Longshore-Transport Model for South Indian and Sri Lankan Coasts

By P. Chandramohan,[1] B. U. Nayak,[2] and V. S. Raju[3]

Abstract: Longshore-sediment transport rates for the south Indian coast from Allur to Cochin and for Sri Lanka are estimated from ship-reported wave data (1968–86). Annual gross sediment transport rate is high (1.5 to 2.0 × 10^6 m^3) along the coasts of north Tamil Nadu and south Kerala and is less (0.5 to 1.0 × 10^6 m^3) along the south Tamil Nadu and Sri Lankan coasts. The annual net transport is southerly along the west coast of India and predominantly northerly along the east coast except near Durgarajupatnam in Andhra Pradesh. Coasts near Tharangampadi, Karaikal, Nagore, Tuticorin, Virapandianpatinam, and Manakkodam in India and Kuchchaveli, Betticola, Pottuvil, Chilaw, and Negombo in Sri Lanka appear to be nodal drift points, with an equal volume of transport in either direction annually.

Introduction

The Indian coastline exceeds 6,000 km and has direct bearing on the socioeconomic development of the nation's sea trade, fishing and marine industry, and human settlement. Erosion near the ports of Madras, Visakhapatnam, and Paradeep and the siltation in most of the tidal inlets is presently of great concern to Indian coastal engineers. A 370 km stretch of Kerala coast undergoes severe erosion that results in the loss of valuable land every year (Baba 1986). Along the 1,560 km of Sri Lankan coastline, the west, southwest and south coastal sectors are subjected to severe erosion (Jacobson et al. 1987). An integrated approach has not been attempted to assess in detail the littoral environment along the entire Indian coast. Instrumentally measured data on wave climate for the Indian coast are limited. Ship-reported wave information published in weather reports were compiled for the present study and used for the estimation of the longshore-sediment transport.

Study Area

The study area comprises of the south Indian coast from Allur in Andhra Pradesh to Cochin in Kerala and the entire Sri Lankan coast (Fig. 1). Three major Indian ports, Madras, Tuticorin, and Cochin, are located in this regiaon. Erosion along the coast between Trivandrum and Cochin has prompted seawall construction in many places. The shoreline of the peninsular tip of India (Kanyakumari) is exposed to the Indian Ocean, Arabian Sea, and Bay of Bengal. The oceanographic environment in this region is predominantly controlled by the monsoon seasons with comparatively high waves occurring during the southwest monsoon (June to September), followed by the north-

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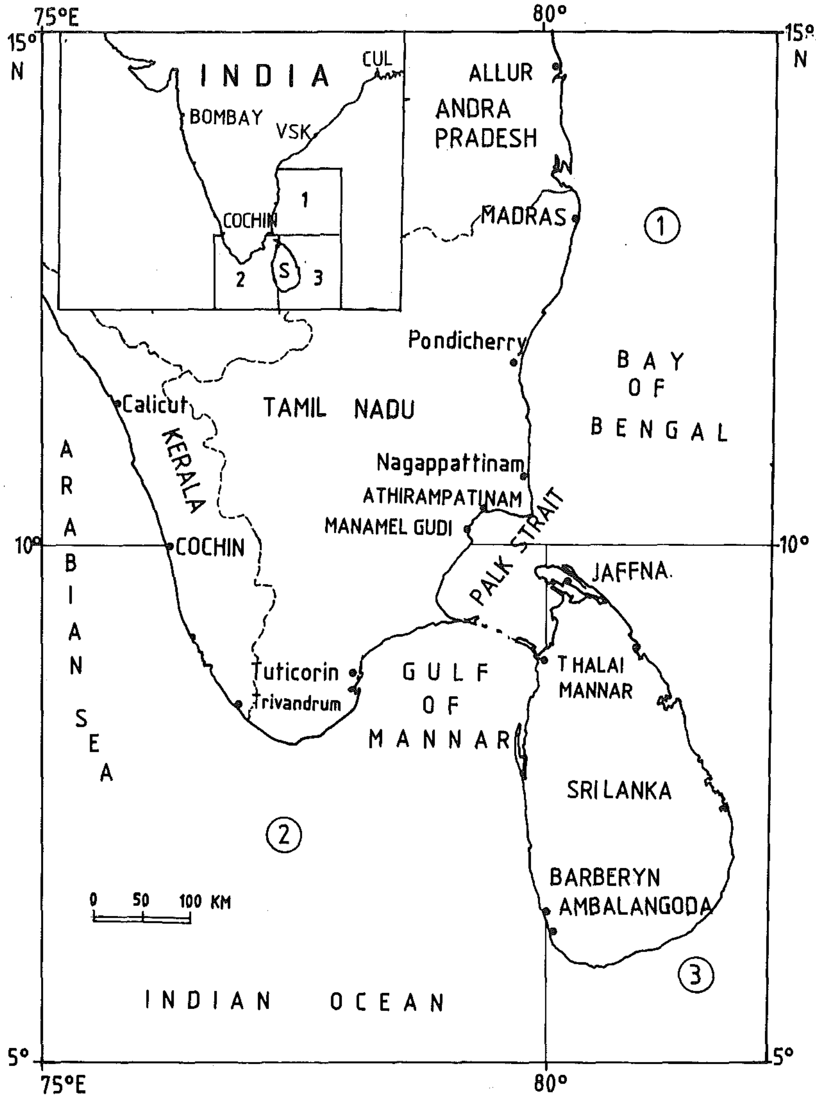

FIG. 1. Location Map

east monsoon (October to January), and calm sea in the nonmonsoon season, (February to May).

