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Longshore sediment transport rate—measurement and estimation, central west coast of India

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Abstract

Measurements of the longshore sediment transport rate (LSTR) along the surf zone at a 4-km-long beach on the central west coast of India were made over a 4-month period. During the study, both the lateral and vertical distributions of the sediment transport rate were measured with traps deployed on a line spanning the surf zone. Sediment transport in the swash zone was not considered in the present study. The longshore current was measured at each trap location. The breaking wave parameters were calculated from a directional wave buoy at 16-m water depth. The measured values were compared with those calculated from three selected empirical formulas. The standard coefficient values in the empirical formulas were used without calibration to the data sets. The measured average gross transport was 726 m^3/day and that calculated were 1108, 1017, and 781 m^3/day based on CERC, Walton and Bruno, and Van Rijn formula. During the data collection 69% of the time, the transport was direct towards north, and in the remaining period, it was direct towards south. The correlation coefficient between the longshore sediment transport rates measured and those calculated by CERC, Walton and Bruno, and Van Rijn formula were 0.38, 0.71, and 0.74, respectively. The average RMS error between the measured and the calculated longshore sediment transport rate based on CERC, Walton and Bruno, and Van Rijn formula were 0.91, 0.57, and 0.47.

Keywords: Longshore sediment transport rate; Field measurements; Sediment trap; Longshore current; Indian coast; Mesh trap; Streamer trap; Surf zone

1. Introduction

The longshore sediment transport rate enters most coastal engineering designs. The longshore current generated by obliquely incident breaking waves plays an important role in transporting sediment in the surf zone. The longshore current velocity varies across the surf zone, reaching a maximum value close to the wave-breaking point (Galvin, 1967; Basco, 1982). For practical purposes, the average longshore current measured in the surf zone should be sufficient for estimating the longshore sediment transport rate (LSTR). LSTR is, in general, calculated using semi-empirical equations, which are mostly based on laboratory data (Shore Protection Manual, 1984). A sediment transport equation incorporating field data would, however, be more reliable for field application at a particular site.

Measurement of the LSTR in the surf zone is important for validation of the routinely used empiri-

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cal formulas. The different methods for measuring the coastal sediment transport in the field are total traps, suspension traps, tracers, optical devices, acoustical devices, impact, conductivity, and radiation. Reviews of a number of methods tried for measuring sand transport in the surf zone and different types of traps and samplers developed for use in the surf zone are given by Kraus (1987) and Majewski (1989). White (1998) described the status of measurement techniques for coastal sediment transport and found that in spite of the availability of many modern techniques, it is still not possible to make accurate measurements of suspension of mixed sizes, suspension very close to the bed or bed load, and hence older and cruder methods of traps and tracers are still used. Wang et al. (1988) compared the measured and calculated rates of sediment transport rates for the low-wave energy coasts. Miller (1999) and Williams and Rose (2001) measured and calculated rates of sediment transport during storm conditions. Bayram et al. (2001) have compared the cross-shore distribution of longshore sediment transport calculated from six predictive formulas with the values collected during the DUCK85, SUPERDUCK, and SANDYDUCK field data collection projects.

In the present study, longshore sediment transport rates across the surf zone on a coast of India from February through May 1990 were measured using traps. Although optical and acoustic techniques are capable of providing measurements with high spatial and temporal resolution, they are not used in the present study due to high cost. The measured LSTR is compared with the values calculated based on three routinely used empirical formulas. The sediment transport in the swash zone was not included in the present study.

1.1. Study area

A 4-km-long segment of beach at Arge near Karwar (Fig. 1), on the west coast of India, was selected for the

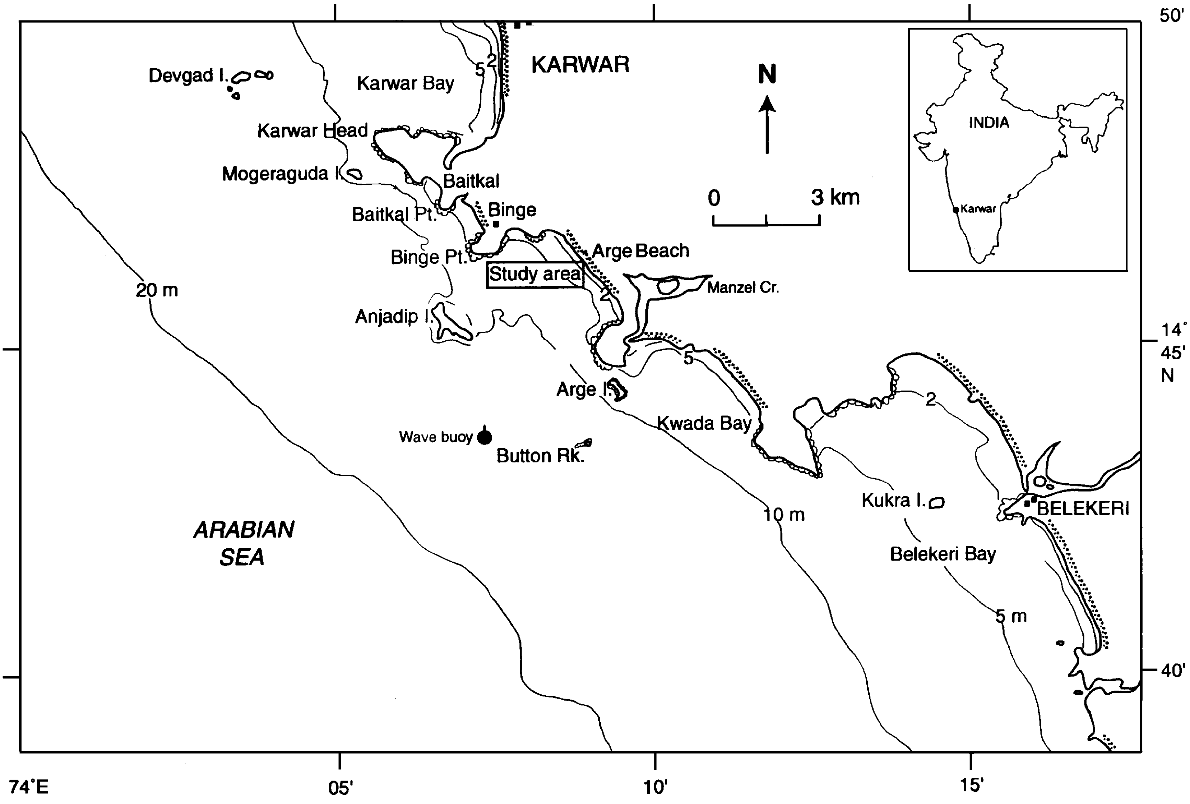

Fig. 1. Study area.

study. The beach is straight and open, and the offshore contours are almost parallel. An offshore island, Anjadip Island, is located at 5 km from the site. Arge Beach is situated between Binge Point and Arge Cape. The average gradient of the shelf of Karwar is around 1:500. The nearshore steepens, with the 10-m contour occurring at an average distance of 4 km from the coast, and the 20-m contour at a distance of about 10 km. The shelf is covered with sand, but close to the coast, mud is found.

