ERDC/CHL CHETN-II-46
March 2002

US Army Corps
of Engineers®

Longshore Sand Transport – Initial Results from Large-Scale Sediment Transport Facility

by Ping Wang, Bruce A. Ebersole, and Ernest R. Smith

PURPOSE: Accurate predictions of the total rate of longshore sand transport (LST) and its cross-shore distribution pattern in the surf zone are central to many coastal engineering studies. Present understanding and methods for calculating the LST rate are largely developed based on field studies (e.g., Komar and Inman 1970; Inman et al. 1981; Kraus et al. 1982; Bodge and Dean 1987a, b; Dean 1989; Schoonees and Theron 1993; Miller 1998; Wang, Kraus, and Davis 1998; Wang 1998; Wang and Kraus 1999; Miller 1999). The Coastal Engineering Research Center (CERC) formula (*Shore Protection Manual* 1984), which is based on field measurements, is often used to calculate the total LST rate. Accuracy of the CERC formula is believed to be ± 30-50 percent and several parameters that logically might influence LST are excluded in the formula, such as breaker type and grain size. The GENESIS shoreline change model, a tool commonly used in shore protection and beach-fill project design, utilizes the CERC formula. In the GENESIS model, the cross-shore distribution of LST is assumed to be uniform across the surf zone. Laboratory data (Bodge 1986; and Kamphuis 1991) and field data (Zenkovitch 1960; Ingle 1966; Bodge and Dean 1987a, b; Miller 1998) suggest that the distribution is not uniform.

This technical note summarizes results of initial experiments conducted in the new Large-scale Sediment Transport Facility (LSTF) (see Fowler at al. 1995; Hamilton and Ebersole 2001 for additional details about the LSTF). Experiments are underway to investigate the importance of breaker type (spilling and plunging breakers) on LST, to examine the accuracy of presently used methods for calculating the total LST rate, and to aid in developing improved predictors for both the total LST rate and its cross-shore distribution patterns for varying surf conditions. Initial results concerning the cross-shore distribution pattern for the two different types of breaking waves are also presented. The LTSF experiments are intended to span the gap between laboratory measurements and low-energy field measurements. The LSTF is capable of simulating wave conditions that are almost directly comparable to annual averages along many low-wave-energy coasts, for example a majority of estuarine beaches (Nordstrom 1992) and many beaches along the Gulf of Mexico and the Great Lakes in the U.S.

BACKGROUND: A commonly used tool for predicting the total rate of longshore transport is the CERC formula (*Shore Protection Manual* 1984),

$$Q = \frac{K_l}{16\sqrt{\gamma}} \rho g^{\frac{3}{2}} H_{sb}^{\frac{5}{2}} \sin\left(2\theta_b\right) \tag{1}$$

where γ is the breaker index, often taken to be 0.78, ρ is the density of water, g is gravitational acceleration, H_{sb} is significant breaking wave height, θ_b is wave breaker angle, and K_l is an empirical coefficient. Based on the original field study by Komar and Inman (1970), the *Shore Protection Manual* recommends a K_l value of 0.39. Bodge and Kraus (1991) re-examined the derivation and suggested a lower K_l value of 0.32. Schoonees and Theron (1993, 1994) re-examined the 46 most reliable of the 240 existing field measurements that have been compiled and recommended a K_l value of approximately 0.2. In a number of GENESIS model applications, where calibration involves adjustment of the K_l value to maximize replication of observed shoreline changes and net and gross LST rates based on local knowledge of the sediment budget, optimal K_l values often range from 25 to 50 percent of the value recommended in the *Shore Protection Manual*.

Based on similar field data, Kamphuis et al. (1986) developed an empirical formula that includes the beach slope and sediment grain size,

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

where, d is sediment grain size, and m is beach slope. Based on a series of laboratory studies and re-examination of existing field data, Kamphuis (1991) suggested an empirical formula for the prediction of total longshore sediment transport rate, modifying the 1986 formula and adding the influence of peak wave period, T_p

$$Q = 6.4\times10^4\, H_{sb}^2 T_p^{1.5} m^{0.75} d^{-0.25} \sin^{0.6}(2\theta_b) \tag{3}$$

It is noted that the dependence on grain size and wave height are greatly reduced as compared to Equation 2. The influences of beach slope and incident wave angle are also reduced. The coefficients in the preceding Kamphuis-86 and -91 formulas were determined using metric units.