Wave Data

Weather data transmitted by ships plying the Indian waters is published in the form of Indian Daily Weather Reports by the India Meteorological Department. Wave heights in half meters, periods in seconds, and directions

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in 10° resolutions are reported (*Ships* 1982). Since the directional information is not given for the sea waves, only the swell data reported for the period 1968–1986 have been considered for the present study. The area was divided into three grids, 5° × 5° each (about 600 km × 600 km), and the swell data pertaining to each grid was compiled (Fig. 1). Total number of wave data points thus compiled are 2,695, 6,783, and 6,394 for grids 1, 2, and 3, respectively. A wave data point contains information on wave height, period, and direction. *Shore protection manual* (1984) and Jardine (1979) have suggested consideration of the visually observed wave height as equivalent to significant wave height for coastal engineering applications. Hence, the ship-reported wave heights are considered equal to deep-water significant wave heights (H_s) and the visually measured wave periods as zero-crossing wave periods (T_z).

Longshore-Sediment Transport Equation

The longshore-sediment transport rate is generally estimated from an empirical equation relating the longshore energy flux in the breaker zone to the longshore transport rate. Several discussions have already appeared on the selection of suitable equations for the estimation of the longshore sediment transport (Graff and Overeem 1979; Willis 1980). Chandramohan et al. (1988) have discussed the suitability of the *Shore protection manual* equation for estimating the longshore transport rate for the Indian coast. Based on the *Shore protection manual* (1975, 1984), the deep-water version of the longshore transport equation, which is related to the longshore component of the wave energy flux factor, is given by

$$Q = 1{,}290 \frac{\rho g^2}{64\pi} T(H_0 \cdot Kr)^2 \sin 2\alpha_b \quad (1)$$

where Q = volume rate of longshore transport in m^3/year; g = acceleration due to gravity in m/s^2; T = wave period in s; α_b is the breaker angle; H_0 = deep-water wave height; and Kr = refraction coefficient.

By incorporating the effect of wave shoaling and bottom friction, Eq. 1 can be rewritten

$$Q = 1{,}290 \frac{\rho g^2}{64\pi} T(H_0 \cdot Kr \cdot Ks \cdot Kf)^2 \sin 2\alpha_b \quad (2)$$

where Ks and Kf = shoaling and bottom friction coefficients, respectively.

As the data compiled for the present study correspond to the deep-water condition, Eq. 2 is used for estimating the longshore-sediment transport rate.

Estimation of *Ks*, *Kr*, and *Kf*

The bottom contours are assumed to be straight and parallel and the average slopes of the nearshore at grids 1, 2, and 3 are estimated as 1:220, 1:350, and 1:150 from the *Hydrographic charts* (1976). The procedure explained in Skovgaard et al. (1975) is followed to compute the shoaling, refraction, and bottom friction coefficients.

Small-amplitude-wave theory gives the shoaling coefficient as

$$Ks = \left[\tanh kh\left(1 + \frac{2hk}{\sinh 2kh}\right)\right]^{-0.5} \quad (3)$$

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where h = water depth; k = wave number = $2\pi/L$; and L = wavelength.

The differential equation for the refraction of wave orthogonals in Cartesian coordinate system of x- and y-axes is given by (Munk and Arthur 1952; Orr and Herbich 1969)

$$\frac{d^2\beta}{dt} + p(t)\frac{d\beta}{dt} + q(t) = 0 \qquad (4)$$

where β, the orthogonal separation factor, is related to the refraction coefficient as

$$Kr = \frac{1}{\sqrt{\beta}} \qquad (5)$$

and

$$p(t) = -2\left(\cos\theta\frac{\partial c}{\partial x} - \sin\theta\frac{\partial c}{\partial y}\right)$$

$$q(t) = c\left[\left(\sin^2\theta\frac{\partial^2 c}{\partial x^2}\right) - \left(\sin 2\theta\frac{\partial^2 c}{\partial x\partial y}\right) + \left(\cos^2\theta\frac{\partial^2 c}{\partial y^2}\right)\right]$$

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where c = wave celerity; and θ = direction of wave orthogonal with x-axis. The effect of bottom friction is incorporated using the relationship (Skovgaard 1975)

$$\frac{dKf}{dt} = -\left(\frac{8}{3L}\frac{dc}{dh}\right)a_m feKf \qquad (6a)$$

where a_m, the horizontal particle amplitude at bed, is given as

$$a_m = \frac{H}{2}\frac{1}{\sinh Kh} \qquad (6b)$$

In Jonsson and Carlsen (1976), the friction parameter, fe, is given as

$$fe = 0.3 \qquad \text{for } \frac{a_m}{k_N} < 1.57 \qquad (6c)$$

$$\frac{1}{4\sqrt{fe}} + \log\left(\frac{1}{4\sqrt{fe}}\right) = -0.08 + \log\frac{a_m}{k_N} \qquad \text{for } \frac{a_m}{k_N} > 1.57 \qquad (6d)$$

where k_N = Nikuradse roughness parameter. There is a lot of inconsistency in arriving k_N, and it has been considered twice the 90% particle size at seabed as suggested by Lambrakos (1982).

In a Cartesian coordinate system, with the x-axis parallel to the coast and y-axis perpendicular and θ, the angle of the incoming wave orthogonal to the x-axis, Eq. 4 is solved using the Runge-Gill method with initial condition, $\beta = 1$ in deep water. More details of the numerical scheme are presented in Skovgaard et al. (1975). Thus, the shoaling (Ks) refraction (Kr) and bottom friction (Kf) coefficients and the breaker angle (α_b) are determined and used in Eq. 2 for obtaining the breaking-wave height.

