Proc., Coastal Sediments '91; ASCE
pp. 139-155.

CRITICAL EXAMINATION OF LONGSHORE TRANSPORT RATE MAGNITUDE

Kevin R. Bodge[1], M. ASCE and Nicholas C. Kraus[2], M. ASCE

ABSTRACT: Inconsistencies in the field data and predictions of longshore sediment transport (LST) rates associated with the CERC and Bagnold formulae are discussed. Practical errors in direct application of the formulae can result in overprediction of LST by a factor of up to 1.8. The degree of wave-averaging affects LST prediction by factors of 1.5 to 2.5. Use of the formulae with hindcast wave data results in overprediction of LST by factors of 2 to 5. Consideration of non-linear effects contradict laboratory findings that relate LST to wave steepness or surf similarity. Reasonable errors in field measurements potentially yield errors in the LST formulae by factors of 2 to 4. The functional dependence on wave height of the CERC and Bagnold formulae is validated by consideration of long-term shoreline change at long shore-normal structures.

INTRODUCTION

Prediction of the rate of longshore sediment transport (LST) is central to many, if not most, coastal engineering studies. The present paper explores a paradox associated with the commonly used formulae that relate LST and surf zone kinematic properties. That is, the capability of the formulae to predict LST with an apparent narrow range of empirical proportionality coefficients suggests that their basic functional dependencies are reasonable; however, the range in empirical coefficients obtained from field and numerical studies suggests that the conclusions of these studies are biased and/or that the nature of the formulas' empirical proportionality coefficients (often treated as constants) must be modified. Specifically, this paper attempts to identify potential errors in the experiments used to calibrate the LST formulae and to present evidence that both supports and refutes the validity of these formulae. Space limitations force us to limit coverage of the extensive literature on LST. Emphasis will be placed upon the most commonly used predictive expressions; viz., the CERC and Bagnold formulae.

---

1) Senior Engineer, Olsen Assoc., Inc., 4438 Herschel St., Jacksonville, FL 32210;
2) Senior Scientist, Coastal Engrg. Res. Center, U.S. Army Engr. Waterways Expt. Stn., 3909 Halls Ferry Rd., Vicksburg, MS 39180-6199.

BACKGROUND

The CERC Formula relates the immersed weight longshore sediment transport rate I and a longshore wave energy flux factor P_ℓ by

$$I = KP_\ell \tag{1}$$

where K is an empirical coefficient of proportionality, and

$$P_\ell = (EC_g \sin\theta \cos\theta)_b \tag{2}$$

The subscript b refers to breaking. The energy density E and group celerity C_g at breaking are given or approximated by linear-wave theory as

$$E = \frac{1}{8} \rho g H_b^2 \tag{3}$$

$$C_g = \left(\frac{g H_b}{\gamma}\right)^{1/2} \tag{4}$$

where ρ = fluid density, g = gravitational acceleration, H_b and θ_b = wave height and angle at breaking, and $\gamma = H_b/h_b$, where h_b = water depth at breaking. Eq. 1 is then

$$I = \frac{K}{16\sqrt{\gamma}} \rho g^{3/2} H_b^{5/2} \sin(2\theta_b) \tag{5}$$

Early calibration of the CERC Formula (USACE 1966) was based upon nine field data points (four from Watts 1953, and five from Caldwell 1956), and 150 laboratory data points (Krumbein 1944, Saville 1950, Shay and Johnson 1951, Savage and Vincent 1954, Savage 1962). This resulted in the value K = 0.42 (for use with root-mean-square (rms) wave height). Subsequent calibration used the original nine field data points plus fourteen additional field data points (Komar and Inman 1970), with all laboratory data deleted. This resulted in the value K = 0.77 -- the recommended value to date for use with rms wave height (Shore Protection Manual (SPM) (1977, 1984).

Since revision of the K-coefficient in about 1977, at least another 33 field data points from nine separate investigations have become available (excluding the tracer data of Kraus et al. 1982, and the DUCK85 and SUPERDUCK data of Kraus et al. 1989 and Rosati et al. 1990). For experiments conducted on sandy beaches, the K-values reported for these additional studies range from about 0.2 to 1.6. The mean value of K (taken simply as the mean value of the average reported K-value from each study) is about 0.78.

The tracer data of Kraus et al. (1982) suggest a mean value of K = 0.49. The first half of this data set (1978-79) yields a mean value of K = 0.74 and the second half (1980-82) yields a mean value of K = 0.23. Kraus et al. recommended a design value of 0.58 and Komar (1990) in a review of the LST data base tends to accept this value.

A more fundamental relationship between LST and longshore current is (Bagnold 1963),

$$I = K'(EC_g)_b \frac{v_\ell}{u_m} \tag{6}$$

where v_ℓ = average longshore current speed, and u_m = the maximum horizontal component of the near-bottom wave orbital velocity at breaking. Komar and Inman (1970) found K' = 0.28 from sand tracer experiments. Kraus et al. (1982) determined K' = 0.21 from their own sand tracer experiments. Both K'-values pertain to rms wave height.

Eq. 6 can be simplified through the assumption of shallow-water wave conditions (Kraus et al. 1982, Komar 1990):

$$I = 0.026 \ \rho g H_{sb}^2 v_\ell \tag{7}$$

if K' = 0.21 and significant breaking wave height H_{sb} are used. The Bagnold expression reduces to the CERC Formula upon substitution of $v_\ell = K_v\, u_m \sin\theta_b \cos\theta_b$ in Eq. 6, where k_v is a function of the bottom friction coefficient (Longuet-Higgins 1970) or is taken as an empirically determined constant k_v = 2.7 (Komar and Inman 1970).

The field data of Kraus et al. (1988) and Rosati et al. (1990) using streamer traps during the DUCK85 and SUPERDUCK field data collection projects suggest values of K' from 0.014 to 0.056, which are 3.5 to 15 times smaller than the previously determined value of K. These data were collected for conditions of H_s = 0.9 to 1.1 m, period T = 8 to 12 s, and v_ℓ = 0.2 to 0.3 m/s, with median grain sizes of about 0.17 to 0.2 mm.

DISCUSSION OF THE PREDICTIVE FORMULAE

Potential Errors in Practical Application

In practical application of the LST formula, three obvious errors or approximations can affect the magnitude of the computed LST. The first regards use of significant wave height H_s. The coefficient K = 0.77, as noted above, is intended for use with rms wave height. For Rayleigh-distributed heights, $H_s = \sqrt{2}\, H_{rms}$. Because the LST rate in the CERC Formula is proportional to $H^{5/2}$, the appropriate coefficient for use with H_s is K = 0.32. This value is 18% less than the K = 0.39 value suggested in the SPM (1984).

Second, the SPM (1984) also recommends use of the approximation

$$C_{gb} = (2 g H_b)^{1/2} \tag{8}$$

which may provide a more accurate estimate of C_{gb} than linear-wave theory, but results in estimates of P_ℓ that are about 1.25 times higher than those arising from Eq. 2. This, in turn, results in LST computations that are probably 1.25 times too large, considering that most field investigators appear to have used Eq. 4 in computing P_ℓ for calibration of the CERC Formula.

