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Longshore Sediment Transport Model for the Indian West Coast

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ABSTRACT

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Longshore sediment transport rates for the Indian west coast from Cochin to Porbandar are estimated from ship observed wave data (1968 to 1986). The sediment transport rate is relatively high during the southwest monsoon period from June to September. Annual gross sediment transport rate is high (1.5–2 × 10^6 m^3) along north Kerala, north Karnataka and south Gujarat coasts. Maharashtra coast shows relatively low annual net transport (0.1 × 10^6 m^3). The annual net transport is south along north Kerala and Karnataka coasts. Coasts near Malvan, Dabhol, Murud and Tarapur appear to be nodal drift points with equal volume of transport in either direction annually.

ADDITIONAL INDEX WORDS: *Sediment transport, Indian coast, longshore transport, nodal drift, littoral drift, rose diagrams.*

INTRODUCTION

India has a vast coastal zone with about 7,000 Km long shoreline bounded by the Bay of Bengal on the east, the Indian Ocean on the south and the Arabian Sea on the west. The morphology of the Indian coast is quite heterogeneous. A low and fairly straight east coast is dominated by long sandy beaches. Whereas the west coast is highly indented with headlands and inlets studded with a number of sandy beaches (Figure 1). The coast along the West Bengal is characterised by shoals and spits, whereas the Orissa, Andhra Pradesh and Tamilnadu coasts are marked by long sandy beaches backed by large sand dunes. Long beaches are found between Cochin and Calicut on the west coast. Low cliffs, pocket beaches and bays are predominant from Calicut to Mangalore. Karnataka and Maharashtra coastal stretches are characterised by creeks, headlands, barriers and pocket beaches. Rocky shores with intermittent sandy beaches are the dominant features along the south Gujarat coast. Gulf of Kutch is marked by deep inlets, offshore islands and marshes. Rann of Kutch gets flooded during the monsoon and becomes dry and barren the rest of the year. Beach erosion is active along the entire stretch of the Kerala coast and at a few places along the Karnataka, Maharashtra and Gujarat coasts. No integrated studies have been undertaken to assess the littoral environment along the west coast. Instrumentally measured wave data for this region are very limited. Ship-reported wave information published in Daily Weather Reports were compiled for the present study for estimating the longshore sediment transport rates. The study area comprises the Indian west coast from Cochin in Kerala to Porbandar in Gujarat (Figure 1).

WAVE DATA

The India Meteorological Department publishes weather data transmitted by ships plying the Indian waters in the form of Indian Daily Weather Reports. Wave heights in half metres, periods in seconds and directions in ten degree resolutions are reported (SHIPS WEATHER CODE, 1982). Since the directional information is not given for the sea waves, only the swell data reported for the periods 1968 to 1986 were considered for the present study. The study region is divided into 3 grids, each of 5° × 5° size and the swell data pertaining to each grid were compiled (Figure 1). The total number of wave data points compiled were 5,402, 2,602 and 1,158 for the grids 1, 2 and 3, respec-