To retain the individual wave data points in the computation, the sum-

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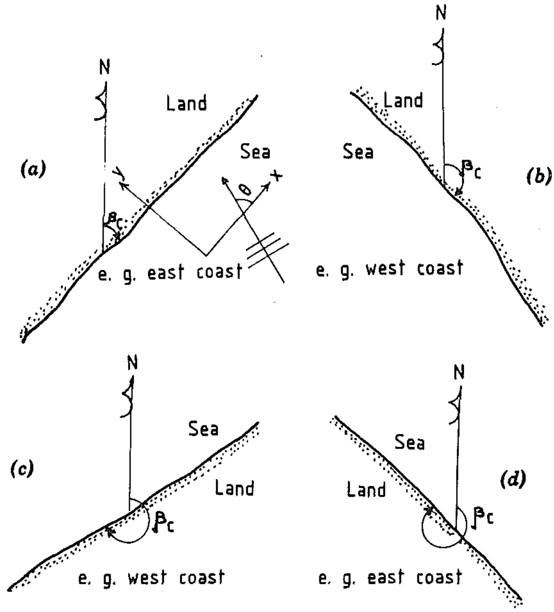

FIG. 2. Definition Sketch for Orientation of Coastline

mation procedure for estimating the monthly transport rate in the model is given by

$$Q_m = \frac{1}{12} \sum_{H=0}^{H=\infty} \sum_{T=0}^{T=\infty} \sum_{\theta=\beta_c}^{\theta=\beta_c+\pi} Q \times f_m(H,T,\theta) \qquad (7)$$

where Q = annual volume rate of longshore transport from Eq. 2; Q_m = monthly volume rate of longshore transport; $f_m(H,T,\theta)$ = frequency of occurrence of a particular set of (H,T,θ) in a month; and β_c = angle of the coastline with reference to north (Fig. 2).

Rose Diagrams

The method for measuring the orientation of the coastline with reference to the north for the place of interest is shown in Fig. 2. Using Eq. 7, the direction and monthly longshore-sediment transport rate for every 10° variation in the orientation of the coastline in each grid are estimated and presented as rose diagrams for the grids 1, 2, and 3 in Figs. 3(*a* and *b*), 4(*a* and *b*) and 5(*a* and *b*), respectively. The following procedure can then be adopted to obtain the sediment transport rate at a given segment of the coast from the rose diagrams: (1) Measure the angle of inclination of the coastline with respect to the north in a clockwise direction (β_c), as shown in Fig. 2, using either the survey instrument in the field or the protractor from the detailed maps; (2) identify the grid in which the coastal segment of interest falls (Fig. 1); (3) referring to the rose diagrams of the corresponding grid, the longshore-sediment transport rate can be read for the known orientation

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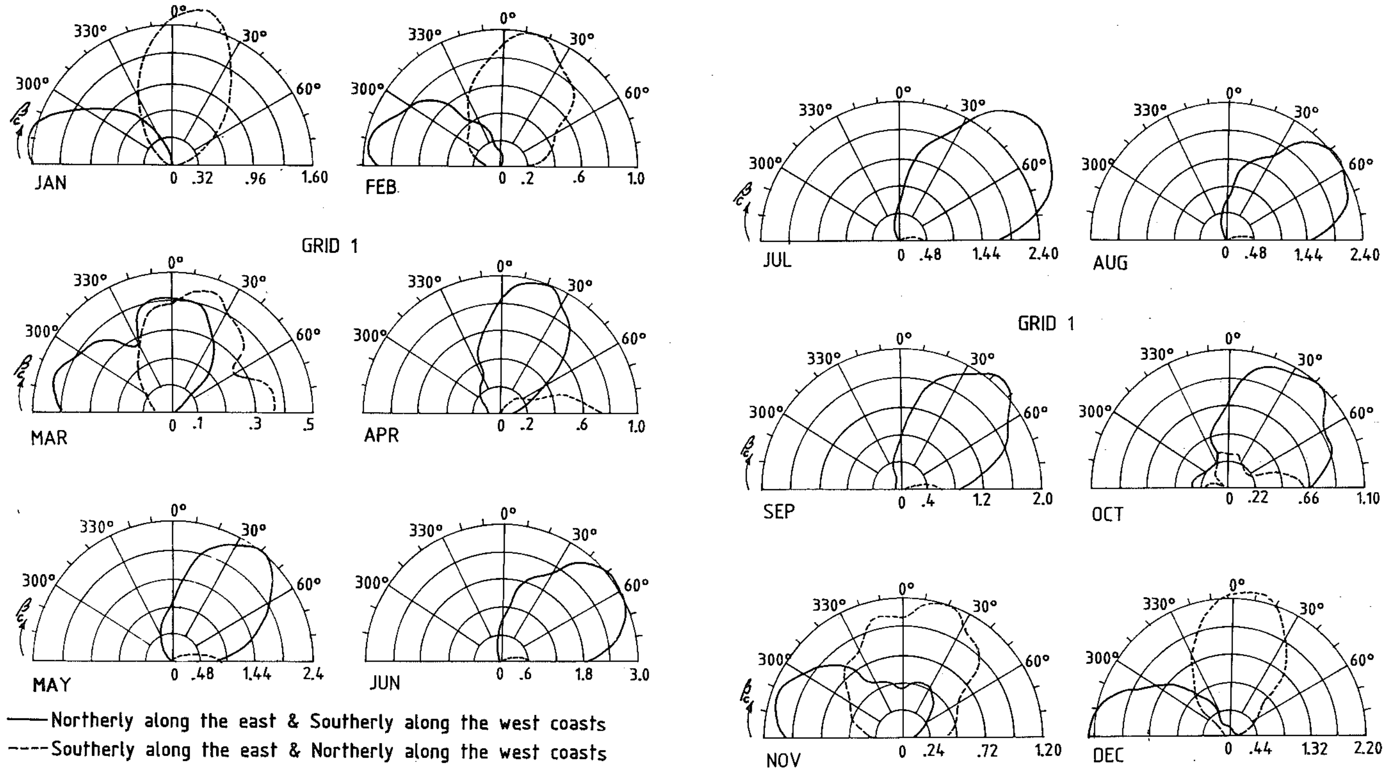

FIG. 3. Variation of Longshore-Sediment Transport Rate (10^5 m^3/Month) with Coastal Orientation between Allur and Athirampatnam