Wang, Kraus, and Davis (1998) found that the Kamphius-91 formula predicted consistently lower total longshore transport rates than those predicted by the broadly used CERC formula and the Kamphuis-86 formula. The relatively lower prediction by the Kamphuis-91 formula, which is typically 1.5 to 3.5 times lower than predictions from the CERC and Kamphuis-86 formulas, occurred over a range of low wave-energy conditions with breaker heights of less than 1 m (Wang, Kraus, and Davis 1998). However, the lower predictions by the Kamphuis-91 matched the measured values closer than the CERC formula predictions for those low-wave conditions. Lower predictions also occurred for storm conditions with breaker heights of nearly 4 m (Miller 1998). However, Miller found that predictions by the CERC formula matched the measured rates closer than the Kamphuis-91 predictions, which were nearly one order of magnitude lower than the measured values.

The effect of breaker type on the rate of LST, and its cross-shore distribution is poorly understood. One of the more commonly used indicators of breaker type is the surf similarity parameter, ξ_b, which is defined as

$$\xi_b = \frac{m}{\sqrt{H_{brms}/L_o}} \tag{4}$$

where m is beach slope, L_o is deepwater wavelength, and H_{brms} is the root-mean-square breaker height. Galvin (1968) found that ξ_b is typically less than 0.4 for spilling breakers. For plunging breakers, ξ_b typically ranges from 0.4 to 2.0. A possible relationship between longshore sediment transport rate and the surf-similarity parameter has been discussed in several studies (e.g., Kamphuis and Readshaw 1978; Vitale 1981; Ozhan 1982; Bodge 1986; Bodge and Kraus 1991). Kamphuis and Readshaw (1978) and Kamphuis et al. (1986) attempted to incorporate the surf similarity parameter into the empirical coefficient in the CERC formula. The development of the Kamphuis-86 and Kamphuis-91 formulas is related to this effort.

In comparison, Kraus, Gingerich, and Rosati (1988) adopted a different approach, which assumes proportionality between the LST rate and longshore wave-energy flux. Kraus, Gingerich, and Rosati (1988) assume that the total rate of LST in the surf zone is proportional to the longshore discharge of water:

$$Q \propto K_d (R - R_c) \tag{5}$$

where K_d is an empirical coefficient that may relate to sediment suspension, R_c is a threshold value for significant longshore sand transport, and R is called the discharge parameter and is proportional to the average discharge of water moving alongshore. Based on field data collected using streamer sediment traps at Duck, N.C., Kraus, Gingerich, and Roasti (1988) suggested a K_d value of 2.7 and R_c value of 3.9 m^3/sec.

WAVE AND BEACH CONDITIONS: Irregular waves with a relatively broad spectral shape, representing typical sea conditions, were generated in the LSTF for both spilling and plunging breakers. The significant breaking wave height, peak spectral period, and mean direction at breaking were 0.27 m, 1.5 sec, and 6.5 deg for the spilling wave case, and 0.24 m, 3.0 sec, and 6.4 deg for the plunging wave case. The surf similarity parameter ξ_b for the spilling breaker was determined to be 0.14, within the range of less than 0.4 as defined by Galvin (1968). However, the ξ_b determined for the plunging breaker was only 0.20, much less than the range of 0.4 to 2.0 as suggested by Galvin (1968). This is influenced by the presence of a substantial bar under the plunging breakers. It is worth noting that the beach slope was determined as the slope between the depth at the main breaker line and the still-water shoreline. Due to the existence of a pronounced breakpoint bar that formed for the plunging wave case, the beach slope under the plunging breaker was substantially gentler than that under the spilling breaker, which resulted in a smaller ξ_b. However, if the bottom of the trough is used to calculate the slope, the surf similarity parameter increases to 0.33.

The LSTF beach is comprised of very well-sorted sand, with a median grain diameter of 0.15 mm. Measurements of LST were made after the beach reached a near-equilibrium condition, under the prolonged influence of the prescribed incident wave conditions. Equilibration was reached after 14 hr of wave runs for the spilling breakers. The adjustment to equilibrium took only 4 hr for the much more energetic plunging breakers (because of the greater wave period). The equilibrium beach conditions for the two wave cases are shown in Figure 1. The cross-shore distribution of measured significant wave height at equilibrium is shown in Figure 2.