Third, the volumetric longshore transport rate is given by

$$Q = \frac{I}{(s-1)\,\rho g a'} \tag{9}$$

where s = specific density of sediment relative to the density of the fluid medium and a' = the ratio of the solid volume to the total volume of the sediment. In practice, s and a' are taken as about 2.65 and 0.6, respectively. In reality, these values may differ by about ±5% and ±17%, respectively. The combined effect of these differences implies that the volumetric rate may be underestimated by as much as 27% for light, well-sorted sediments, or may be overestimated by up to 19% for dense, poorly-sorted sediments.

These three issues represent a combined potential to overestimate LST magnitude by a factor of as much as 1.8; however, these are simply pitfalls presented to the investigator and do not reflect problems in the predictive formulae per se. Other (less obvious) potential problems are discussed below.

Consideration of Non-Linearities

By using stream function wave theory (Dean 1974), it can be shown that the quantity P_ℓ is significantly less for a non-linear wave than is calculated by linear theory (Fig. 1). This effect is greatest for smaller breaking depth to wavelength ratio, h_b/L_o, where h_b = water depth at breaking, and L_o = deep-water wavelength. If the CERC Formula is not simply a functional relationship -- that is, if LST is actually related to physical quantities expressed by P_ℓ -- then one would expect less transport than is predicted by linear theory for waves of smaller h_b/L_o. This expectation contradicts the majority of laboratory findings that suggest LST increases with smaller h_b/L_o. Assuming laboratory models are valid, this disagreement implies that either (1) LST is not related to the physical quantities expressed by P_ℓ, or (2) the dependence of LST upon wave steepness or surf similarity parameter is significant enough to outweigh the linear vs. non-linear wave effect outlined above.

Reasonableness of the Predictive Formulae

The CERC and Bagnold formulae appear to yield reasonable transport magnitudes for reasonable wave conditions. For example, the CERC Formula (as expressed by Eq. 5 with $K = 0.77$) suggests that a net drift rate of 153,000 m^3/yr (200,000 cu/yr) can be developed at a sandy beach with a significant wave height of 1.0 m (3.3 ft), which probabilistically occurs as a cosine-squared distribution centered 5° from the shore normal, and assuming 25% calm events per year. Or, the same net drift rate (at half the gross rate) can be developed with $H_s = 0.8$ m (2.5 ft) centered at $\theta_b = 10^\circ$ in a cosine-squared distribution and 25% annual calms. These average drift and wave conditions are not unreasonable for south Florida's Atlantic beaches. Similarly "reasonable" conditions can be developed for the Bagnold expression. As described later, it is with more "precise" input wave conditions that problems with the formulas' magnitudes arise.

Expressions for the Proportionality Coefficient, K

Numerous investigators have attempted to explain the scatter found for values of the proportionality coefficient K in the CERC Formula. For example, Bajournas (1970), Castanho (1970), van Hijum (1976), Swart (1976), Galvin (unpublished), and Dean (1970) have suggested conflicting relationships between LST and sediment size. From laboratory experiments, Kamphuis and Readshaw (1970), Vitale (1981), Kamphuis and Sayao (1982), and Ozhan (1982) each observed a relationship between K (or a similar coefficient) and the surf similarity parameter, ξ_b:

$$\xi_b = m\left(\frac{H_b}{L_o}\right)^{-1/2} \tag{10}$$

where m = beach slope. Fig. 2 compares the estimated surf similarity parameter and K for several laboratory and field studies. Best-fit expressions for the laboratory and combined field/laboratory data are shown in the figure.

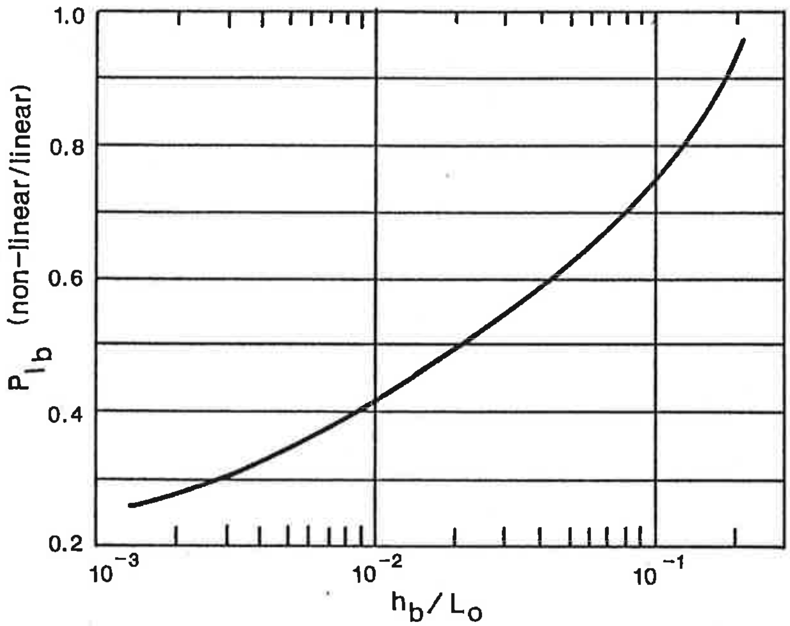

Fig. 1. Comparison of longshore wave energy flux factor P_ℓ computed by non-linear (stream function) and linear-wave theory

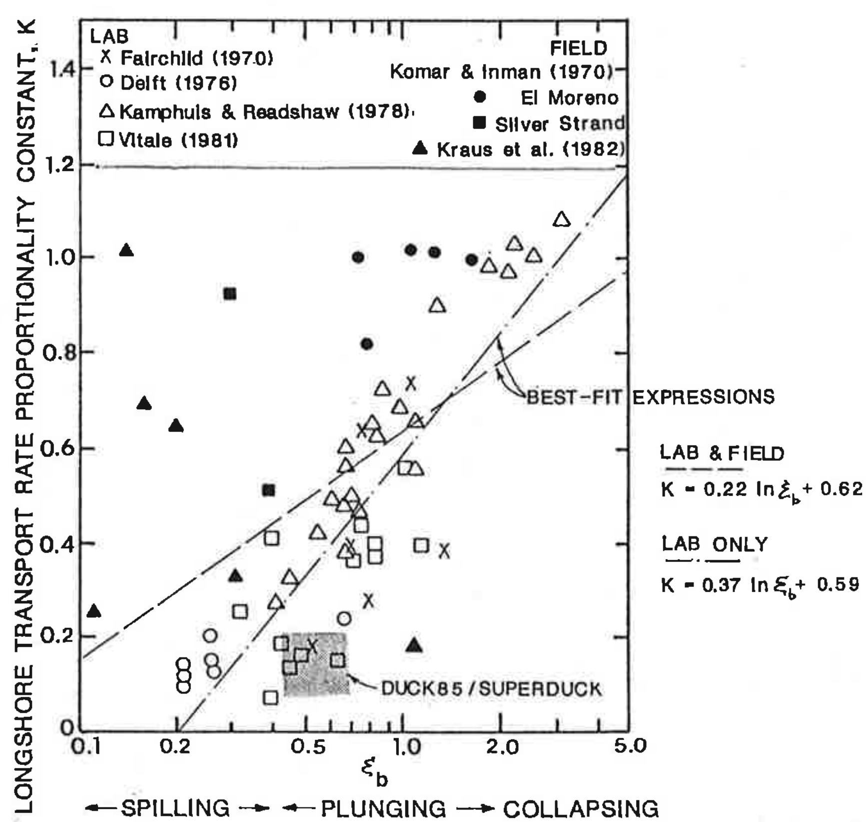

Fig. 2. Variation in CERC formula K-coefficient with surf-similarity parameter for laboratory and field data

