained in this study was 6,510 g, trapped by the bottom streamer at one of the Florida Panhandle sites with a 35-deg incident wave angle. The bottom streamer is designed to measure the sediment flux from seabed to 9 cm above the bottom. This flux is defined as bed-load transport and is similar to that introduced by KOMAR (1978, to 10 cm

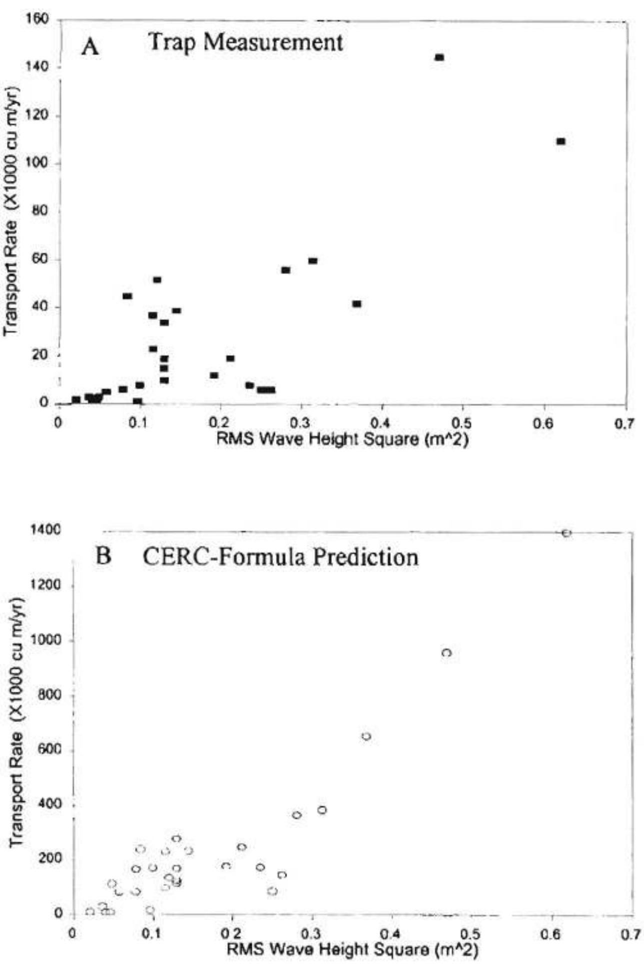


Figure 9. Relationship between transport rates and the square of RMS wave height; (A) trap rate vs. wave height square, and (B) CERC prediction vs. wave height square.

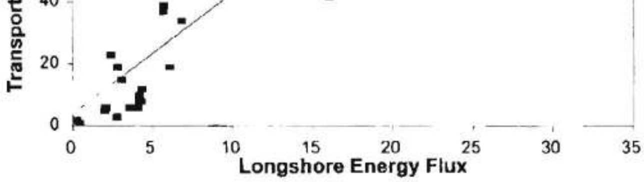


Figure 10. Relationship between measured LST rates and energy flux factor.

Table 4. *Regression analysis: transport rates vs. energy flux factor.*

| Procedure | R Value | Coefficients |
|---|---|---|
| This study | 0.87 | 0.08 |
| CERC (Eq. 10) | 1.00 | 0.77 |
| ACES | 1.00 | 0.96 |
| Kamphuis-86 (Eq. 11) | 0.82 | 0.63 |
| Kamphuis-91 (Eq. 12) | 0.92 | 0.27 |

above the bottom), which led to his conclusion that bed-load transport is dominant. Based on the present author's field experience along low-energy settings, it is judged to be unrealistic to find on average, during 5 min, 9 kg of sediment in suspended load traps which are located at an elevation greater than 10 cm above the bottom.

Using the empirical equation proposed by KOMAR and INMAN (1970), the longshore current velocity at mid-surf position, $v_{ms}$, can be estimated as