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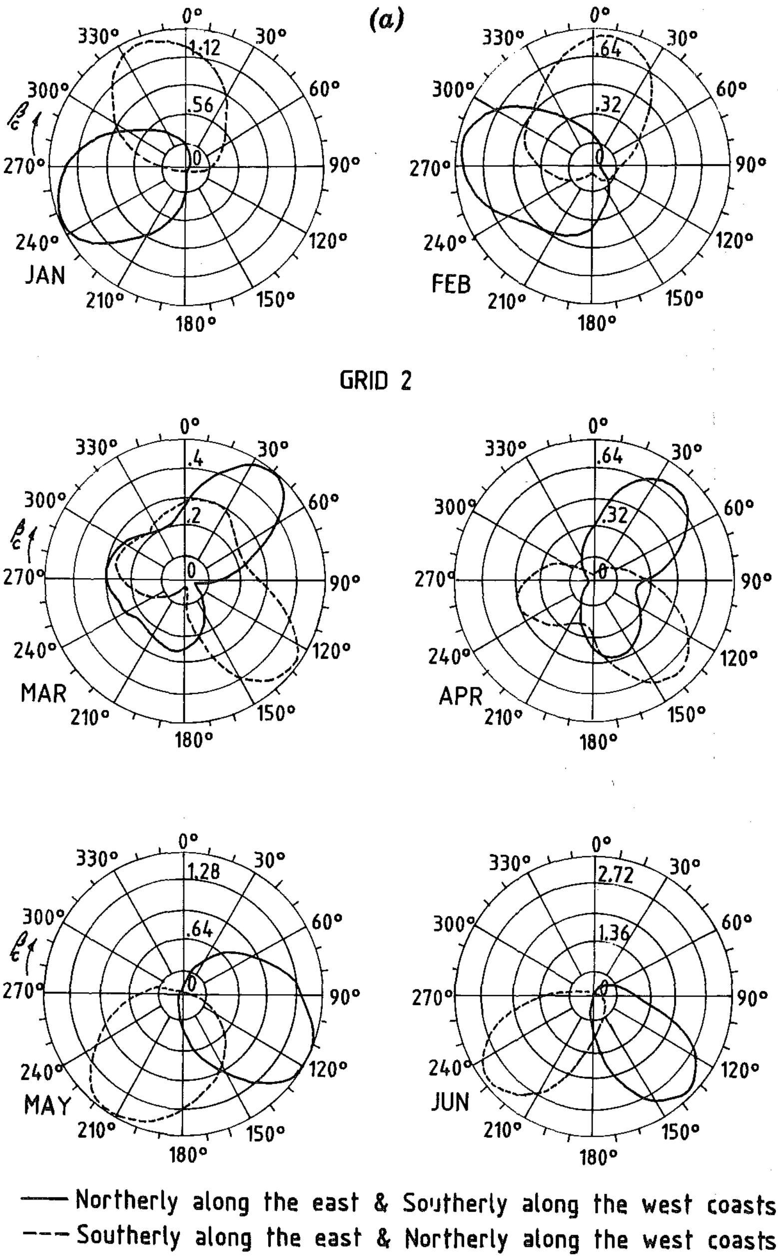

FIG. 4. (*a*) Variation of Longshore-Sediment Transport Rate (10^5 m^3/Month) with Coastal Orientation between Manamelgudi and Cochin (India) and Barberyn to Thalaimannar (Sri Lanka), January to June

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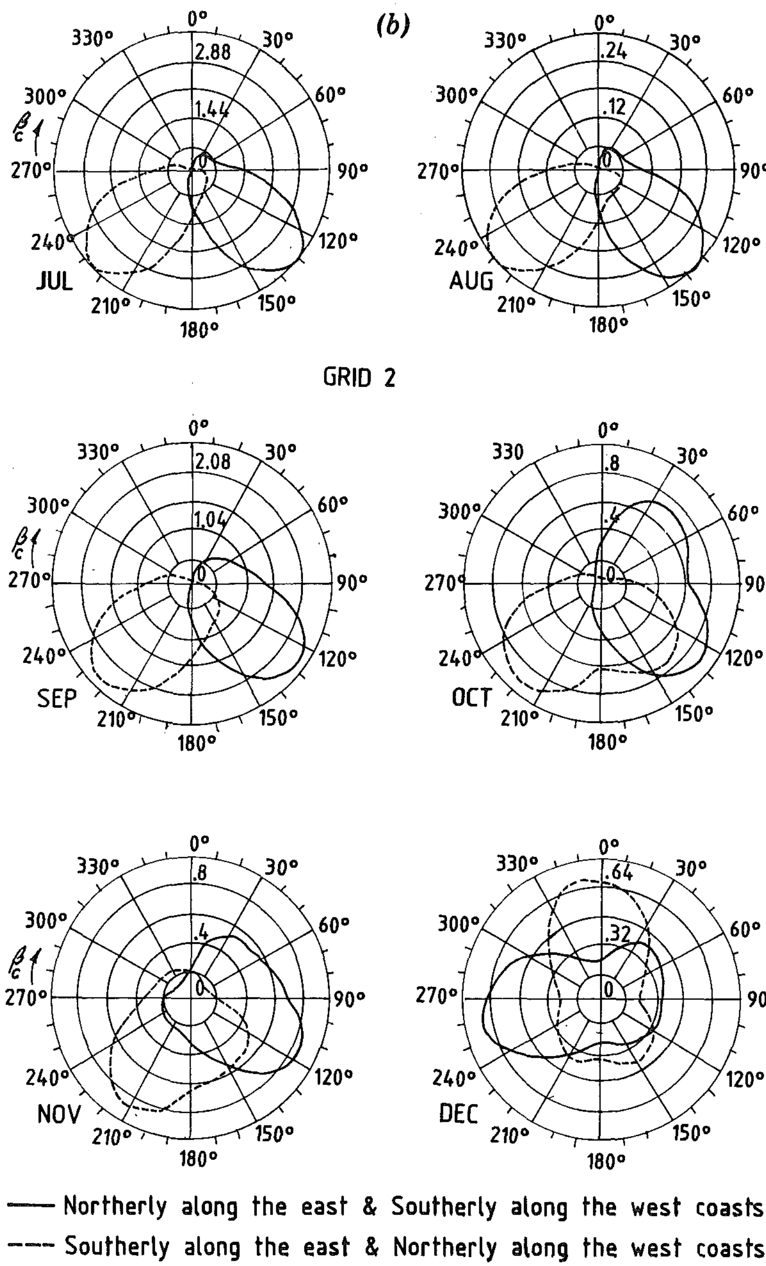