The laboratory data suggest that K increases with increasing ξ_b. The applicable field data are limited to tracer studies (Komar and Inman 1970, Kraus et al. 1982) and streamer trap data (DUCK85 and SUPERDUCK). The former are generally scattered; the latter exhibit low values of K. Field data collected over longer time intervals (such as by impoundment techniques) are not evaluated because the surf similarity parameter presumably varied substantially during the course of the observation period.

Functional Dependence on Wave Height

The CERC Formula, as expressed in Eq. 5, relates LST with the functional dependence $H_b^{5/2}$. In the following paragraphs, we examine the correctness of this functional dependence. To do this, we consider impoundment and erosion in the vicinity of long shore-perpendicular structures and predictions obtained from an analytic solution of shoreline change. Eq. 5 is first expressed in a general form:

$$Q = Q_o \sin(2\theta_b) \tag{11}$$

after Larson, Hanson, and Kraus (1987) where, from Eqs. 5 and 9,

$$Q_o = \frac{K}{16(s-1)a'} H_b^2 C_{gb} \tag{12}$$

Larson et al. document many previous and new solutions of the shoreline change equation first introduced by Pelnard-Considere (1956). Assuming that the breaking wave angle is small and constant, that the profile moves in parallel with itself, and that the wave height is constant (or, more generally, that Q_o is constant), it can be shown that the one-dimensional diffusion equation governs changes in shoreline position y with time t:

$$\frac{\partial y}{\partial t} = \epsilon \frac{\partial^2 y}{\partial x^2} \tag{13}$$

where x = distance alongshore, and ϵ = a diffusion coefficient governing the rate of shoreline change and is given by

$$\epsilon = \frac{2Q_o}{d} \tag{14}$$

where d = depth where no profile change occurs.

For the case of a long, impermeable jetty or groin at which no bypassing occurs, the position of the shoreline at $x = 0$, corresponding to the position of the groin is given as (see Eq. 64 of Larson et al.),

$$y(0, t_i) = 2\left(\frac{\epsilon t_i}{\pi}\right)^{1/2} \tan(\theta_o) \tag{15}$$

where t_i is the time of the i'th shoreline survey, and θ_o is the angle of the wave crests to the x-axis. By dividing shoreline positions at the groin or jetty measured at two different times, the angle θ_o can be eliminated to yield an estimate of ϵ. It is important to note that the form of ϵ as given by Eq. 14 does not involve information about the dependence of Q_o upon wave height. Therefore, by determining estimates of ϵ by using shoreline surveys at long shore-normal structures in different wave climates, correlation between ϵ and H can be made.

Shoreline change satisfying the requirements stated above (principally, no bypassing) was compiled at six sites around the United States, and published Wave Information Study (WIS) hindcasts (e.g., Corson et al. 1982, Jensen 1983) were used to determine H_s at the target coasts. The results are plotted in Fig. 3, showing ϵ as determined from Eq. 15 as a function of wave height. From this analysis we find,

$$\epsilon = 4 H_s^{1.8} \tag{16}$$

From a widely accepted predictive equation of Hallermeier (1983), we have the depth of closure d proportional to the wave height. Therefore,

$$Q_o \propto \epsilon d \propto H^{2.8} \tag{17}$$

a result obtained without appeal to the actual form of Q_o. On the other hand, the CERC Formula (Eq. 5) predicts that the amplitude Q_o should be proportional to $H^{5/2}$. This close agreement suggests that the basic functional dependency of the CERC Formula on wave height is correct in the sense of obtaining long-term estimates of longshore sand transport.

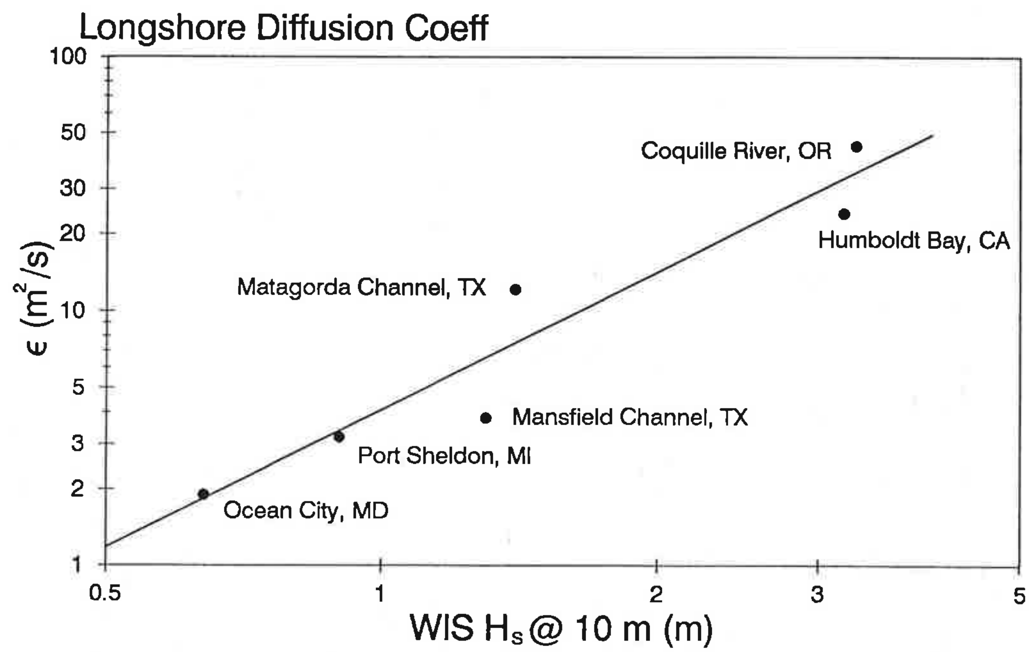

Fig. 3. Longshore diffusion coefficient ϵ as function of mean significant wave height

Use of Hindcast Wave Data

The previous development demonstrated that the functional relationship of the CERC Formula yields proper long-term shoreline response trends with the use of hindcast wave (WIS) data; however, use of the CERC Formula with hindcast wave data typically yields LST magnitudes that are a factor of two to five times larger than "accepted" values, a problem apparently related to the value of K.