$$v_{ms} = 1.17\sqrt{gh_b}\cos(\theta_b)\sin(\theta_b) \tag{15}$$

For the above hypothetical conditions (Table 5), $v_{ms}$ is determined from Equation 15 to be 0.47 m/sec. Assuming 1) the longshore current velocity is homogeneous throughout the surf zone and can be represented by the mid-surf velocity, 2) the sediment concentration is homogeneous throughout the surf zone, and 3) the suspended sediment particles move at the same velocity as the fluid, then to transport 231,000 $m^3$ of sand per year, the sediment concentration needs to be about 5 g/l throughout the surf zone. Instantaneous suspended sediment concentrations have been measured by KANA (1977, 1979), WATTS (1953), FAIRCHILD (1973), and ZAMPOL and INMAN (1989). Although values as great as 110 g/l have been reported in the swash zone (ZAMPOL and INMAN, 1989), the average concentration throughout the surf zone is found to be much less than 5 g/l. The average of KANA's (1977) 650 measurements at Price Inlet, South Carolina, often taken under breaking waves, was less than 1 g/l. The average concentrations reported by WATTS (1953) and FAIRCHILD (1973) were less than 0.5 g/l. Similar results were obtained by the OBS measurements at SUPERTANK (BARKASZI and DALLY, 1993) under breaking waves about 1 m high. These measurements indicate that the inferred average concentration of 5 g/l is much too large.

The third test is a hypothetical tracer experiment. KRAUS *et al.* (1983) and KRAUS (1985) found that the mixing depth Z of sediment tracer can be estimated as

$$Z = 0.027H_{sb} \tag{16}$$

A representative mixing depth for the present 29 experi-

Table 5. *Hydrodynamic and morphologic conditions for the hypothetic runs.*

| Hydrodynamic Conditions | | Morphologic Conditions | |
|---|---|---|---|
| RMS wave height (m) | 0.4 | Beach slope | 0.08 |
| Incident wave angle (deg) | 12 | Surf zone width (m) | 14 |
| Wave period | 4.5 | *Cross-sectional area ($m^2$) | 5.1 |
| Break water depth | 0.48 | Sediment grain size (m) | 0.0006 |

*Average of the major transport areas as listed in Table 1

Table 6. *Comparison of streamer trap, sediment tracer, and short-term impoundment techniques for field measurement of longshore sediment transport.*

| | Streamer Traps | Sediment Tracer | Short-Term Impoundment |
|---|---|---|---|
| Key Measurement | -Dry weight of sand | -Depth of mixing<br>-Center of mass | -3-D morphological changes |
| Causes of hydraulic disturbance | -Trap opening | -None | -The temporary groin |
| Measurement period | -Minutes | -Hours | -Hours to years |
| Influence of tidal water level | -Negligible | -Can be significant | -Can be significant |
| Measurement of sediment flux | -Flux profile | -No | -No |
| Flux distribution in the water column | -Yes | -No | -No |
| Measurement of cross-shore distribution | -Direct measurement with different traps in any location in the surf zone | -Quantify distribution—pattern of multi-color tracers | Quantify cross-shore distribution of morphological changes |
| Uncertainties in measurement of cross-shore distribution | -None | -Mixing of tracers due to cross-shore movement of breaking waves and tides* | -Redistribution of impounded sediment due to cross-shore movement of waves and tides |
| Measurement of total rate | -Interpolated from sediment flux distribution | -Inferred from distribution of sediment tracers | -Calculated from the morphological change |
| Sediment sampling | -Simultaneous sampling of bedload and suspended load | -None | -None |

*: Unless multi-colors of tracer are used (Kraus et al., 1983) which adds greatly to the expense.

ments is then determined to be 1.5 cm. To transport 231,000 $m^3$ of sand per year, the sand advection velocity needs to be 3.5 cm/sec. The average advection velocity of the 14 measurements conducted by KOMAR (1969), which comprise the fundamental database for the CERC formula, is 0.2 cm/sec. The sand advection velocities of the 11 measurements conducted by KRAUS *et al.* (1983) ranged from about 0.2 to 0.5 cm/sec. The advection velocity needed for the hypothetical low-energy settings is therefore required to be 10 to 20 times greater than the commonly accepted existing data. Using the relationship between sand advection velocity $V_a$ and the average longshore current velocity $V_l$ found by KRAUS *et al.* (1983),

$$V_a = 0.014V_l \quad (17)$$

the average longshore current velocity $V_l$ that is needed to generate the 3.5 cm/sec advection velocity $V_a$ is 2.5 m/sec, which is unrealistically large and not observed during the field data collection.

If $H_{sb} = 0.57$ m and $V_l = 0.47$ m/sec are used in Equations. 16 and 17, the TLST rate that would be measured by the sediment tracer is 44,000 $m^3$/yr, only 19% of the CERC prediction. The 44,000 $m^3$/yr which are predicted from the empirical relationship of tracer mixing and advection is rather close to the rate that was measured by the streamer traps, an average of 27,000 $m^3$/yr for the 29 field sites.