The study region is dominated by southwest monsoon (June to September) and non-monsoon period (October to May). Based on wave measurements off Karwar, the significant wave height varied between 1 and 2.1 m from May through August, and between 0.4 and 1 m during September to April. The wave periods varied between 3 and 8 s. The waves approach the coast from the southwest except in January and February during which waves approach from the northwest. The tides in this region are predominantly semi-diurnal. Based on the predicted tides for Karwar port, the average spring tidal range is about 2 m and the neap tidal range is about 0.25 m. Based on the 1-year daily visual observation of breaking wave parameters and measured longshore currents, the longshore sediment transport rate was calculated using Walton and Bruno equation (Walton and Bruno, 1989), and found that annual net transport (0.069×10^6 m^3) was towards north at Arge Beach, and the annual gross transport was about 0.201×10^6 m^3 (Chandramohan et al., 1991).

2. Methods and analysis

2.1. Breaking wave characteristics

The wave data collected by the National Institute of Oceanography using wave buoy at 16-m water depth off Arge Beach is used in the analysis. The significant wave height (Hs), mean wave period (T02), and wave direction with respect to north corresponding to the peak of the wave spectrum (maximum spectral energy) were used. The wave height and direction of the waves measured at 16-m water depth were reduced to wave-breaking zone by the procedure of Skovgaard et al. (1975) and Weishar and Byrne (1978). The wave shoaling coefficients were calculated using small amplitude wave theory. As the contours were almost straight and parallel, the wave direction measured at 16-m water depth was corrected using Snell's law, and the breaker angle was calculated.

2.2. Surf zone characteristics

Daily measurements of surf zone width and the longshore current at the sediment trap locations A, B, C, and D were carried out from February through May. Surf zone width was measured using graduated rope, and the same was used for measuring the distance of the trap location from the shore. Magnitude and direction of the longshore currents were measured using Rhodamine-B dye injected in the trap locations. The distance covered in 2 min was measured, and the average longshore current was calculated.

2.3. Longshore sediment data collection

To obtain the cross-shore distribution of LSTR, simultaneous measurements were carried out daily at six points across the surf zone from February through May. At each point, vertical distributions of the LSTR were obtained by placing a number of traps in an array. Mesh traps having circular openings were used for measuring the suspended load transport and the streamer traps were used for measuring bed load transport.

The streamer trap name derives from the long rectangular bags of sieve cloth that stream out with current and capture sediment, while letting water pass through. The streamer trap used in the present study is similar to that described by Kraus (1987). The opening of the trap was 0.2 × 0.15 m in rectangular shape. The filter cloth mesh opening size was 90 μm. Visual observation indicates that the streamer trap does not noticeably disturb the flow and hence was used for measuring the bed load. The trapping efficiency of streamer trap has been extensively investigated through laboratory experiments by Rosati and Kraus (1988). The mesh trap used in the present study is shown in Fig. 2. The opening of the mesh trap was circular, and the diameter of the opening was 0.034 m.

The configuration of the traps is given in Fig. 3. Depending on the surf zone width, the placing of the

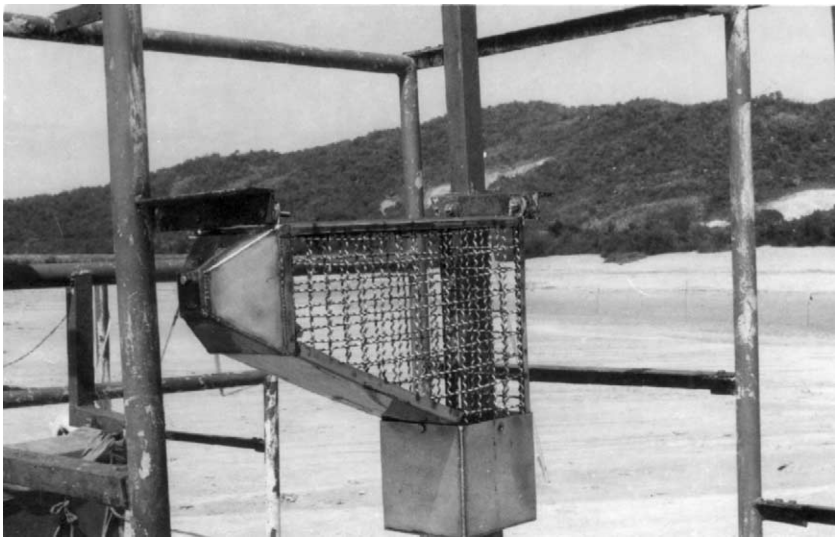

Fig. 2. Mesh trap used for sediment collection.

samplers was done during each measurement. The sediment transport rate along the swash zone was not measured. The tallest frame (A-frame) was deployed at the significant breaker point. The tallest frame was 1.5 m in height (A-frame); the next one was B-frame with 1-m height; C-frame was 0.75 m high; D-frame was 0.5 m high; E-frame was 0.3 m high; and the smallest one was the F-frame (0.15 m height). All the traps were below water line during the measurement period. Depending upon the direction of the longshore current, the opening of the traps was kept facing the longshore current so that the traps opposed the direction of longshore current. Hence, only the shore parallel sediment transport was measured. The mesh trap was deployed for duration of 6 h daily from 0700 to 1300 h irrespective of the tide levels. This results in measurement in all phases of the tide during different days. The streamer trap was deployed for 5-min