As an example, Table 1 lists net and gross LST rates computed from Phase II and Phase III WIS hindcast wave data. The estimates were developed by refracting the hindcast wave data to incipient breaking over straight and parallel contours, computing the associated LST rate by the CERC Formula, and weighting the LST result by the hindcast wave occurrence. The first estimate in each pair reflects use of a single average wave height and period for each directional sector (i.e., directionally-averaged events). The second estimate is the result obtained by treating individual wave conditions hindcast at 3-hr intervals. For each, Eqs. 5 and 9 were used with $K = 0.32$ (for H_s), $s = 2.65$, and $a' = 0.6$.

Two points are immediately apparent. First, most estimates appear to be unreasonably high. For instance, computed estimates of net drift along the Florida stations exceed the generally accepted average rate of about 153,000 m^3/yr (200,000 cu/yr) by factors of 2.4 to 4.8. The rate of 153,000 m^3/yr is an average of the net LST estimates developed by the Corps of Engineers from various methods including examination of dredging records, volumetric surveys, and pumping rates at sand bypassing plants (Walton 1973). This leads one to suspect the WIS wave data for these stations. Comparisons between the WIS data and nearshore wave gauge data near Stations 47, 83, and 143 (Fig. 4) suggest that the hindcast wave heights are underpredicted. This would result in an underprediction of LST. Periods are also underpredicted (Fig. 4). This would result in an overprediction of breaking wave angle and a corresponding overprediction of LST. However, this latter effect is less significant than the underprediction caused by the wave height because of the greater non-linearity between LST and wave height and because the underpredicted periods are generally associated with lower wave heights. In at least some situations, then, when estimating LST rates from older WIS hindcasts, investigators must typically reduce the K coefficient from its recommended value by a factor of 2 to 4 to achieve reasonable LST magnitudes.

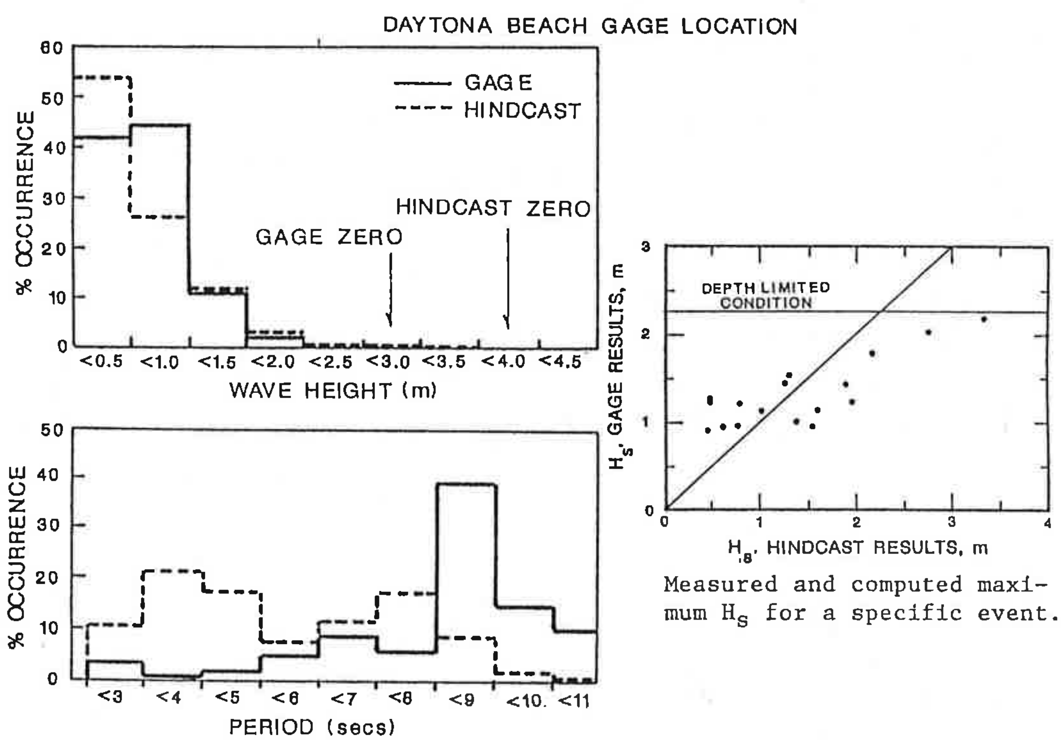

Fig. 4. Comparison of hindcast and measured wave height and period near Daytona Beach, Florida, at WIS Phase III Station 143 (after Jensen 1983)

Adjustment of the CERC Formula K is found in shoreline change numerical models as well. For example, Hanson and Kraus (1989) caution that the LST coefficients in the GENESIS model (which uses a modified form of the CERC Formula) should be viewed as calibration coefficients that are to be adjusted to match measured positions of shoreline change. These models can accept both hindcast or measured wave data. In numerical simulations of shoreline change at Oarai Beach, Japan, Kraus and Harikai (1983) note that the K-coefficient had to be reduced by a factor of 2.5 in order to reproduce measured changes during calibration trials. Their investigation used measured (not hindcast) wave data at 6-hr intervals. In a careful numerical simulation of shoreline change obtained in a physical model, Hanson and Kraus (1991) obtain $K = 0.3$, in the range of K-values typically found in the field. They conclude K-values may be similar in the laboratory and in the field.

The second point raised by Table 1 is that drift estimates developed by use of distinct wave events are 1.5 to 2.5 times larger than those developed by directionally-averaged wave events. This difference, produced by wave averaging, is not unexpected. The non-linearity of the CERC Formula with respect to wave height and angle lends significance to the degree to which these parameters are temporally-averaged. If, for example, wave heights are Rayleigh distributed over a day and the transport rate is proportional to $H^{5/2}$, the transport rate computed using the distribution of wave heights will be about 1.53 times larger than that computed using only the average daily wave height.

Table 1: LST estimates from WIS hindcast data[1].

WIS STN.	NET LST cu.m./yr	GROSS LST cu.m./yr	Approximate Location
47-III	-220,000	552,000	South Hampton, N.Y.
	-421,000	1,057,000	
54-III[2]	113,000	176,000	Northern, N.J.
	274,000	419,000	
83-III	359,000	578,000	Nags Head, N.C.
	578,000	1,478,000	
143-III	302,000	~~485,000~~ 948,000	Daytona Beach, Fla.
	485,000	1,646,000	
159-III	396,000	698,000	Del Ray Beach, Fla.
	698,000	968,000	
71- II	254,000	454,000	Fisher Island, Fla.
	442,000	658,000	(south of Miami Beach)

1) First estimate developed from weighted-average wave height and period for each directional sector. Second estimate developed from individual data hindcast at 3-hr intervals.
2) Assumed shoreline orientation of 354° (Gravens 1988).