FIG. 4. (*b*) Variation of Longshore-Sediment Transport Rate (10^5 m^3/Month) with Coastal Orientation between Manamelgudi and Cochin (India) and Barberyn to Thalaimannar (Sri Lanka), July to December

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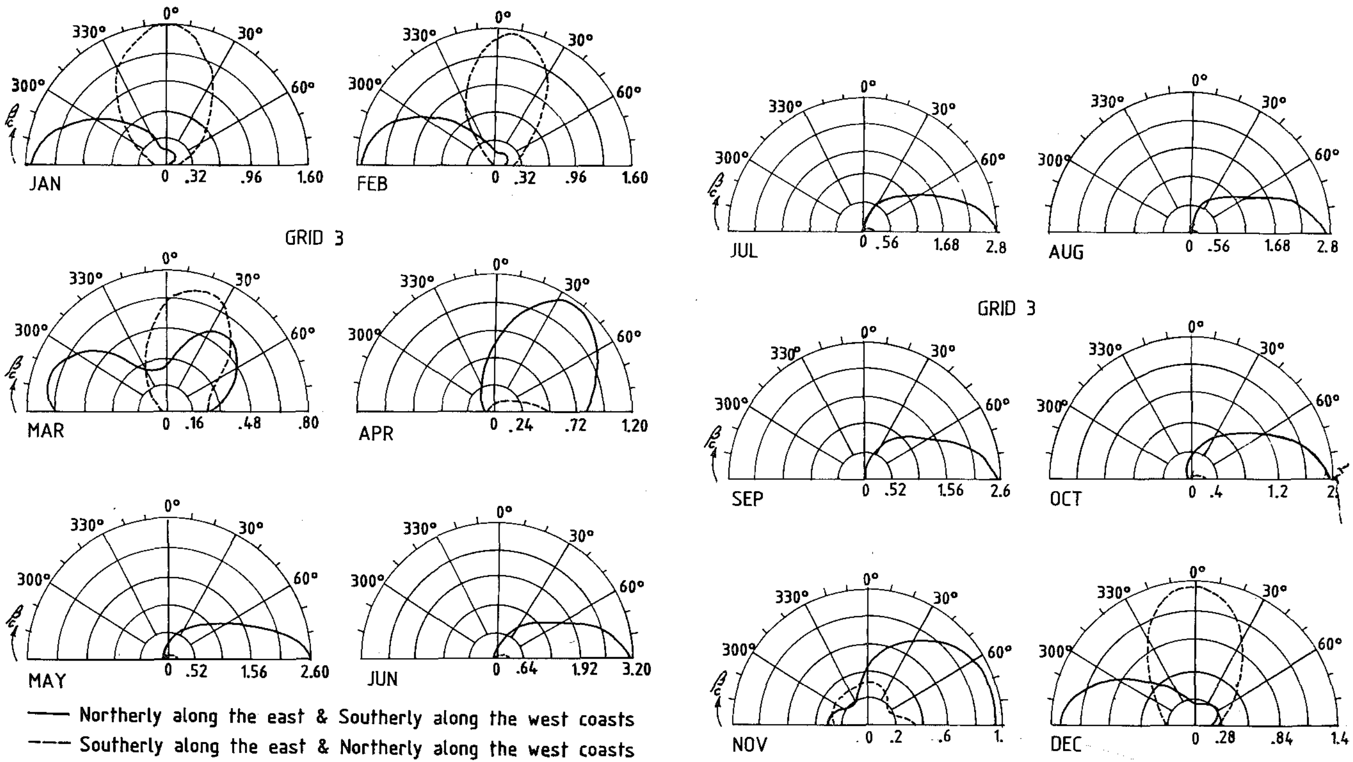

FIG. 5. Variation of Longshore-Sediment Transport Rate (10^5 m^3/Month) with Coastal Orientation between Jaffna and Ambalngoda (Sri Lanka)

of the coastal segment; and (4) linear interpolation is made for the coast oriented with an intermediate angle.

For example, the orientation of the coastal segment at Madras beach is 16° to north. From Fig. 1, it is seen that the Madras coast lies on the east coast in grid 1. Referring to the rose diagrams corresponding to grid 1 in Fig. 3(*a*) for the month of January, the sediment-transport rate for the orientation of 10° and 20° are 1.71×10^5 m^3 and 1.63×10^5 m^3, respectively. Hence, for Madras, having an orientation of 16°, and using linear interpolation, the sediment-transport rate in January is estimated to be 1.68×10^5 m^3 per month in a southerly direction, and there is no transport northerly. Walton (1973) has presented similar rose diagrams for the Florida coast.

Results and Analysis

Grid 1 covers the coast from Allur to Athirampatinam (620 km), grid 2 from Manamelgudi to Cochin in India (600 km) and Barberyn to Thalaimannar in Sri Lanka (350 km), and grid 3 from Jaffna to Ambalngoda in Sri Lanka (660 km) (Fig. 1). Annual gross and net transport rates for the grids 1–3 are presented in Fig. 6. The transport rates at selected locations of the study area are presented in Table 1.