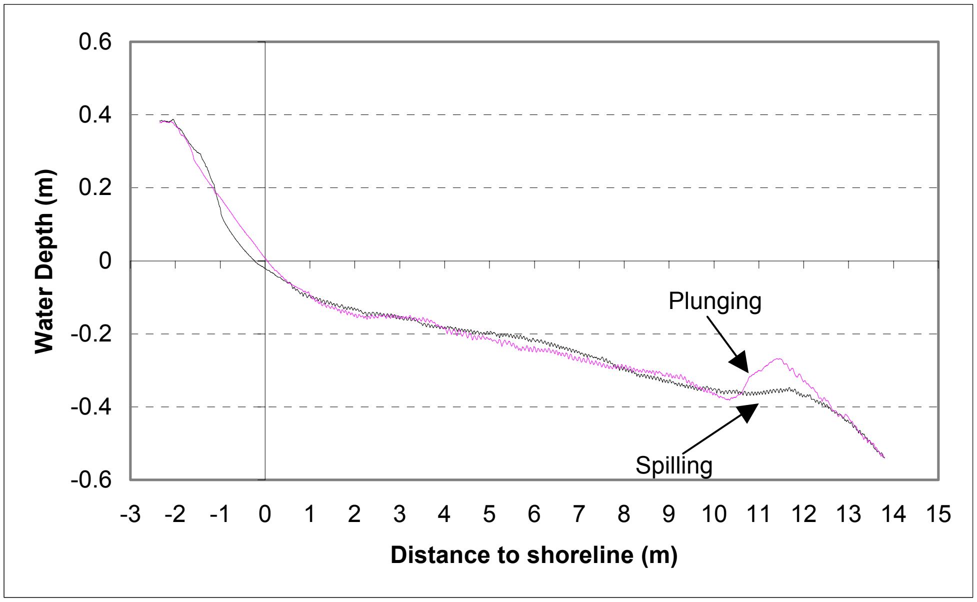

Figure 1. Equilibrium beach profile shape

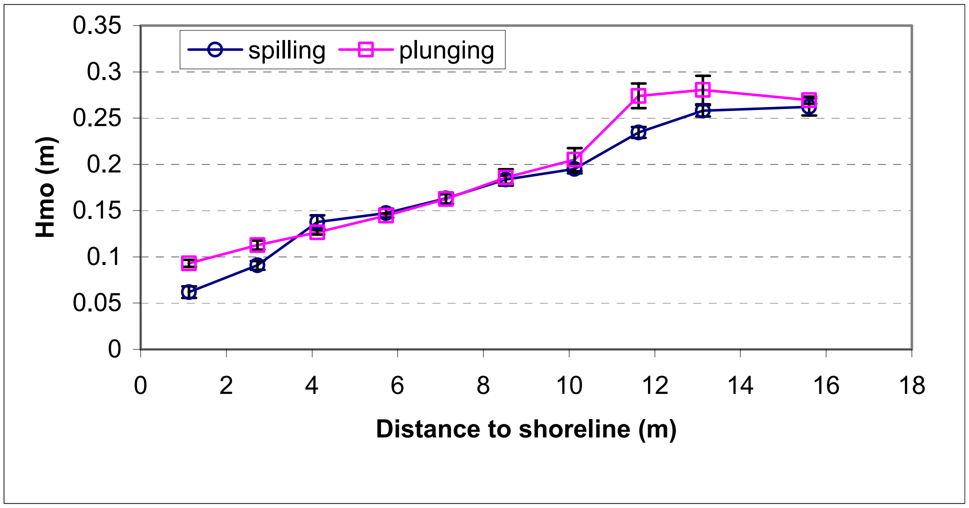

Figure 2. Cross-shore distribution of significant wave height

CROSS-SHORE DISTRIBUTION OF LST: The cross-shore distribution patterns of the depth-integrated longshore sediment flux measured at downdrift bottom traps in the facility were quite different during the plunging and spilling cases (see Figure 3).