We are left to question the amount of wave averaging that is appropriate for use with LST predictions. In computation of P_ℓ in the CERC Formula, early investigators used broad, daily-averaged wave observations. Recent investigators typically use hourly or 3-hr observations. Because the WIS data are similarly hindcast at 3-hr intervals, we might expect that use of individual wave conditions from the WIS data is appropriate; yet this procedure yields LST magnitude that are judged to produce great overpredictions.

In shoreline change modelling, increasing the amount of wave-averaging over time can be undesirable. For example, in their model for Oarai Beach, Kraus and Harikai (1983) found that wave conditions averaged over 5-day intervals yielded poor results relative to more frequent updating of wave conditions. Hence it is important that expressions for LST produce acceptable results for wave conditions representative of times on the order of hours.

Selected Recently Proposed Expressions

Kamphuis (1990) introduced the following expression for the LST rate based upon three-dimensional movable-bed laboratory tests with sands 0.105 and 0.18 mm in median diameter:

$$\frac{I}{\dfrac{\rho g H_s^3}{T}} = K^* m^{0.75} \left(\frac{H_s}{L_o}\right)^{-1.25} \left(\frac{H_s}{D}\right)^{0.25} \sin^{0.6}(2\theta_b) \tag{18}$$

where here T = spectral peak period, m = beach slope across the surf zone, D = median sediment size, and significant wave height and wave angle are evaluated at breaking. For irregular waves, $K^* = 0.0013$. Kamphuis reported 95% of his data points lie within a factor of ± 1.6 times Eq. 18. The conditions were T = 0.9 to 1.5 s, and H_s = 4.5 to 14 cm.

Eq. 18 can be re-expressed as

$$I = K^* \rho g \left(\frac{g}{2\pi}\right)^{0.75} \xi_b T^{0.5} (mD)^{-0.25} H_s^{2.5} \sin^{0.6}(2\theta_b) \tag{19}$$

Eq. 19 reflects a dependence upon $H^{2.5}$ that supports the form of the CERC Formula. It also suggests a weak dependence upon grain size and proportionality to the surf similarity parameter. The latter is consistent with other laboratory results that describe an increase of LST rate (or the proportionality coefficient K) with the surf-similarity parameter:

$$K = K^* \frac{16 g^{0.25} \xi_b \sqrt{\gamma T}}{(2\pi)^{0.75} (mD)^{0.25} \sin^{0.4}(2\theta_b)} \tag{20}$$

For the reasonable values of ξ_b = 0.2 to 2.0, T = 4 to 16 s, γ = 0.8 to 1.0, m = 1/10 to 1/50, d = 0.1 mm to 0.3 mm, θ_b = 3 to 15 $^\circ$, and K^* = 0.0013, Eq. 20 yields values of K from 0.06 to 4.8, with typical values in the range of 0.2 to 0.7. Recall that this should be compared to the recommended value of K = 0.32 because significant wave height is used. Kamphuis (1990) notes that K = 0.12 best fits the laboratory data.

Interestingly, use of Eq. 20 for K in the CERC Formula with the WIS hindcast wave data yields LST estimates that are typically smaller than if a fixed value of K = 0.32 is used. For example, for an assumed constant beach slope of 1/30 and a sediment diameter of 0.2 mm, the net annual LST estimate at Del Ray Beach, Florida (Phase III Station 159) is reduced by 17% to 577,000 m^3/yr. These estimates were developed through consideration of individual wave height and period events for each direction. From surveyed volume changes and sand bypassing records at Lake Worth and Boynton Inlets north of Del Ray Beach, net transport rates of 137,000 to 193,000 m^3/yr since 1955 were estimated for this shoreline area (Walker and Dunham 1977, Bodge et al., 1990). In another example, the net annual LST estimate at Nags Head, North Carolina (WIS Phase III Station 83) is reduced by 51% to 286,000 m^3/yr. This assumes a constant beach slope of 1/30 and 0.2 mm sand diameter, approximately representing average site conditions.

On the other hand, Eq. 20 suggests that the K-value for the experimental conditions of Kraus et al. (1988) and Rosati et al. (1990) should be about 0.6 to 1.2, or fairly close to the design value of 0.77. Recall that these data, developed from streamer traps, yielded LST estimates that were 3.5 to 15 times smaller than predicted by the Bagnold expression. If the Bagnold and CERC formulae empirical coefficients are related (or at least yield similar magnitudes of transport), then it does not appear that the Kraus et al. and Rosati et al. data can be explained by a variation in the K coefficient expressed by Eq. 20.

Drift Potential

As a cautionary note, comparison of predicted and "measured" LST rates at sites which are sediment-starved may be misleading. In these locations, actual or "measured" drift rates may be less than rates predicted by formulae calibrated in sediment-rich conditions. That is, the formulae pertain to the potential LST rate.

FIELD VERIFICATION OF THE PREDICTIVE FORMULAE

Field data collection projects performed to verify or calibrate the LST formulae number about a dozen since formal investigation began in the 1950's. Such studies attempt to measure (1) the total LST across the surf zone, or (2) the transport at a given point (or points) across the surf zone. The former is more often a "long-term" technique i.e., physical integration of the sediment transport (usually by impoundment or dredging) and subsequent comparison to numerical integration of directional wave conditions over days or weeks. The latter is more often a "short-term" technique, i.e., sampling over minutes or hours.

Furthermore, measurement can be "direct" or "indirect." The former typically includes physically trapping, surveying, and or weighing the motive transport (e.g., by impoundment, streamer traps, bedload traps, etc.). The latter typically measures sediment tracer movements, or samples sediment concentration and longshore current velocity simultaneously and combines the two quantities to estimate LST.

Adequacy of the Field Data

If the LST predictive formulae are generally correct, then the magnitude of transport they yield is overpredicted only if (1) the field data collection sampled only a narrow range of surf conditions that are not representative of broader conditions, or (2) the field data used to calibrate the formula were biased in one direction.

In considering the first possibility, we note that there has been some effort to vary sediment size between experiments. About 12 of the 60-some field data points (20%) were collected at beaches with median grain size in excess of 0.59 mm; the remainder include sizes of about 0.3 mm or less. However, there is no conclusive evidence that grain size is the determining factor in variations of the LST proportionality coefficients (Komar 1990). It is possible that other surf conditions (such as directional wave spread, surf beat, or surf similarity parameter) are of equal or greater importance.

Because surf conditions such as the similarity parameter vary hourly or daily, long-term field data points can not be assigned a single meaningful parameter that characterizes these conditions. These data yield little insight to "fine-tuning" of the LST predictive formulae except for verifying their basic functional form or, say, exploring relationships between the proportionality constants and local surf-zone "constants" such as grain size. The latter efforts have been less than successful to date (Komar 1990). Short-term field data points have been collected for average estimated surf similarity conditions (ξ_b) varying from about 0.15 to 1.2 (see Fig. 2). However, these data are all from tracer studies that are subject to suspicion (see below) or from streamer studies for which the data quality is still not completely certain.

A second possibility exists that the field data are biased in more or less the same direction. This is briefly discussed for individual measurement techniques below.