Allur to Athirampatinam (Grid 1)

Referring to Fig. 3(*a* and *b*), the transport is northerly from April to October and southerly from November to March. The transport rate is high throughout the year, with a maximum of about 2×10^5 m^3 per month in June and a minimum of about 0.7×10^5 m^3 per month in March. The annual gross and net transport rates in the north of Pondicherry are about 1.79×10^6 m^3 and 0.44×10^6 m^3, respectively. South of Pondicherry till Point Calimere, the gross and net transport rates are 1.25×10^6 m^3 and 0.06×10^6 m^3, respectively. The annual net transport is northerly between Pondicherry and Allur and southerly from Point Calimere to Chidambaram. However, the annual net volume rate of transport in the latter segment is low, around 0.06×10^6 m^3. The northerly and southerly components of annual sediment transport rate along the Madras coast are estimated to be 1.03×10^6 m^3 and 0.68×10^6 m^3, respectively. The coast between Point Calimere and Athirampatnam in Palk Bay is sheltered from south, southeast, and easterly waves by Sri Lanka.

Manamelkudi to Cochin (Grid 2)

Fig. 4(*a* and *b*) shows that the coast from Manamelkudi to Tuticorin in the Palk Bay and Gulf of Mannar is sheltered by Sri Lanka, and the rest of the coast is exposed to open ocean. The direction of transport between Manamelgudi to Kanyakumari is northerly from March to December and southerly in January and February. The longshore-sediment transport rate is almost equal in all the months of the year, with an average of about 0.60×10^5 m^3 per month. The coastal segments near Tharangampadi, Karaikal, Nagore, Tuticorin, and Virapandianpattinam appear to be nodal drift points with the northerly drift rate balancing the southerly drift rate over a year. The transport rate in each direction at the first three places is about 0.65×10^6 m^3 per year and at the next two places, is it about 0.33×10^6 m^3 per year.

The sediment transport between Kanyakumari and Trivandrum is southerly

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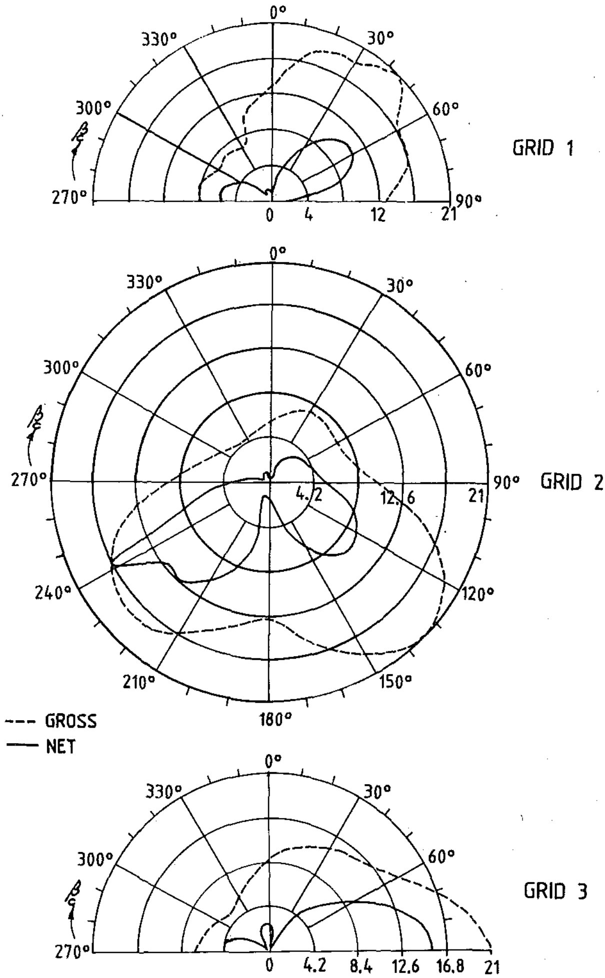

FIG. 6. Variation of Annual Gross and net Longshore-Transport Rates (10^5 m^3/yr) with Coastal Orientation

from May to December and northerly from January to April. Between Trivandrum and Cochin, it is southerly from January to March and June to September and northerly in April, May, and October to December. The monthly longshore-sediment transport rate is about 3.0×10^5 m^3 in June, July, and August and about 0.60×10^5 m^3 during the rest of the year. The coast near Trivandrum experiences a northerly transport of 0.62×10^6 m^3 and a southerly transport of 1.63×10^6 m^3 per year. The coast near Cochin experiences a northerly transport of 0.69×10^6 m^3 and a southerly transport of 0.98×10^6 m^3 per year. Manakkodam, the place south of Cochin, appears to be a nodal drift point with a longshore-sediment transport rate of 0.75×10^6 m^3 per year from either direction.