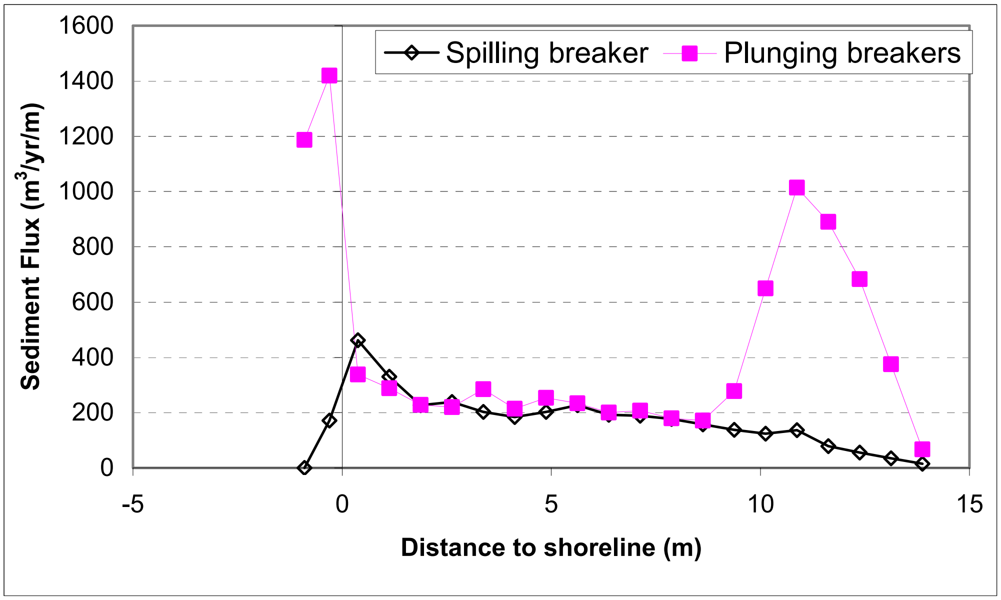

Figure 3. Cross-shore distribution of LST for both spilling and plunging waves

For both cases, significant sediment transport was measured in the swash zone. For the spilling case, about 27 percent of the total LST occurred in the narrow swash zone. For the plunging case, about 34 percent of the total LST occurred in the swash zone. Visual observations during the experiments indicated that the uprush was much more active during the long-period plunging case than that during the spilling case. This is probably responsible for the much greater sediment flux above the still-water shoreline. Active sediment transport in the swash zone was also observed in several field studies (Kraus et al. 1982; Kraus and Dean 1987; Wang 1998).

A substantial peak in the longshore sediment transport distribution was measured in the vicinity of the breaker line for the plunging breaker case. This peak is obviously related to the active sediment suspension throughout the entire water column induced by the turbulent plunging-type breaking. Measured sediment concentrations in the water column (at distances greater than 5 cm off the bed) were an order of magnitude greater for the plunging breaker case. Nearly 35 percent of the total longshore sediment transport occurred in the 3-m-wide breaker zone from 10 to 13 m. Combined with the swash-zone peak, nearly 70 percent of the total LST occurred in the breaker and swash zones. These two areas together occupied less than 40 percent of the total surf zone width.

No transport peak was measured at the spilling breaker line. A gradual trend of increasing sediment flux toward the shoreline was measured during this case. The cross-shore distribution of LST was close to being linear. Cross-shore distributions in both cases were not uniform.

The similarity in LST rate in the inner surf zone (region between the swash zone and the incipient breaker zone) for both the spilling and plunging wave cases is notable. In this region the broken waves were surf bores with very similar wave heights. The measured mean longshore current in this region was also similar for the two wave cases; in fact it was very similar across the entire surf zone except near shore where the measured current was higher for the plunging wave case. The large difference in LST rate at the incipient breaker line between the plunging and spilling cases is attributed to the much higher sediment concentrations higher in the water column that were created by the plunging breakers. In the swash zone, differences seem to be attributed to the much higher energy of the uprush and downrush associated with the longer-period waves that characterized the plunging case.