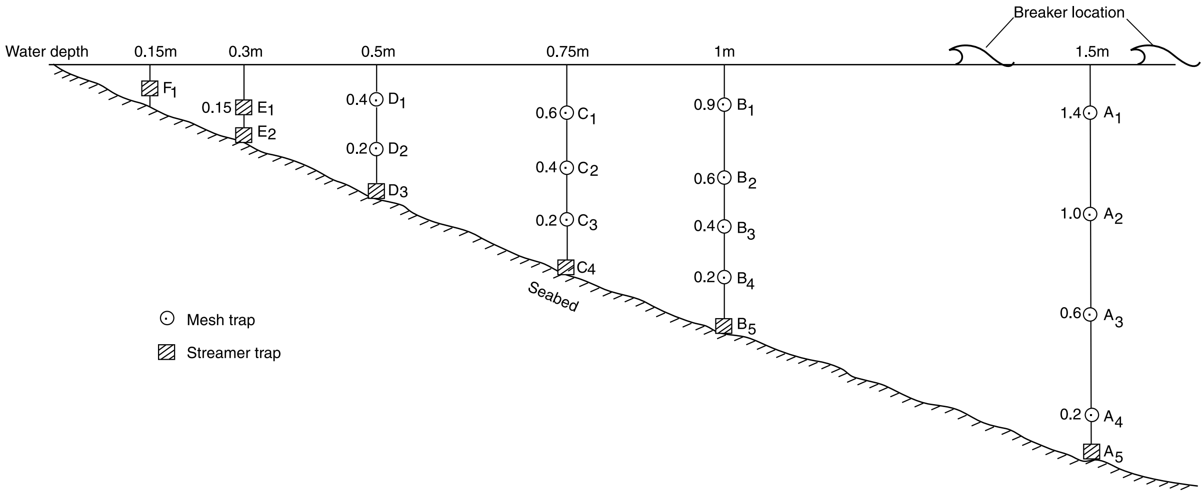

Fig. 3. Configuration of samplers used.

duration at hourly interval six times from 0700 through 1300 h. At the end of the sampling interval, the frame was brought to the beach, and the traps were removed from the frame. The streamer was immersed in a large bucket and gently lifted up and down. The streamer was opened and allowed the sediments to be washed into a container, and the sediments were weighed at the beach. Similarly, the weight of the sediments retained in the mesh trap was obtained. Based on the size of the opening and the duration for each trap, weight of sediment in kg/s/m^2 was calculated. From the measured wet weight of sand, the dry volume of sand transport was calculated for comparison with the theoretical values. The total transport was calculated using the trapezoidal rule at each frame and then along the surf zone following procedure described by Kraus (1987).

Sediment samples collected at each trap location during February, March, and April were used for the sieve analysis to estimate the median grain size.

2.4. Longshore sediment transport rate

The LSTR was calculated from the empirical equation relating the longshore energy flux in the breaker zone to the longshore transport rate (Komar and Inman, 1970). One of the simplest and most commonly used method for calculating LSTR is the Coastal Engineering Research Center (CERC) formula (Shore Protection Manual, 1984). As per the CERC, the longshore transport rate is given by

$$Q = KA\frac{\rho g^2}{64\pi}TH_b^2\sin 2\alpha_b \tag{1}$$

where Q = volume of longshore transport rate in m^3/year, K = dimensionless constant relating sand transport to longshore energy flux and was taken as 0.39, $A = 1/[(\rho_s-\rho)g(1-p)]$, ρ_s = mass density of the sediment (2650 kg/m^3), ρ = mass density of seawater (1025 kg/m^3), g = acceleration due to gravity (9.81 m/s^2), p = porosity of sediment (0.4), T = wave period in s, H_b = breaking wave height in m, and α_b = breaker angle with respect to coastline.

The computed breaker parameters based on the measured waves were input for estimating LSTR using the CERC formula.

Using the computed breaker height, measured surf zone width, and average longshore current velocity in the surf zone, the LSTR was calculated using Walton and Bruno equation (Walton and Bruno, 1989):

$$Q = \frac{KA\rho g H_b WVC_f}{0.78\left(\frac{5\pi}{2}\right)\left(\frac{v}{v_0}\right)_{LH}} \tag{2}$$

where C_f = the friction coefficient (0.005), W = surf zone width in m, V = measured longshore current velocity in m/s, and $(v/v_0)_{LH}$ = theoretical dimensionless longshore current velocity with the mixing parameter as 0.4 (Longuet-Higgins, 1970).

The sediment transport rate was also calculated using TRANSPOR (Van Rijn, 1989). The standard coefficient values as given in the literature were used without calibration. From the measured surface currents, the depth averaged current (U) was calculated from the following Eq. (3) and used as input along with the calculated d_{50} and d_{90} size of the sediments collected at traps.

$$\begin{aligned} U(z) &= \left(\frac{z}{0.32h}\right)^{1/7}U \quad \text{for } 0 < z < 0.5\text{ h} \\ &= 1.07\ U \quad \text{for } 0.5\text{ h} < z < h \end{aligned} \tag{3}$$

where h = the water depth, z = the distance from seabed, and $U(z)$ = the current at z depth.

The salinity was taken as 35‰ and the temperature as 28 °C. The bed roughness value was taken as 0.1 m. The rate was calculated considering the local wave and current parameters, and integrating over the surf zone width. The wave-breaking angle calculated from the measured wave data was used to calculate the angle between the waves and currents.

All the measured data used for the analysis in this paper are available in the report of Kumar et al. (2002).

3. Results and discussions

3.1. Breaker characteristics

The daily variation of breaking significant wave height, wave period, and breaker angle calculated from the wave measurements along with the predicted tide are shown in Fig. 4. The breaking wave height varied from 0.5 to 1.2 m with an average value of 0.8 m from February through May. Wave heights were greatest (≥ 1 m) during May, just before the onset of the southwest monsoon. The wave period mostly varied from 3 to 9 s with an average value of 6 s, and the average wave-breaking angle was 5.6°. The breaking waves approached the coast predominantly from the south (positive values). The average surf zone width was about 41 m from February through May.