Impoundment Techniques

Central to impoundment techniques are surveys of the volume of sediment trapped or dredged within a control area. Measurement errors accrue with the impoundment of sand not related to longshore processes (for example, diffraction currents leeward of a structure or unaccounted drift reversals). These "spurious" signals are, at best, difficult to isolate. If present and not deconvolved from the data, they will bias the measured longshore transport signal upwards and result in over-estimation of the net drift. In an order-of-magnitude examination, consider the contribution of longshore gradients in wave height to the LST rate as introduced by Ozasa and Brampton (1980):

$$Q' = (H^2 C_g)_b \left(- a_2 \cos\theta \frac{dH}{dx} \right)_b \tag{21}$$

where $a_2 = K_2/[8(s - 1)a'm]$. Relative to the CERC Formula, this contribution can be shown to be (Kraus and Harikai 1983)

$$\frac{Q'}{Q} = \frac{r}{2m\sin\theta} \frac{dH}{dx} \tag{22}$$

where $r = K_2/K$, or $r = 0.5$ to 1.0, after Hanson and Kraus (1989). For typical values $m = 1/30$, $\theta = 10\,^{\circ}$, $r = 0.75$, and $dH/dx = 1/1000$, the ratio of the longshore gradient contribution to LST relative to the CERC Formula estimate is 0.09, or about 10%.

From Eq. 22, the significance of longshore gradient contributions increases as the angle of wave incidence approaches zero deg. Evidence of this effect in the database is suggested by Bruno, Dean, and Gable (1980), who surveyed volume changes behind a detached breakwater at Channel Islands Harbor, Calif. They note that at least two out of the seven data points (for which $K = 2.58$ and $K = 1.35$) exhibit an upward bias in transport for low energy flux "due to the tendency of the trap to collect material even for waves propagating directly toward shore." Bruno et al. found an average value $K = 0.87$.

Spurious impoundment probably also biases the earliest LST data. Watts (1953) assumed that 10% of the measured sand mechanically bypassed at the South Lake Worth Inlet, Florida, study area was due to drift reversals and gradient effects not accounted for in the wave data. Conversations with the bypassing plant operator of the last 10 years suggests that significant amounts of sand consistently enter the plant's sand trap area during intervals of drift reversal or shore-normal wave incidence (Bodge et al. 1990). Caldwell (1956) developed data points from surveys downdrift of a littoral barrier. At least one point was discarded because of a negative relation between Q_ℓ and P_ℓ. Neglecting wave measurement error, this suggests that spurious impoundment is also present in the Caldwell LST field data.

A second source of measurement error is survey inaccuracies -- most often manifest as a failure for consecutive surveys to "close" at the seaward or updrift edge of the survey area. In an order-of-magnitude examination of this error, consider a survey area which is 2000 m alongshore by 300 m offshore (2200 yd x 330 yd) -- about equal to that of the Nearshore Sediment Transport Study (NSTS) survey grids (Dean et al. 1987) A vertical datum or closure error of only 3 cm (0.1 ft) -- the practical limit of survey accuracy -- would yield an 18,000-cubic meter error. This is equal to the expected total net drift rate for an experiment conducted on a moderate energy beach over a 6-week interval, i.e., the average survey interval for the NSTS experiments. Although efforts are made to vertically "float" surveys as necessary for closure, the effect of this potential error can be significant.

Another source of error, shared with other experimental techniques, is that of directional wave data resolution. For example, a 10% error in wave height and in breaking wave angle results in approximately a 30% error in the longshore energy flux factor. Greer and Madsen (1978) suggest that the computed values of P_ℓ from Watts (1953) and Caldwell (1956) may be in error by factors of 5 to 10, respectively, because of inaccuracies in wave observation and computed transformation to breaking conditions. More recently, two directional wave gauges deployed for the Santa Barbara, Calif., NSTS experiment (Dean et al. 1987) disagreed significantly: one yielded estimates of the longshore radiation stress (S_{xy}) almost twice that of the other. Results from the lower-energy gauge were used in the LST data analysis. Assuming that the error in P_ℓ was similar, the average discovered value of K = 1.23 may be over-estimated by a factor of 2 due solely to wave data uncertainties.

Lastly, long-term impoundment experiments are poorly conditioned to correlate longshore transport rate with specific beach/surf conditions; these techniques temporally and spatially "smear" the transport signal. Accordingly, inadequacies of the LST formulas' basic formulations, functional dependencies of the proportionality coefficient, and/or the effects of isolated high- or low-energy wave events within an impoundment interval can not be identified. Short-term impoundment experiments (Bodge and Dean 1987) have so far studied the LST distribution across the surf zone and have not attempted to accurately measure the total LST rate.

Selected Other Topics (Tracer and Suspended-Load Studies)

Here we mention two other inconsistencies associated with field measurement of LST rates to enter these problems in the record and stimulate thought and investigation on them.

Kraus et al. (1982), in their series of eight spatial integration, multicolor fluorescent sand tracer experiments, sampled the grid between two and four times over the course of each 2- or 3-hour experiment "to check reproducibility of the results by reference back to a previous position of the center of mass, not necessarily the injection line." As pointed out by those authors, the results of successive sampling were inconclusive in that there was a tendency for the tracer to move rapidly during the first hour after injection and then slow down greatly; some samplings after longer elapsed times showed apparent movement of tracer against the current, indicating the limits of grid resolution. Tracer advection speeds (Table 3 of Kraus et al.) sometimes varied by a factor of about four, depending on the elapsed time. This indicates that K-values obtained from short-term tracer experiments can be in error by a factor of four due purely to limitations in sampling methodology. Kraus et al. typically employed from 20 to 40 divers to accurately and quickly obtain a large number of samples, suggesting that less labor-intensive tracer experiments may have larger errors.

Measurements of total LST rates by means of instruments that measure only suspended load have produced K-values close to the design value of 0.78 (e.g., instantaneous traps, Kana 1977; Optical Backscatter Sensors (OBS), Sternberg, Shi, and Downing 1984). However, it is generally accepted that the sediment concentration is maximum at the sea bed and decreases in the water column. For example, Kraus, Gingerich, and Rosati (1988) measured LST fluxes through the water column including at the bed and found an exponential decay starting at the bed.

If suspended load represents no more than, say, 50% of the total LST, and because measurement of only the suspended load LST produced the design value of K (which accounts for both suspended and bedload LST), then (1) the suspended load measurements must be biased to yield transport estimates which are too high by a factor of 2 or more, or (2) the design K-value is too large by a factor of 2 or more. These two possibilities imply that the suspended load measurement schemes are either suspect or accurate, respectively. We note that Rosati et al. (1991) report that OBS transport measurements are a factor or 3 to 4 higher than streamer trap measurements under very unfavorable conditions, and that the efficiency of the streamer trap in collecting net downstream transport was laboratory-calibrated by Rosati and Kraus (1989). We also note that streamer trap results yield K-values which are 3.5 to 15 times smaller than the design value. This implies that either or both possibilities might be true.