TOTAL RATE OF LST: In the LSTF, the total rate of LST was obtained by simply summing the sediment flux per unit width measured at a series of traps located at the downdrift end of the facility. The total rate measured during the spilling case was 2,660 m^3/year, substantially less than the total rate of 7,040 m^3/year measured during the plunging case. It is worth noting that the breaking wave (significant height) was about 13 percent higher during the plunging case, 0.27 m, versus 0.24 m during the spilling case. However, the 13 percent higher breaking wave height certainly could not explain the fact that measured LST rates differed by a factor of 2.65.

The measured total transport rates were substantially lower than the predictions from the CERC (Equation 1) and the Kamphuis-86 formulas (Equation 2) for both the spilling and plunging cases (see Table 1). The Kamphuis-91 (Equation 3) formula, on the other hand, underpredicted the measured rates for both cases. The empirical K_l value of 0.39 as recommended by the *Shore Protection Manual* was used in the CERC formula.

Table 1
Comparison among Measured and Predicted Total Rates of LST

	Spilling Case	Plunging Case
Transport Rates (m^3/year)		
Measured (m^3/year)	2,660	7,040
CERC formula (m^3/year)	18,040	23,850
Kamphuis-86 (m^3/year)	8,130	9,100
Kamphuis-91 (m^3/year)	1,870	5,360
Kraus-88 (m^3/year)	2,670	3,150
Percentage Over (+) Or Under (-) Prediction		
CERC	+578%	+239%
Kamphuis-86	+206%	+29%
Kamphuis-91	-30%	-24%
Kraus-88 (m^3/year)	0%	-55%

The CERC formula overpredicted the total rate for the spilling condition by nearly 600 percent, while for the plunging waves, the overprediction was less than 250 percent. This inconsistency of the CERC formula under different breaker types indicates that a simple reduction of the K_l value as examined by Bodge and Kraus (1991), Schoonees and Theron (1993), and Wang, Kraus, and Davis (1998) cannot completely address the discrepancy. In other words, the comprehension that the total rate of LST is proportional to a measure of the longshore wave-energy flux might not be complete. The Kamphuis-86 formula also had a similar inconsistency. Using it, the spilling case was overpredicted by more than 200 percent, while the plunging case was overpredicted by less than 30 percent.

By incorporating wave period to a power of 1.5, the Kamphuis-91 formula produced much more consistent predictions for the different breaker types, relative to the measured values. Wave period, which is linked to the wavelength through the dispersion relation, has significant influence on wave steepness and hence, breaker type. The Kamphuis-91 formula underpredicted the spilling and plunging cases by 30 percent and 24 percent, respectively. The consistent underprediction, if proven to be true with more data, could be resolved by adjusting the empirical coefficient.

A different formulation and parameterization were used in the Kraus, Gingerich, and Rosati (1988) formula. The threshold value R_c of 3.9 m^3/sec, which was determined from an Atlantic Ocean surf zone, is too large for application to the LSTF conditions. For purposes of comparison, the R_c parameter is ignored. The recommended K_d value of 2.7 is still used. The longshore discharge was measured directly in the LSTF. Predictions from the Kraus-88 formula are also compared in Table 1. The predicted value compared well for the spilling case, but underpredicted the plunging case by 55 percent. As discussed in Kraus, Gingerich, and Rosati (1988), the coefficient K_d is related to sediment suspension. Sediment suspension in the vicinity of the spilling and plunging breaker lines was substantially different. The inconsistency in the prediction using the method of Kraus, Gingerich, and Rosati (1988) was caused by neglecting the different magnitude of sediment suspension and using the same K_d value. It would be reasonable to use a greater K_d value for plunging breakers due to the much more active sediment suspension. Similar inconsistencies in using the CERC and Kamphuis-86 formulas probably arise for the same reason. The significantly improved consistency of the Kamphuis-91 formula is attributed to incorporation of wave period, which has significant influence on the breaker type.

SUMMARY AND CONCLUSIONS: The total rate and cross-shore distribution pattern of LST were significantly different during the plunging and spilling cases. Nearly 170 percent more longshore sediment transport was measured for the plunging breaker than for the spilling breaker, although the plunging breaker height was only 13 percent higher than the spilling breaker height. The cross-shore distribution patterns of LST were far from being uniform. During the spilling-breaker case, peak longshore transport was measured in the swash zone. During the plunging-breaker case, two transport peaks were measured, one in the swash zone and one in the vicinity of the breaker line. Substantial amounts of longshore sediment transport were measured in the swash zone during both cases. Interestingly, in the mid-surf zone which is dominated by surf-bore motions, the measured transport rates were quite similar for both the spilling and plunging cases. In other words, the much greater rate of total longshore transport measured for the plunging case was mainly due to the much more active sediment suspension and transport in the breaker zone and more transport in the wider and more energetic swash zone.