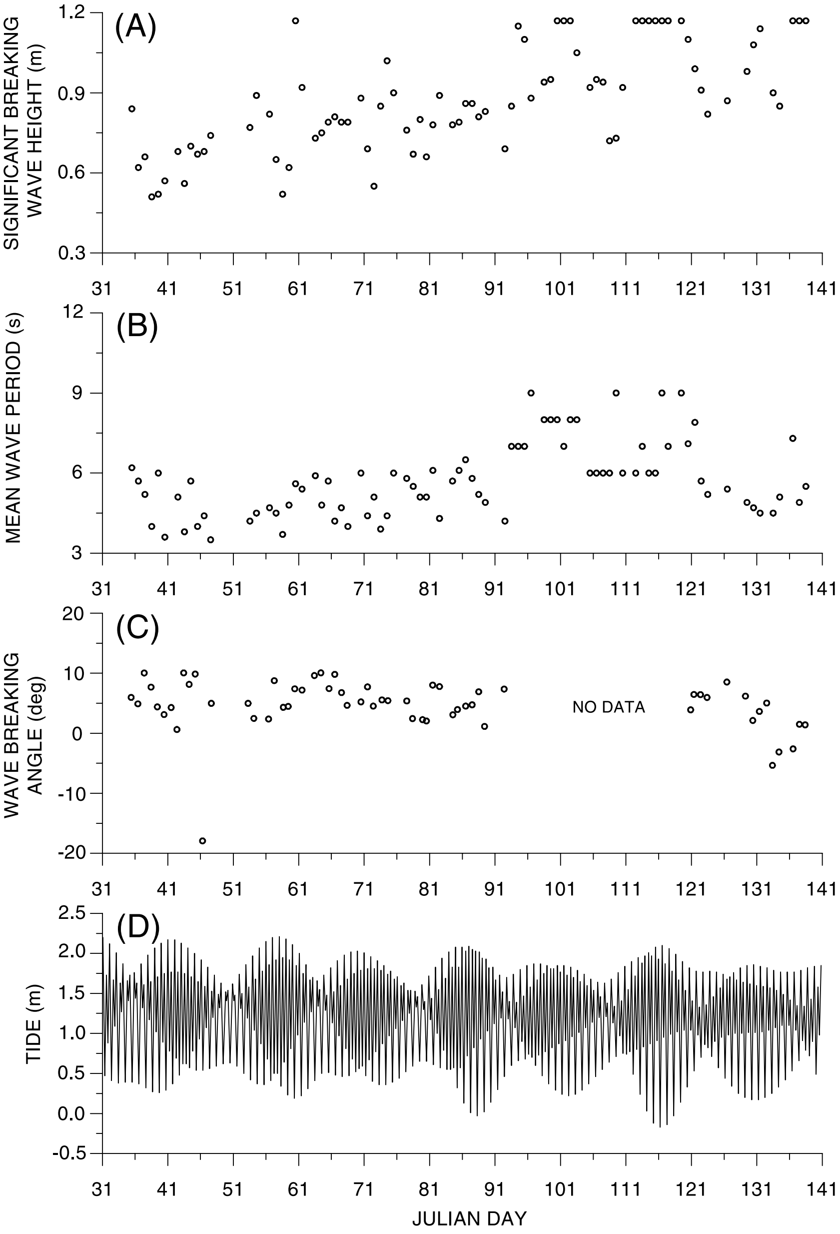

Fig. 4. Variation of (A) breaker height, (B) breaker period, (C) breaker angle, and (D) tide from February through May.

3.2. Longshore current

The average coastal orientation of the coast is N39°W (i.e. 321° clockwise to north). The longshore current direction towards 141° is mentioned as the flow towards south, and that towards 321° is mentioned as north in this study. Daily variations of longshore current velocity measured at trap locations

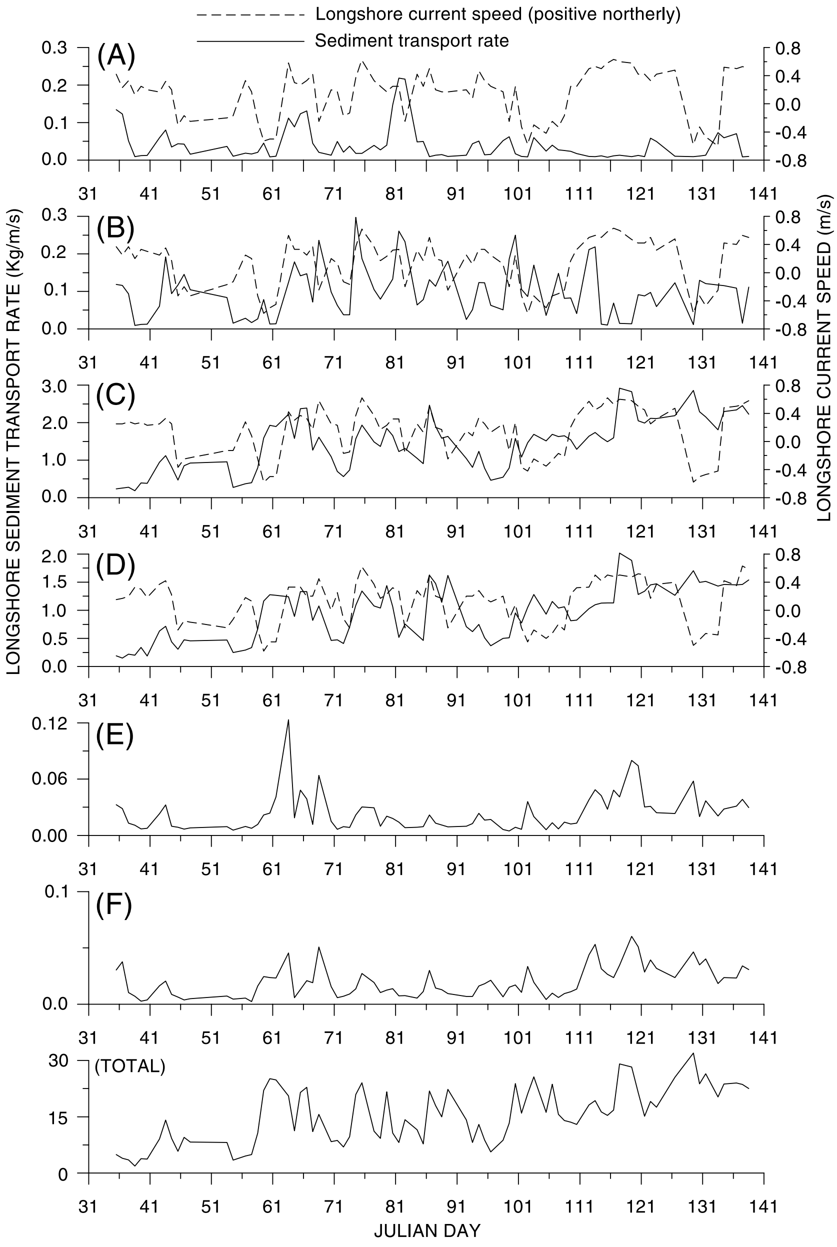

Fig. 5. Sediment transport rate and longshore current across surf zone from February through May.

A, B, C, and D in the water surface is presented in Fig. 5. The longshore current velocities at trap locations A, B, C, and D were identical with values varying from 0.1 to 0.6 m/s with an average value of 0.3 m/s. The longshore current velocity was not measured at trap locations E, and F and was considered as similar to that at location D in the further calculations. The longshore current was predominantly directed to the north during the study period.