CONCLUSIONS

This paper has examined several inconsistencies in the field data and predictions associated with the Bagnold and CERC Formulas for LST. Issues raised are summarized as:

1. Problems in practical application of the formulae (e.g., improper adjustment of K or K' for H_s, choice of expressions for C_g, choice of sediment density and porosity) can result in an overprediction of LST magnitude by a factor of up to 1.8.

2. Calculation of energy flux or P_ℓ by non-linear theory instead of linear theory suggests that LST is overpredicted for low-steepness waves; however, this contradicts most laboratory findings.

3. Numerical simulation of shoreline change near a long shore-perpendicular barrier demonstrates a functional relationship between LST and $H^{2.8}$. This generally agrees with the CERC Formula for which $Q \sim H^{2.5}$.

4. In the most pragmatic sense, the CERC and Bagnold formulae yield reasonable transport magnitudes for reasonable wave conditions. However, if used with hindcast wave data, the predicted LST magnitude may be overpredicted by factors of 2 to 5.

5. The appropriate amount of wave-averaging for use in the predictive formulae is unclear. Discrete 3-hr hindcast wave conditions yield LST magnitudes that are 1.5 to 2.5 times larger than if directionally-averaged wave conditions are used.

6. Predicted LST magnitude is reduced if an expression for the K-coefficient developed after Kamphuis (1990) is used (which is proportional to surf similarity parameter). However, the expression does not explain discovered values of K and K' from streamer trap experiments that are 3.5 to 15 times smaller than the design values.

7. Scatter in the discovered values of the proportionality coefficients from field data may be a result of (a) inadequate recognition of surf or beach conditions which affect LST or insufficient variability in surf or beach conditions between experiments, and/or (b) bias or error in the field database.

8. Impoundment techniques are subject to potentially significant (10% to 100%) error in transport measurement due to spurious trapping unrelated to LST. Survey inaccuracies can likewise potentially represent up to 100% of the LST signal. Wave data error or inaccuracy significantly biases the field data base; recent (NSTS) results may overpredict *K* by a factor of 2 due solely to wave gauge uncertainties.

9. LST estimates derived from tracer studies can be in error by a factor of 4 due purely to limitations in sampling methodology.

10. Measurements of suspended load LST alone yield values of the proportionality coefficients close to the design values. Because these measurements exclude bedload, one suspects that they may overestimate drift magnitude.

Field measurements are needed to refine the predictive LST formulae and clarify issues discussed here. In particular, data collection should be made over diverse beach/surf conditions during quasi-steady directional wave events using techniques that are verified or calibrated for accuracy of transport measurement, and potential errors and ambiguities such as described in this paper should be addressed to optimize experiment design.

ACKNOWLEDGEMENTS

This study was supported by the work unit "Surf Zone Sediment Transport Processes" of the Coastal Program conducted for Headquarters, U.S. Army Corps of Engineers, at the Coastal Engineering Research Center (CERC). The authors appreciate permission to publish this information granted by the Chief of Engineers. Special thanks go to Ms. Barbara Warner, Olsen Assoc., for her ability to keep the authors in touch across many miles, field trips, and time zones, and to Mses. Holley Messing and Jane Stauble, both of CERC, for retyping the manuscript (a long story). Also, the authors would like to acknowledge the assistance of Dr. Magnus Larson, U. of Lund, Sweden, and Ms. Julie Dean Rosati, CERC, for collecting the data and performing the analysis leading to Fig. 3.

REFERENCES

Bagnold, R.A. 1963. "Mechanics of Marine Sedimentation," in The Sea, M.N. Hill (ed.), Wiley-Interscience, NY, 507-582.

Bajouornas, L. 1970. "Littoral Transport and Energy Relationships," Proc. 12th Coastal Engrg. Conf., ASCE, 787-798.

Bodge, K.R. and Dean, R.G. 1987. "Short-term Impoundment of Longshore Transport," Proc. Coastal Seds. '87, ASCE, 468-483.

Bodge, K.R., Olsen, E.J., and Savage, R. 1990. "Sand Management Plan, South Lake Worth Inlet, Fla.," Olsen Assoc., Inc., Jacksonville, FL.

Bruno, R.O., Dean, R.G., and Gable, C.G. 1980. "Littoral Transport Evaluations at a Detached Breakwater," Proc. 17th Coastal Engrg. Conf., ASCE, 1452-1475.

Caldwell, J. 1956. "Wave Action and Sand Movement Near Anaheim Bay, California," Tech. Memo. No. 68, Beach Erosion Board, U.S. Army Engr. Waterways Expt. Stn., Vicksburg, MS.

Castanho, J. 1970. "Influence of Grain Size on Littoral Drift," Proc. 12th Coastal Engrg. Conf., ASCE, 891-898.

Corson, W., Resio, D., Brooks, R., Ebersole, B., Jensen, R., Ragsdale, D. and Tracy, B. 1982. "Atlantic Coast Hindcast, Phase II Wave Information," U.S. Army Corps of Engr., Hyd. Lab., WIS Rep. 6.

Dean, R.G. 1974. "Evaluation and Development of Water Wave Theories for Engineering Application," Vols. 1 and 2, Special Rep. No. 1, U.S. Army Corps of Engr., Coastal Engrg. Res. Center, Vicksburg, MS.

Dean, R.G. 1978. "Review of Sediment Transport Relationship and the Data Base," Proc. Workshop on Coastal Sed. Transport, Dept. of Civil Engrg. and Sea Grant Col. Prog., U. of Del., Newark, DE.

Dean, R.G., Berek, E.P., Bodge, K.R., and Gable, C.G. 1987. "NSTS Measurements of Total Longshore Transport," Proc. Coastal Seds. '87, ASCE, 652-667.

Galvin, C. (unpublished). "Size Effect in Longshore Sand Transport."

Gravens, M. 1988. "Use of Hindcast Wave Data for Estimation of Longshore Sediment Transport," Proc. Symp. on Coastal Water Res., Amer. Water Res. Assn, 63-72.

Greer, M.N. and Madsen, O.S. 1978. "Longshore Sediment Transport Data: A Review," Proc. 16th Coastal Engrg. Conf., ASCE, 1563-1576.

Hallermeier, R.J. 1983. "Sand Transport Limits in Coastal Structure Design," Proc. Coastal Structures 83, ASCE, 703-16.

Hanson, M., and Kraus, N.C. 1989. "GENESIS: Generalized Model for Simulating Shoreline Change," Report 1: Technical Reference, Tech. Rep. CERC-89-19, U.S. Army Engr. Waterways Expt. Stn., Coastal Engrg. Res. Center, Vicksburg, MS.

Hanson, M. and Kraus, N.C. 1991. "Comparison of Shoreline Change Obtained with Physical and Numerical Models," Proc. Coastal Seds. '91, ASCE, in press.

Jensen, R. 1983. "Atlantic Coast Hindcast, Shallow-Water Significant Wave Information," WIS Rep. 9, U.S. Army Engr. Waterways Expt. Stn., Vicksburg, MS.