The artificially stabilized John's Pass is located at the south end of Sand Key beach (Figure 1), where 11 trap measurements and the one short-term impoundment experiment were conducted. Historical study (DAVIS and GIBEAUT, 1990) shows that the John's Pass ebb tidal delta has been fairly stable for the last three decades. The volume of the ebb-tidal delta was determined to be 4,817,000 $m^3$ in 1952 and 3,838,000 in 1984, eroding at an average rate of 31,000 $m^3$yr. From 1974 to 1992, the 1,700-m long shoreline updrift (north) of John's Pass accreted at an average rate of 11,000 $m^3$/yr, were dredged from John's Pass navigational channel (USACE, 1992). The 11 streamer trap rates range from 1,000 to 145,000 $m^3$/yr measured at the end of a winter storm. The average of the measured rates is 24,000 $m^3$/yr, in approximate agreement with the rates inferred from dredging and shoreline change. The CERC prediction for the 11 cases ranges from 12,000 to 961,000 $m^3$/yr, with an average of 180,000 $m^3$/yr. The CERC formula prediction is extremely high compared to the existing dredging and shoreline change data at John's Pass.

In summary, the above straight forward hypothetical tests and estimate of ebb tidal volume indicate that the values that are needed to achieve the rate predicted by the CERC formula are unrealistically high based on our experience in field measurements along low-wave energy coasts.

## Comparison of Rates Obtained by Different Measurement Techniques

Although all three field techniques, sediment tracer, short-term impoundment, and streamer sediment traps, are capable of measuring the TLST rate, they differ in fundamental assumptions, key measurements, and calculation algorithms. The differences in the three techniques are summarized in Table 6.

As pointed out at the beginning of this paper, both the two key measurements in sediment-tracer technique, mixing depth and center of mass, are ambiguously defined and difficult to quantify. The short-term impoundment technique suffers from significant disturbance to the hydrodynamic conditions and potential uncertainties associated with quantifying volume change. BODGE (1986) concluded that the total rate obtained by the short-term impoundment technique was not reliable. The relatively long measuring duration makes the tracer and impoundment techniques vulnerable to significant tidal influences which are very difficult to quantify.

The streamer-trap technique is confined to low-energy conditions. Until now, the sand trapping efficiency has been taken to be unity. Although field observations and the high hydraulic efficiency (ROSATI and KRAUS, 1988) both imply a sand trapping efficiency of close to unity, direct evidence from field study is not available. A 1- to 3-cm deep scour hole was sometimes observed beneath the bottom streamer. The influence of the scour hole on the bed-load trapping is not clear. The mobility of the streamers is reduced as the bags collect sand. It is possible that the sand trapping efficiency decreases as the mobility decreases because greater disturbance to the water could be generated by less mobile streamers, and hydraulic efficiency may decrease as the bags fill.

The predicted rates largely represent the sediment tracer measurements because the empirical coefficient was originally developed from tracer measurements. The general discrepancy between measured and predicted rates found in this study and previous studies (BODGE, 1986; KRAUS *et al.*, 1989; ROSATI *et al.*, 1990, 1991; LEVOY *et al.*, 1995) indicates that the three techniques may not be directly comparable. However, most of the existing tracer measurements seem to agree with each other, as do streamer trap measurements.

## CONCLUSIONS

The TLST rates measured by the streamer sediment traps and short-term impoundment along the low-wave energy coasts are generally lower than the rates predicted by the various empirical formulas. The commonly used CERC-formula predictions are unrealistically high for the studied low-energy settings.

The linear relationship between the energy flux factor and TLST rate contained in the CERC formula is supported by the streamer trap measurements. However, an order-of-magnitude lower empirical coefficient, 0.08 instead of 0.78 recommended by *Shore Protection Manual* (1984), is suggested by the trap data for low-energy coast.

The TLST rate predicted by the KAMPHUIS (1991) formula was 3 times lower than the CERC prediction and closer to the measured values. The relationships between TLST rate with the wave period, beach slope, and sediment grain size established in the KAMPHUIS (1991) formula are supported by the present study.

It is essential to reconcile the different measurement techniques of tracer, traps, and short-term impoundment. Further studies on the comparability of the field techniques are recommended. Relationship among the different key measurements (Table 6) needs to be explored to further understand their compatibility.

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