3.3. Sediment size distribution

The variations of median size (d_{50}) and d_{90} of the sediment at each trap location from February through April are shown in Fig. 6. As expect, d_{50} increased from the water surface to the seabed at each trap location. In general, the sediments consist of fine sand (d_{50} = 0.15 to 0.2 mm) to medium sand (d_{50} = 0.2 to 0.25 mm).

3.4. Measured LSTR

The measured vertical distribution of LSTR is shown in Figs. 7–9. The measurement shows that the LSTR was high at A4, B4, C3, D2, and E2 at trap locations A to E, respectively. The minimum, maximum, and average values of the LSTR during the measurement period at all trap locations are given in Table 1. Close to the bed, the transport rate was around 0.1 to 0.7 times the respective maximum values observed. Sediment concentration will be greater near bed than in suspension, whereas the measurements show a relatively small value, suggesting that accurate measurement of the bed load was not

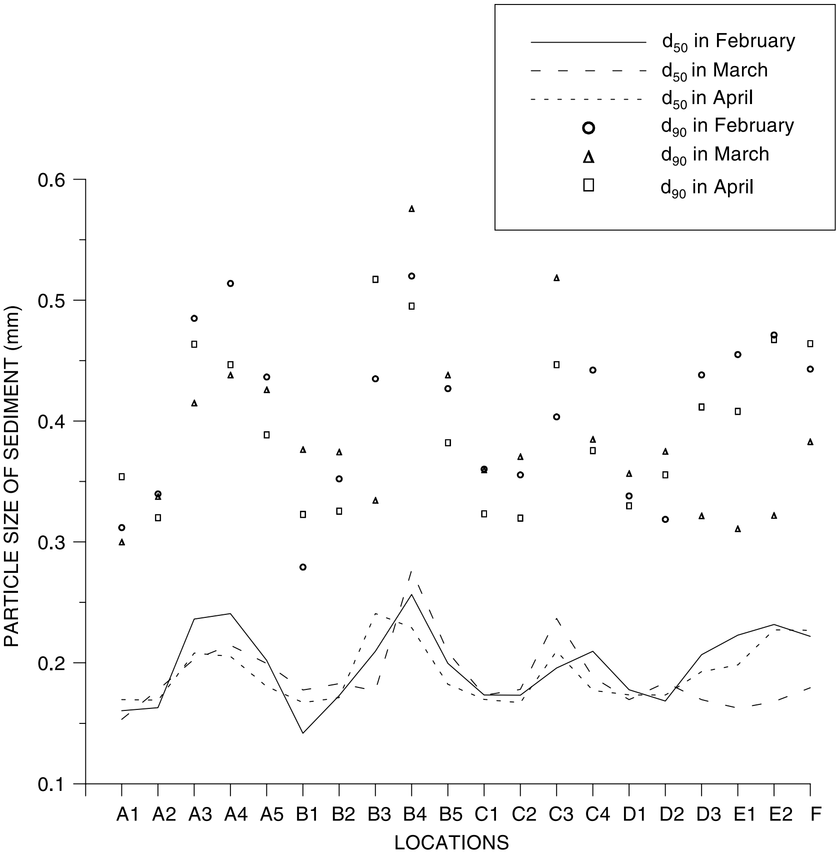

Fig. 6. Variation of median size (d_{50}) and d_{90} of sediment collected at different trap locations.

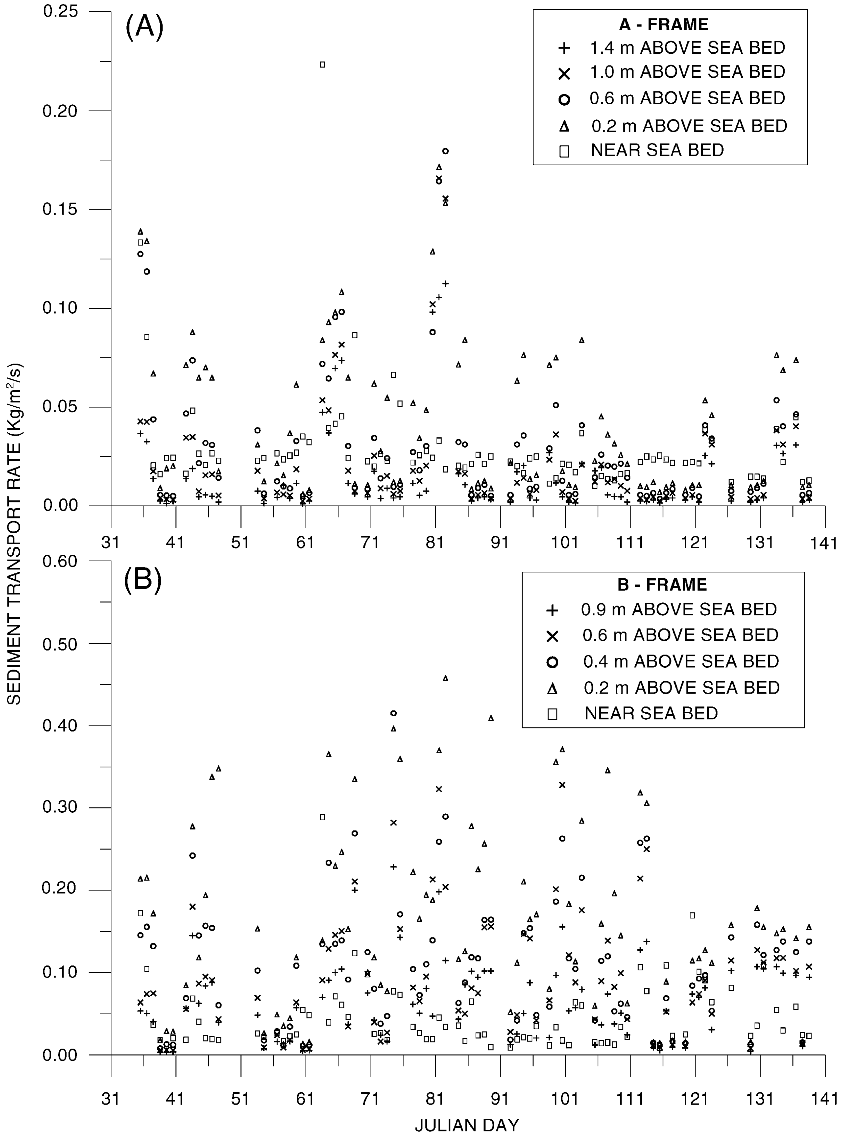

Fig. 7. Vertical distribution of longshore sediment transport rate (A) at A-frame and (B) at B-frame locations.

made. Also, the suspended load measurement was continuous for duration of 6 h, whereas the bed load measurement was for duration of 5 min at hourly interval. The transport rate was high at trap locations C and D as compared to other locations (Fig. 5). The average transport rate was 0.04, 0.099, 1.42, 0.94, 0.023, and 0.019 kg/m/s at trap locations A to F. The transport was more than 1 kg/m/s between 15 and 27 m from the waterline from February through May.