Kamphuis, J.W. 1990. "Alongshore Sediment Transport Rate," Proc. 22nd Coastal Engrg. Conf., ASCE, in press.

Kamphuis, J.W. and Readshaw, J.S. 1978. "A Model Study of Alongshore Sed. Transport Rate," Proc. 16th Coastal Engrg. Conf., ASCE, 1656-1674.

Kamphuis, J.W. and Sayao, O.J. 1982. "Model Tests on Littoral Sand Transport Rate," Proc. 18th Coastal Engrg. Conf., ASCE, 1305-1325.

Kana, T.W. 1977. "Suspended Sediment Transport at Price Inlet, S.C.," Proc. Coastal Seds. '77, ASCE, 366-382.

Komar, P.D. 1990. "Littoral Sediment Transport," in Herbich, J. (ed.), Handbook of Coastal and Ocean Engrg., Vol. 2, Gulf Pub. Co., Houston, TX, 681-714.

Komar, P.D. and Inman, D.L. 1970. "Longshore Sand Transport on Beaches," J. Geophys. Res., 75(30), 5914-5927.

Kraus, N.C., Gingerich, K.J., and Rosati, J.D. 1988. "Toward an Improved Empirical Formula for Longshore Sand Transport," Proc. 21st Coastal Engrg. Conf., ASCE, 1182-1196.

Kraus, N.C. and Harikai, S. 1983. "Numerical Model of the Shoreline Change at Oarai Beach," Coastal Engrg., 7(1), 1-28.

Kraus, N.C., Isobe, M., Igarashi, H., Sasaki, T. and Horikawa, K. 1982. "Field Experiments on Longshore Sand Transport in the Surf Zone," Proc. 18th Coastal Engrg. Conf., ASCE, 969-988.

Kraus, N.C., Rosati, J.D., and Gingerich, K.J. 1989. "DUCK85 Surf Zone Sand Transport Experiment," Tech. Rep. CERC-89-5, U.S. Army Engr. Waterways Expt. Stn., Coastal Engrg. Res. Center, Vicksburg, MS.

Krumbein, W. 1944. "Shore Currents and Sand Movement on a Model Beach," Beach Erosion Board, Tech. Memo No. 7, U.S. Army Engr. Waterways Expt. Stn, Vicksburg, MS.

Larson, M., Hanson, M., and Kraus, N.C. 1987. "Analytical Solutions of the One-Line Model of Shoreline Change," Tech. Rep. CERC-87-15, U.S. Army Engr. Waterways Expt. Stn., Coastal Engrg. Res. Center, Vicksburg, MS.

Longuet-Higgins, M.S. 1970. "Longshore Currents Generated by Obliquely Incident Waves, 1," J. Geophys. Res., 75, 6778-6789.

Ozasa, H. and Brampton, A.H. 1980. "Mathematical Modeling of Beaches Backed by Seawalls," Coastal Engrg., 47-64.

Ozhan, E. 1982. "Laboratory Study of Breaker Type Effect on Longshore Sand Transport," in Mechanics of Sediment Transport, B.M. Sumer and A. Muller (eds.), Proc. Euromech 156, A.A. Balkema, Rotterdam, 265-274.

Pelnard-Considere, R. 1956. "Essai de Theorie de l'Evolution des Froms de Rivages en Plage de Sable et de Galets," 4th Journees de l'Hydraulique, Les Energies de la Mer, Question III, Rapport No. 1, 289-298.

Rosati, J.D., Gingerich, K.J., and Kraus, N.C. 1990. "SUPERDUCK Surf Zone Sand Transport Experiment," Tech. Rep. CERC-90-10, U.S. Army Engr. Waterways Expt. Stn., Coastal Engrg. Res. Center, Vicksburg, MS.

Rosati, J.D., and Kraus, N.C. 1989. "Development of a Portable Sand Trap for Nearshore Use," Tech. Rep. CERC-89-11, U.S. Army Engr. Waterways Expt. Stn., Coastal Engrg. Res. Center, Vicksburg, MS.

Rosati, J.D., Gingerich, K.J., Kraus, N.C., Smith, J.M. and Beach, R. 1991. "Distributions of Longshore Transport Measured in Lake Michigan," Proc. Coastal Seds. '91, ASCE, in press.

Sauvage, S-M. and Vincent, G. 1954. "Transport Littoral Formation de Fleches et de Tombolos," Proc. 5th Coastal Engrg. Conf., ASCE, 296-328.

Savage, R.P. 1962. "Laboratory Determination of Littoral Transport Rates," J. Waterways and Harbors Div., ASCE, Vol. 88 No. WW2, 69-92.

Saville Jr., T. 1950. "Model Study of Sand Transport along an Infinitely Long, Straight Beach," Trans. Amer. Geophys. Union, 31, 555-565.

Shay, E.A. and Johnson, J.W. 1951. "Model Studies of the Movement of Sand Transported by Wave Action Along a Straight Beach," Inst. of Engrg. Res., Univ. of Calif., Berkeley, Series 14.

Shore Protection Manual. 1977. 3rd ed. U.S. Army Corps of Engrs., Coastal Engrg. Res. Center, U.S. Govt. Printing Office, Washington, DC.

Shore Protection Manual. 1984. 4th ed. U.S. Army Corps of Engrs., Coastal Engrg. Res. Center, U.S. Govt. Printing Office, Washington, DC.

Sternberg, R.W., Shi, N.C., and Downing, J.P. 1984. "Field Investigation of Suspended Sediment Transport in the Nearshore Zone," Proc. 19th Coastal Engrg. Conf., ASCE, 1782-1798.

Swart, D.H. 1976. "Predictive Equations Regarding Coastal Transport," Proc. 15th Coastal Engrg. Conf., ASCE, 1113-1132.

USACE. 1966. Shore Protection, Planning and Design, Tech. Rep. 4 (3rd ed.), Coastal Engr. Res. Center, U.S. Army Engr. Waterways Expt. Stn., Vicksburg, MS.

van Hijum, E. 1976. "Equilibrium Profiles and Longshore Transport of Coarse Material Under Oblique Wave Attack," Proc. 15th Coastal Engrg. Conf., ASCE, 1-32.

Vitale, P. 1981. "Movable-Bed Laboratory Experiments Comparing Radiation Stress and Energy Flux Factor as Predictors of Longshore Transport Rate," Coastal Engrg. Res. Center, R.M. 81-4, Vicksburg, MS.

Walker, J.R. and Dunham, J.W. 1977. "Lake Worth Inlet: Case Study," Proc. Coastal Seds. '77, ASCE, 602-621.

Walton, T. 1973. "Littoral Drift Computations along the Coast of Florida by Means of Ship Wave Observations," U. of Fla., Dept. of Coastal Engrg., Tech. Rep. 15.

Watts, G.M. 1953. "A Study of Sand Movement at South Lake Worth Inlet, Florida," Tech. Memo. No. 42, Beach Erosion Board, U.S. Army Engr. Waterways Expt. Stn., Coastal Engrg. Res. Center, Vicksburg, MS.