The commonly used CERC formula predicted inconsistent total longshore sediment transport rate under the spilling and plunging breakers. By including wave period, which has significant influence on breaker type, the Kamphius-91 formula produced consistent predictions for both the spilling and plunging cases. Results from the present study suggest that breaker type has a significant influence on the total rate of longshore sediment transport and its cross-shore distribution pattern. Parameterization of predictive formulas should include factors that reflect the breaker type; however, additional data and research are needed to derive the relationship between LST and breaker type.

Experiences from shoreline change modeling studies, and results from reanalysis of data used to derive the CERC formula by several researchers, suggest that the formula (using a K_l value of 0.39) may overpredict the LST rate when considering the entire wave climate for a particular site. Miller (1998, 1999) found the CERC formula predicted LST rates during storms reasonably well. The field measurements during storms cited by Miller do not capture swash transport. If swash transport was as significant during the storm events that were studied, as is suggested by the laboratory measurements, the CERC formula may in fact underpredict LST rates during high-energy conditions. Evidence from field and laboratory experiments suggests that the CERC formula overestimates LST for lower wave conditions. Evidence suggests that the Kamphuis-91 formula is a better estimator of LST for lower wave conditions, but it may produce an underestimate.

Based on presently available information from a number of sources, the following guidance is offered. When attempting to develop long-term LST estimates for a site using a long-term record of measured or hindcast wave information, coastal engineering practitioners should consider using the Kamphuis-91 formula to develop a lower-bound estimate and the CERC formula to derive an upper bound estimate. A K_l value of approximately 0.2 might provide more realistic estimates for expected LST rates using the CERC formula, rather than a value of 0.39. However, a more appropriate K_l value can be estimated from a shoreline change model calibration/validation exercise and/or scaling of calculated LST rates to match those derived from knowledge of the local sediment budget. For specific events, at present, it seems most appropriate to use the CERC formula for storm events and the Kamphuis–91 formula for low-energy events (less than 1 m in height). Additional field and laboratory data and research, are needed to develop more accurate and robust predictors for both the magnitude of LST and its cross-shore distribution pattern, which properly account for factors such as breaking wave type and grain size.

ADDITIONAL INFORMATION: Questions about this CHETN can be addressed to Mr. Bruce A. Ebersole (601) 634-3209, *Bruce.A..Ebersole@erdc.usace.army.mil*. The contributions of William Halford, David Daily, and Tim Nisley, who provided technical support to this study, are gratefully acknowledged. This technical note should be cited as follows:

> Wang, P., Ebersole, B. A., and Smith, E. R. (2002). “Longshore sand transport – initial results from lage-scale sediment transport facility,” ERDC/CHL CHETN-II-46, U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://chl.erdc.usace.army.mil/

REFERENCES

Bodge, K. R. (1986). “Short-term impoundment of longshore sediment transport,” Ph.D. diss., University of Florida, 345 p.

Bodge, K. R., and Dean, R. G. (1987a). “Short-term impoundment of longshore transport,” Proceedings of Coastal Sediments '87, ASCE, New York, 468-483.

. (1987b). “Short-term impoundment of longshore sediment transport,” Miscellaneous Paper CERC-87-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

8

Bodge, K. R., and Kraus, N. C. (1991). "Critical examination of longshore transport rate magnitude," *Proceedings Coastal Sediments '91*, ASCE Press, New York, 139-155.

Dean, R. G. (1989). "Measuring longshore sediment transport with traps," *Nearshore sediment transport.* R. J. Seymour, ed., Plenum Press, New York, 313-337.

Fowler, J. E., Rosati, J. D., Hamilton, D. G., and Smith, J. M. (1995). "Development of a large-scale laboratory facility for longshore sediment transport research," *The CERCular, CERC-95-2*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Galvin, C. J. (1968). "Breaker type classifications of three laboratory beaches," *Journal of Geophysical Research* 73, 3651-3659.