Total measured LSTRs across the surf zone varied from 1.86 to 31.9 kg/m/s, with an average value of 15.2 kg/m/s from February through May (Fig. 5). During some days, when the wave height was more than 1 m, the traps could not be deployed and are not plotted at regular intervals. In the calculation, the sediment transport direction was taken as that of the longshore current direction. The measured LSTR values varied from − 1532 to

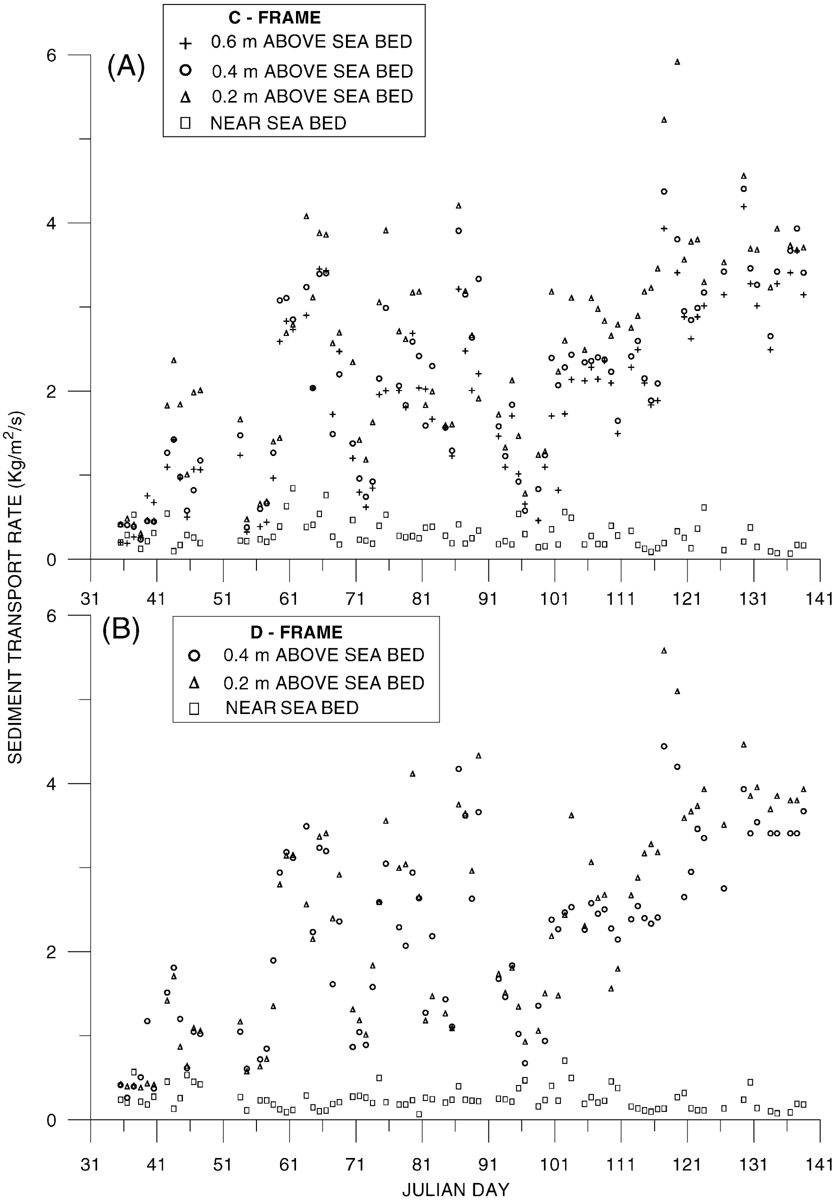

Fig. 8. Vertical distribution of longshore sediment transport rate (A) at C-frame and (B) at D-frame locations.

1396 m^3/day with an average gross transport of 726 m^3/day. The negative sign indicates the southerly transport.

3.5. Calculated LSTR

The wave measurements transformed to the breaker zone were input to the CERC (Eq. (1)), and the calculated values are presented in Fig. 10. The LSTR varied from -2090 to 3380 m^3/day with an average gross transport rate of 1108 m^3/day and the transport was predominantly towards the north. The direction of the LSTR depends on the value of the breaker angle calculated.

The LSTR was also calculated using Walton and Bruno equation, and presented in Fig. 10. The net