TABLE 1. Longshore Transport Rate

Place (1)	Southerly (10^6 m^3) (2)	Northerly (10^6 m^3) (3)
	(a) India (east)	
Krishnapatnam	0.698	−0.895
Durgarajupatnam	0.523	−0.399
Pulicat	0.542	−0.419
Madras	0.683	−1.027
Mahabalipuram	0.677	−1.071
Cheyur	0.551	−1.228
Pondicherry	0.692	−0.939
Cuddalore	0.698	−0.895
PortNovo	0.431	−0.315
Tharangampadi	0.665	−0.685
Karaikal	0.660	−0.656
Nagore	0.651	−0.595
Nagapatnam	0.660	−0.656
Vedaranyam	0.640	−0.567
Manamelkudi	0.490	−1.432
Kilakarai	0.200	−0.673
Sayalkudi	0.217	−0.724
Tuticorin	0.330	−0.330
Virapandianpatinam	0.330	−0.330
Thiruchendur	0.328	−0.193
Kulasekarapattinam	0.220	−0.603
Eastcape	0.188	−0.623
Kanyakumari (east)	0.312	−0.398
Kanyakumari (tip)	0.336	−1.086
	(b) India (west)	
Kolachal	−1.585	0.525
Vizhingam	−1.679	0.586
Trivandrum	−1.630	0.615
Quilon	−1.573	0.623
Alleppey	−1.062	0.677
Manakkodam	−0.812	0.741
Cochin	−0.977	0.693
	(c) Sri Lanka (east)	
Point Pedro	0.221	−0.308
Mullai Thevu	0.399	−0.222
Kuchchaveli	0.251	−0.280
Triconamale	0.327	−0.238
Betticola	0.266	−0.267
Kalmunai	0.453	−0.220
Thirukkovil	0.562	−0.305
Pottuvil	0.523	−0.523
Palatupana	0.269	−1.016
Hambantota	0.258	−1.753
Tangalla	0.265	−1.035
Dondra	0.281	−1.824
	(d) Sri Lanka (west)	
Barberyn	−1.062	0.677
Columbo	−1.062	0.677
Negombo	−0.758	0.761
Chilaw	−0.758	0.761
Puttalam	−1.062	0.677
Kalpitiya	−0.649	0.799

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Barberyn to Thalaimannar, Sri Lanka (Grid 2)

The coast north of Thalaimannar is sheltered by the Indian peninsula. The longshore-sediment transport is southerly from January to March and northerly from September to December, and the transport rate is equal in both directions in April and June through August. October through March is a calm period with very low transport.

Jaffna to Ambalangoda, Sri Lanka (Grid 3)

Along the northeastern part of Sri Lanka, between Point Pedro and Pottuvil, the longshore transport rate is higher during northeast monsoon than in southwest monsoon. The monthly volume rate of transport is less compared to that along the Indian coast with 1.0×10^5 m^3 per month from October to January and 0.09×10^5 m^3 per month from June to September [Fig. 5(*a* and *b*)]. The direction of annual net transport varies considerably. It is northerly between Point Pedro and Triconomale and southerly between

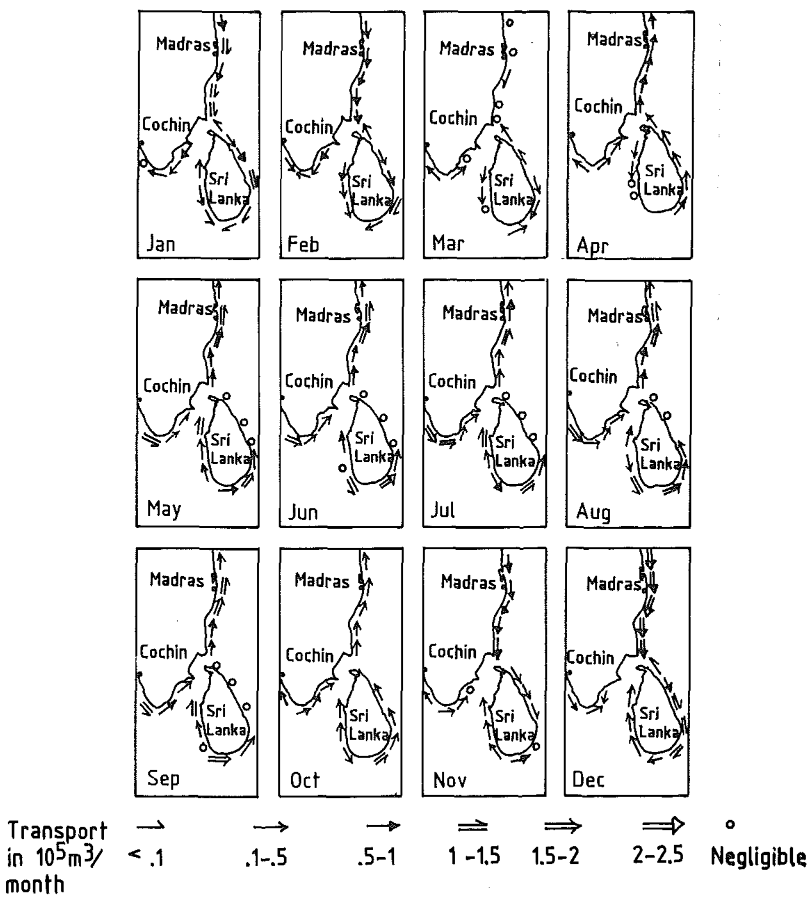

FIG. 7. Monthly Sediment Transport along Southern Indian and Sri Lankan Coasts

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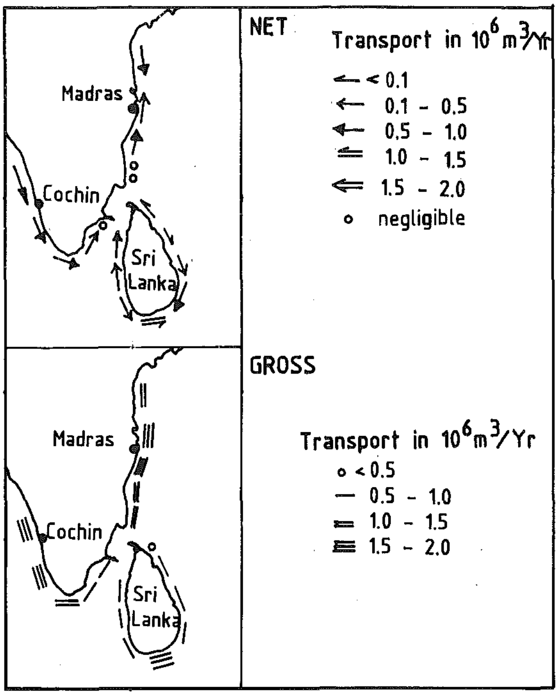

FIG. 8. Annual Sediment Transport along Southern Indian and Sri Lankan Coasts

Triconomale and Pottuvil. Most of the coastal stretches on the east and north have extremely low annual gross and net transport rates compared to the other part of Sri Lanka and India. The transport between Pottuvil to Ambalangoda is northerly from March to November and southerly during the rest of the year. The monthly volume rate of transport is high, about 2.0×10^5 m^3 per month from June to September and is low, about 0.40×10^5 m^3 per month December through March. The annual net transport is negligible near Kuchchaveli, Betticola, Pottuvil, Chilaw, and Negombo and they behave close to nodal drift points.