Hamilton, D. G., and Ebersole, B. A. (2001). "Establishing uniform longshore currents in a large-scale laboratory facility," *Coastal Engineering* 42, 199-218.

Ingle, J. C. (1966). "The movement of beach sand, and analysis using fluorescent grains," Department of Geology, University of Southern California, Los Angeles, CA, Elsevier Publishing Company, New York, NY.

Inman, D. L., Zampol, J. A., White, T. E., Hanes, B. W., Waldorf, B. W., and Kastens, K. A. (1981). "Field measurements of sand motion in the surf zone," *Proceedings of 17th International Conference on Coastal Engineering*, ASCE, New York, 1215-1234.

Kamphuis, J. W. (1991). "Alongshore sediment transport rate," *Journal of Waterways, Port, Coastal and Ocean Engineering*, ASCE, 117(6), 624-641.

Kamphuis, J. W., and Readshaw, J. S. (1978). "A model study of alongshore sediment transport rate," *Proceedings of 16th International Conference on Coastal Engineering*, ASCE Press, New York, 1656-1674.

Kamphuis, J. W., Davies, M. H., Nairn, R. B., and Sayao, O. J. (1986). "Calculation of littoral sand transport rate," *Coastal Engineering* 10, 1-21.

Komar, P. D., and Inman, D. L. (1970). "Longshore sand transport on beaches," *Journal of Geophysical Research* 75(30), 5514-5527.

Kraus, N. C., Isobe, M., Igarashi, H., Sasaki, T. O., and Horikawa, K. (1982). "Field experiments on longshore transport in the surf zone," *Proceedings of 18th International Conference on Coastal Engineering*, ASCE, New York, 969-988.

Kraus, N. C., and Dean, J. L. (1987). "Longshore sediment transport rate distributions measured by trap," *Proceedings of Coastal Sediments'91*, ASCE, 818-896.

Kraus, N. C., Gingerich, K. J., and Rosati, J. D. (1988). "Toward an improved empirical formula for longshore sand transport," *Proceedings of 21st Coastal Engineering Conference*, ASCE Press, New York, 1183-1196.

Miller, H. C. (1998). "Comparison of storm longshore transport rates to predictions," *Proceedings of 26th International Conference on Coastal Engineering*, ASCE Press.

______ . (1999). "Field measurements of longshore sediment transport during storms," *Coastal Engineering* 36, 301-321.

Nordstrom, K. F. (1992). *Estuarine beaches*. Elsevier Applied Science, 225 pp.

Ozhan, E. (1982). "Laboratory study of breaker type effect on longshore sand transport," *Mechanics of sediment transport.* B. M. Sumer and A. Muller, ed., *Proceedings of Euromech* 156, 265-274.

Schoonees, J. S., and Theron, A. K. (1993). "Review of the field data base for longshore sediment transport," *Coastal Engineering* 19, 1-25.

______ . (1994). "Accuracy and applicability of the SPM longshore transport formula," *Proceedings of the 24th Coastal Engineering Conference*, ASCE Press, New York, 2595-2609.

Shore protection manual. (1984). 4th ed., 2 Vol, U.S. Army Engineer Waterways Experiment Station, U.S. Government Printing Office, Washington, DC.

Vitale, P. (1981). “Movable-bed laboratory experiments comparing radiation stress and energy flux factor as predictors of longshore transport rate,” Miscellaneous Report No. 81-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Wang, P. (1998). “Longshore sediment flux in the water column and across the surf zone,” *Journal of Waterway, Port, Coastal & Ocean Engineering* ASCE, 124, 108-117.

Wang, P., Kraus, N. C., and Davis, R. A., Jr. (1998). “Total rate of longshore sediment transport in the surf zone: Field measurements and empirical predictions,” *Journal of Coastal Research* 14(1), 269-283.

Wang, P., and Kraus, N. C. (1999). “Longshore sediment transport rate measured by short-term impoundment,” *Journal of Waterway, Port, Coastal and Ocean Engineering,* ASCE, 125, 118-126.

Zenkovitch, V. P. (1960). “Flourescent substances as tracers for studying the movement of sand on the sea bed,” (conducted in the USSR), *Dock and Harbor Authority* 40, 280-283.