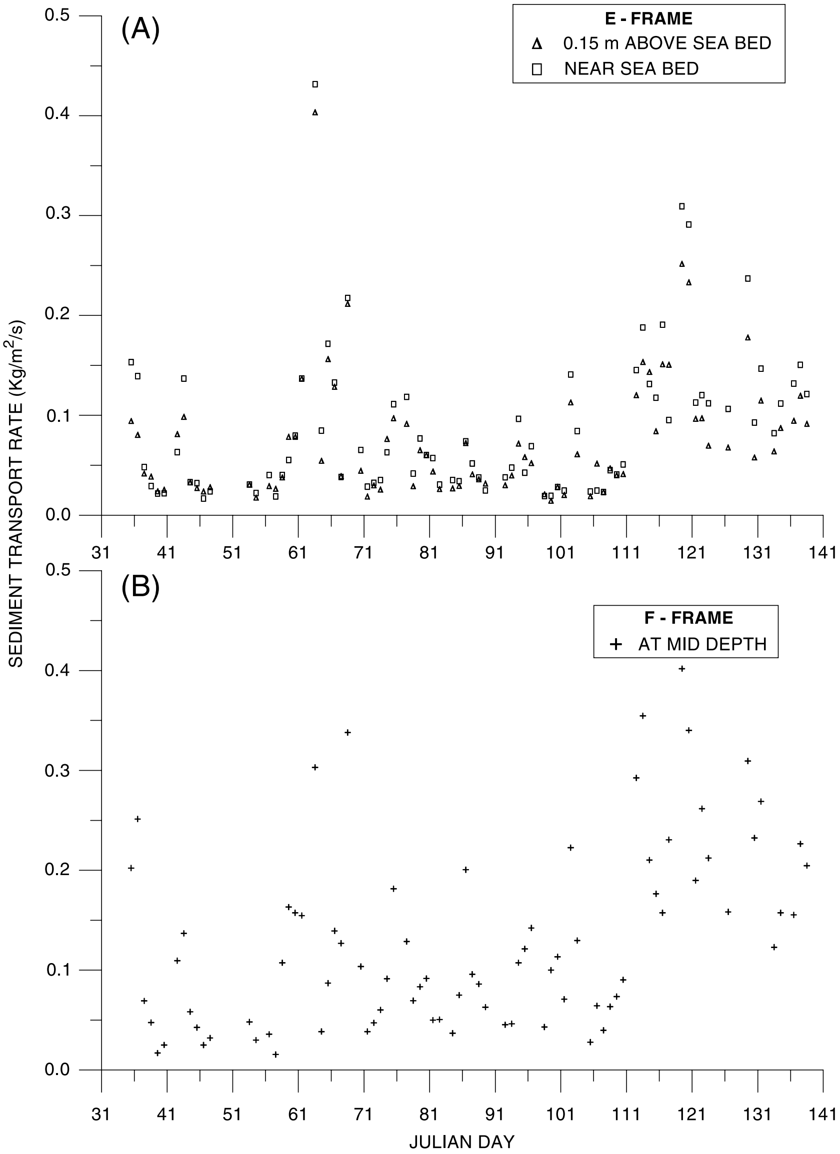

Fig. 9. Vertical distribution of longshore sediment transport rate (A) at E-frame and (B) at F-frame locations.

sediment transport was towards the north during the study period. The LSTR varied from − 2478 to 2178 m^3/day with an average gross value of 1017 m^3/day. About 69% of the time during the study period, the transport was direct towards north, and in the remaining period, it was direct towards south. Here, the direction of the LSTR depends on the longshore current direction.

The difference in estimates between the two approaches is due to the fact that in Eq. (1), the estimation was made based on the assumption of long and open sandy coast with adequate supply of sand. However, the present study was carried out at pocket beach bounded by headlands. Wang and Kraus (1999) performed the measurements of the total longshore sediment transport rate in the surf

Table 1
Minimum, maximum, and average value of the sediment transport rates at different traps

Trap location	Sediment transport rate (kg/m^2/s)		
	Minimum	Maximum	Average
A1	0.001	0.113	0.015
A2	0.003	0.166	0.020
A3	0.004	0.180	0.030
A4	0.006	0.172	0.043
A5	0.010	0.223	0.030
B1	0.003	0.228	0.065
B2	0.006	0.328	0.092
B3	0.008	0.415	0.110
B4	0.014	0.458	0.167
B5	0.009	0.289	0.046
C1	0.189	4.194	1.897
C2	0.236	4.404	2.089
C3	0.311	5.920	2.503
C4	0.068	0.844	0.287
D1	0.262	4.443	2.194
D2	0.385	5.583	2.384
D3	0.066	0.705	0.242
E1	0.015	0.404	0.075
E2	0.017	0.432	0.087
F	0.016	0.402	0.129

zone at a temporary groin installed at Indian Rocks Beach, west central Florida. They concluded that coefficient K appearing in the CERC formula is not a constant and other factors may enter, such as breaker type, turbulence intensity, and threshold for sediment transport. Also, the CERC formulation assumes all of the energy is associated with a single peak in the wave spectra. Kumar et al. (2001) compared the sediment transport estimate based on CERC formula including the sea and swell waves, and Walton and Bruno formula incorporating site-specific measurement of longshore currents. They found that both estimates were reasonably agreeing well for a long and open sandy beach. The presence of an offshore island, Anjadip Island, at 5-km distance from the coastline will influence the breaker values calculated. It was observed that for waves approaching southwesterly, the longshore current was towards south instead of north. The direction of the LSTR in CERC depends on the breaker angle. The correction for refraction effect was applied theoretically to estimate the breaker angle, and the resultant wave height based on linear wave theory in very shallow water. Also, the grid size used for the wave transformation was 50 m, whereas the average surf zone width was 41 m. These will introduce error in estimation of the breaker parameters. Hence, the LSTR calculated based on CERC was in opposite direction to the same calculated based on measured longshore current in 24% of the data collected. The change in direction of LSTR could be due to the change in tide levels (Fig. 4) during the data collection.

From the measured currents at the surface of the water column, the depth-averaged current was calculated and used as the input to TRANSPOR (Van Rijn, 1989). The LSTR calculated based on TRANSPOR are given in Fig. 10. The LSTR varied from − 1502 to 1486 m^3/day with an average gross transport of 781 m^3/day.

3.6. Comparison of measured and calculated LSTR

As a measure of scatter, the RMS error (σ_{rms}) was calculated according to

$$\sigma_{\mathrm{rms}} = \left[\frac{\sum_{1}^{N} \left[\log(q_{\mathrm{c}}) - \log(q_{\mathrm{m}}) \right]^2}{N-1} \right]^{1/2} \tag{4}$$

where N is the number of data points, q_{c} is the calculated LSTR, and q_{m} is the measured LSTR.

The correlation coefficient (r) between the measured and calculated LSTRs was also calculated. For a perfect matching, the correlation coefficient value will be unity.

The RMS error between the measured and that calculated based on CERC formula was 0.91 and the correlation coefficient (r) calculated was 0.38. The smaller RMS error implies smaller scatter. Kamphuis et al. (1986) found reasonable results with the CERC formula for particle size in the range of 0.2 to 0.6 mm. In the present case, the median size varied from 0.15 to 0.25 mm, but the deviation between the measured and that predicted by CERC was large. Based on the measured total LSTR by the streamer traps and short-term impoundment along the low-wave energy coasts,