General Distribution

Monthly longshore-sediment transport rate and direction at different locations along the Indian and Sri Lankan coasts are shown in Fig. 7. Along the east coast of India, the longshore transport is southerly from November to February, northerly from April to September and variable in March and October. The annual gross and net transport rates are presented in Fig. 8. The annual gross sediment-transport rate is high (1.5 to 2.0×10^6 m^3) along the coasts of north Tamil Nadu and south Kerala, whereas it is comparatively less (0.5 to 1.0×10^6 m^3) along the south Tamil Nadu coast. The annual net transport is southerly on the west coast of India and northerly on the east coast except near Durgarajupatnam in Andrha Pradesh.

In Sri Lanka, along the east coast, the transport is southerly from November to February and northerly in April and October. The longshore transport is negligible from May to September and the direction is transitional in March. Longshore-transport direction along the Point Pedro region is northerly throughout the year. Along the west coast of Sri Lanka, the longshore transport is southerly from January to March and northerly in May, November, and December. The direction is variable from June to October. The net transport rate is negligible in April. The direction of annual net transport indicates high variability along the Sri Lankan coast. Annual gross transport rate is less all along the Sri Lankan coast except the southern part of the coast.

VERIFICATION OF MODEL

Field experiments were conducted in April 1986 12 km south of Madras harbor. Sediment-loaded water samples were collected at the surface, mid-depth, and bottom along six vertical profiles across the surf zone using 10 L Van Dorn samplers. The average longshore current across the surf zone was determined using fluorescent dye. A total of 22 cycles of experiments were carried out from April 1 to 15, 1986; and the sediment load across the surf zone was estimated. The sediment-transport rate (Q) is estimated from the total sediment load across the surf zone (S) and the corresponding average longshore-current velocity (V) using $Q = S \times V$. The average longshore-transport rate in April, based on the field experiment, was 1.13×10^5 m^3/month, whereas the model shows 1.03×10^5 m^3/month. This shows that the model result closely agrees with the field experiment.

Soon after the construction of the Madras harbor breakwaters in 1875, a large accretion of sediment resulted on the southern side, and the width of the shoreline had increased to 1,200 m by 1985. On the other hand, an approximately 8 km long shoreline on the northern side was exposed to eroding forces, thereby resulting in the loss of an approximately 75 m wide strip of land. The phenomenon of accretion on the southern side and erosion on the northern side of the breakwaters clearly indicates that the net sediment transport is in northerly direction, which is also evidenced by the present model.

CONCLUSION

There are many major commercial harbors and small fishing harbors along the Indian and Sri Lankan coasts that are confronted with serious erosion and siltation problems. The present information on sediment transport rates and wave climate is very limited. In this context, the present study provides firsthand information on the sediment transport environment for the entire coastline. Particularly, the rose diagrams provide the monthly and annual sediment transport rates as well as direction of transport for a given coastal segment along the south Indian and Sri Lankan coasts. The consolidated results presented in Table 1 facilitate coastal engineers' understanding of the sediment transport rates for almost all important places along the coast.

The present study is based on the ship-reported visually observed wave data; it is assumed that the coast comprises long sandy beaches with adequate sand supply. In spite of these limitations, the results are of practical value.

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Even though no detailed studies have been carried out on longshore-sediment transport along the Indian coast, shoreline changes in the vicinity of existing ports indicate that the annual net transport is in the northerly direction along the east coast of India and the southerly direction along the west coast. The presence of the shoal across the Palk Straight between India and Sri Lanka can be explained by the present study, which shows accumulation of littoral sediment in the region during the annual sediment process. The annual gross sediment transport rate is high (1.5 to 2.0 $\times$ 10^6 m^3) along the coasts of north Tamil Nadu and south Kerala, whereas it is comparatively low (0.5 to 1.0 $\times$ 10^6 m^3) along the south Tamil Nadu and Sri Lankan coasts. The annual net transport is southerly along the west coast of India and northerly along the east coast except near Durgarajupatnam, in Andhra Pradesh. The annual gross and net transport rates along the Sri Lankan coast are very low compared to the Indian coast. The coasts near Tharangampadi, Karaikal, Nagore, Tuticorin, Virapandianpatinam, and Manakkodam, in India, and the coasts near Kuchchaveli, Betticola, Pottuvil, Chilaw, and Negombo, in Sri Lanka appear to be nodal drift points.

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Appendix I. References

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Appendix II. Notation

The following symbols are used in this paper:

a_m = maximum horizontal particle amplitude at seabed;
c = wave celerity;
f_m = frequency of occurrence;
fe = friction parameter;
g = acceleration due to gravity;
H = wave height;
H_b = breaking wave height;
H_0 = deepwater wave height;
H_s = significant wave height;
h = water depth;
k = wave number;
k_N = Nikuradse roughness parameter;
Kf = coefficient of friction loss;
Kr = refraction coefficient;
Ks = shoaling coefficient;
L = wavelength;
Q = annual longshore sediment transport rate;
Q_m = monthly longshore sediment transport rate;
t = time;
T = wave period;
T_z = zero crossing wave period;
x and y = axes in Cartesian coordinate;
α = wave direction;
α_b = breaking wave angle;
β = orthogonal separation factor;
β_c = orientation of the coast w.r.t. north;
θ = wave direction w.r.t. north; and
ρ = density of sea water.

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