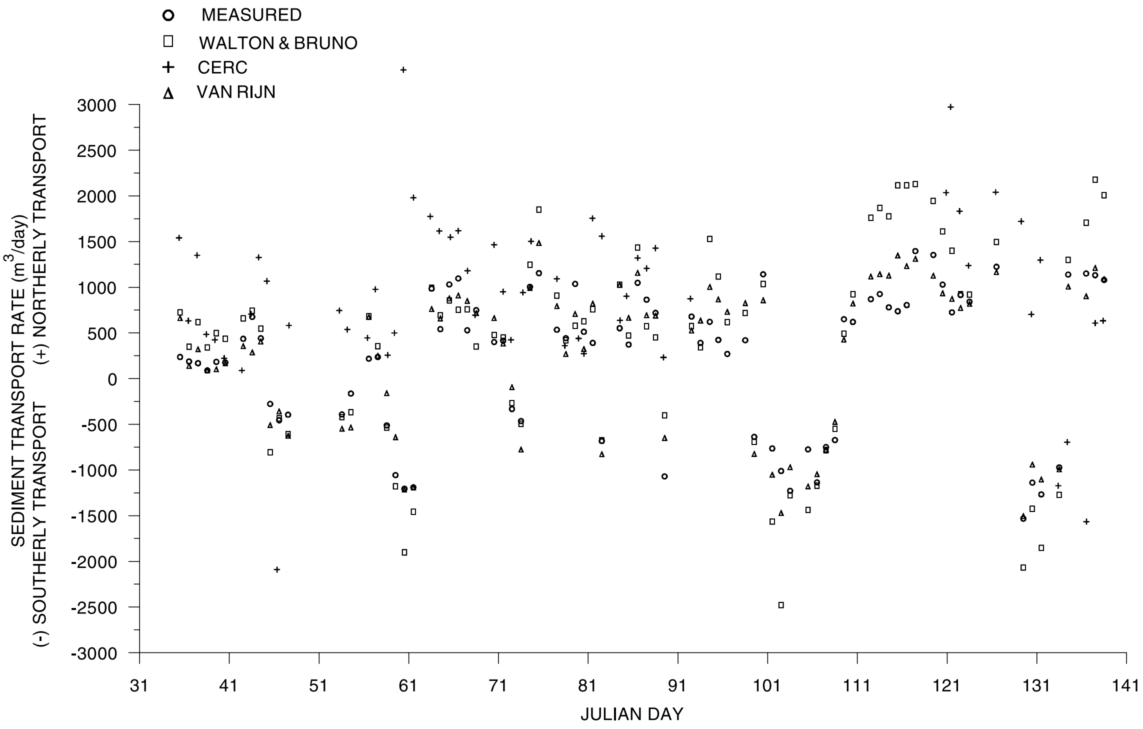

Fig. 10. Time series plot of measured and calculated sediment transport rate.

Wang et al. (1998) found that the rates measured were lower than that predicted by the various empirical formulas. Using the root mean square wave height in the CERC formula, the empirical coefficient K was found to be 0.08 instead of 0.78 recommended in the Shore Protection Manual. For an average wave height of 0.4 m, Wang et al. (1998) found that the values calculated using CERC formula is nine times greater than the trap-measured values. Because the average wave height in the present study was double the value observed by Wang et al. (1998), a better correlation was found between the measured and calculated values.

The RMS error between the measured and that calculated based on Walton and Bruno formula was 0.57, and the correlation coefficient (r) calculated was 0.71. The average measured LSTR was found to be 0.65 times the value calculated using Walton's equation (Fig. 11). The high values calculated by the empirical formulas could be due to the fact that these equations were developed for the high-energy coast, whereas during the present study period, the average wave height was about 0.8 m.

The measured LSTR was found to be 0.9 times the value calculated using Van Rijn formula and the correlation coefficient (r) was 0.74 (Fig. 11). The RMS error between the measured and calculated LSTR was 0.47. The difference was due to the fact that (i) even though the currents vary with depth especially for the low-wave energy coasts, the longshore currents were measured only at the surface and used in calculations and (ii) the tidal influence was not included in the calculations.

The above shows that LSTR can be calculated reasonably well using Van Rijn formula compared to CERC and Walton and Bruno formula. The scatter is smaller and the correlation coefficient is higher for the values calculated by the Van Rijn formula. Bayram et al. (2001) compared the cross-shore distribution of longshore sediment transport calculated based on six predictive formulas and that measured during the DUCK85, SUPERDUCK, and SANDYDUCK field

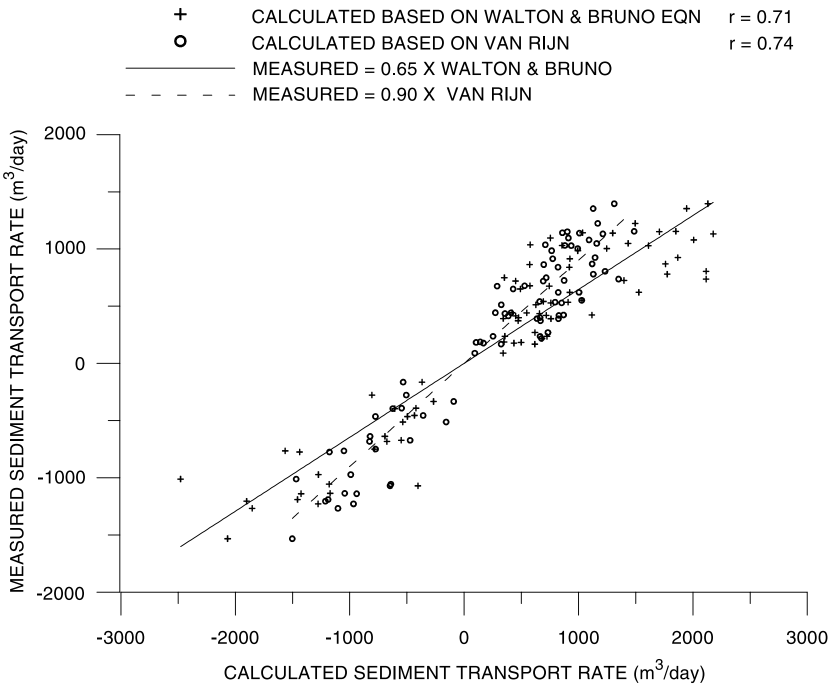

Fig. 11. Variation of measured and calculated sediment transport rate.

data collection projects. They found that the Van Rijn formula (TRANSPOR) gave the most reliable predictions over the entire range of wave conditions (swell and storm).

4. Conclusions

The breaking wave height varied from 0.5 to 1.2 m with an average value of 0.8 m from February through May and the wave period mostly varied from 3 to 8 s. The breaking waves approached the coast predominantly from the south and average wave-breaking angle was 5.6°. The average longshore current velocity was 0.3 m/s and was direct to the north during 69% of time. The sediments were of fine to medium sand. The average measured transport rate was 0.04, 0.099, 1.42, 0.94, 0.023, and 0.019 kg/m/s at trap locations A to F. The transport rate was high at trap locations C and D (15 to 27 m from the waterline) as compared to other locations.

Based on the comparison of the measured values with the three commonly used empirical equations, it was found that LSTR calculated using the Van Rijn formula was close to the measured values with a correlation coefficient of 0.74 and an RMS error of 0.47. The difference between the measured and calculated values is attributed in part to the following: (a) the error in the measurement of bed load, (b) even though the currents vary with depth especially for the low-wave energy coasts, the longshore currents were measured at the surface and used in the calculations, and (c) use of the empirical formulas developed for the high-energy coast during relatively low wave conditions as the average wave height during the study period was 0.8 m.

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