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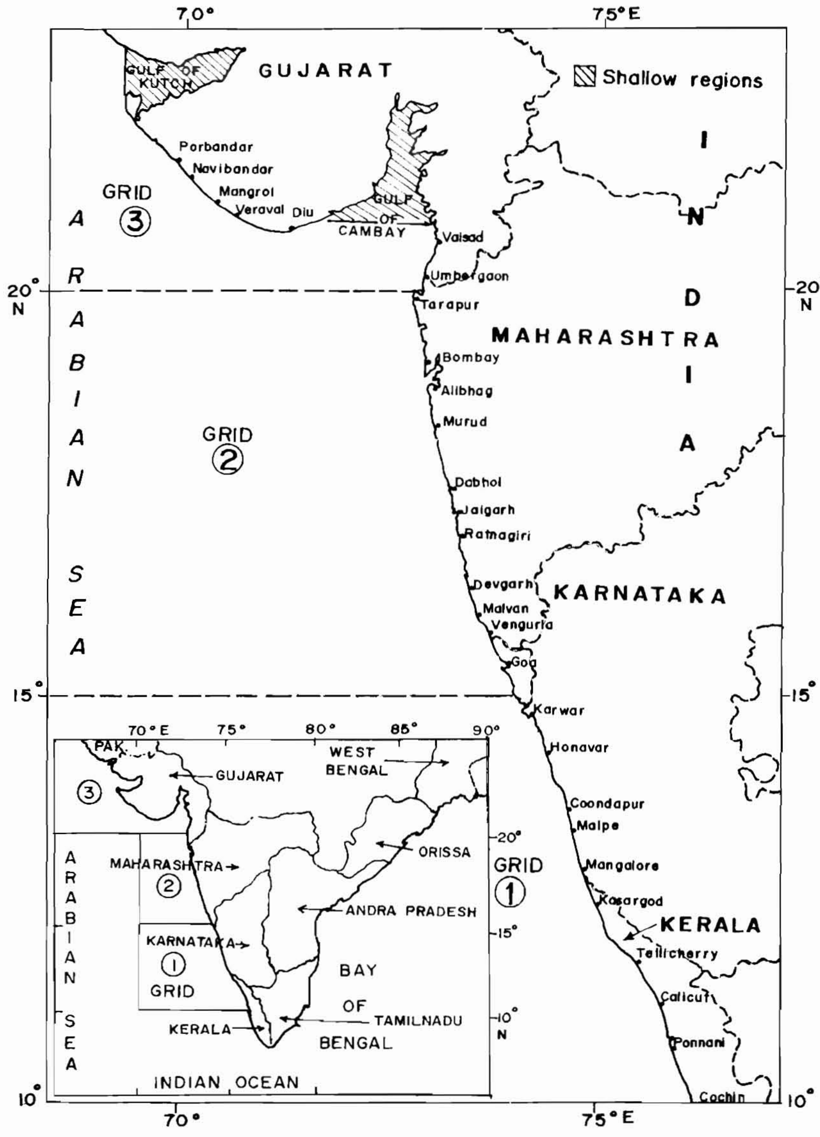

Figure 1. Location map.

tively. A wave data point contains information on wave height, period and direction.

Both the Shore Protection Manual (1984) and Jardine (1979) suggested consideration of visually observed wave height as 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 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,

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

where, Q = volume rate of longshore sediment transport in m^3/yr, ρ = sea water density in Kg/m^3, g = acceleration due to gravity in m/sec^2, T = wave period in sec, α_b is the breaker angle and H_0 is the deep water wave height in m, and K_r is the refraction coefficient.

By incorporating the effect of wave shoaling and bottom friction, Eqn. (1) can be rewritten as,

$$Q = 1{,}290\frac{\rho g^2}{64\pi}T(H_0 \cdot K_r \cdot K_s \cdot K_f)^2 \sin 2\alpha_b \qquad (2)$$

where, K_s and K_f are the shoaling and bottom friction coefficients.

As the data compiled for the present study correspond to deep water conditions, Eqn. (2) is used to estimate the longshore sediment transport rate.

Estimation of K_s, K_r and K_f

The bottom contours are assumed to be straight and parallel and the average slope of the nearshore study region is estimated as 1:600 (Hydrographic Charts, 1976). The procedure explained in Skovgaard and others (1975), is followed to compute the shoaling, refraction and bottom friction coefficients.

Small amplitude wave theory gives the shoaling coefficient as,

$$K_s = \left[\tanh kh\left(1 + \frac{2kh}{\sinh 2kh}\right)\right]^{0.5} \qquad (3)$$

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

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),

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

where, β = the orthogonal separation factor and is related to the refraction coeficient as,

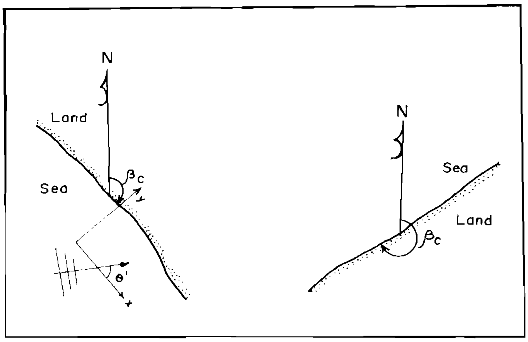

Figure 2. Definition sketch for the orientation of the coastline.

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

and,

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

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

where, c = wave celerity, θ = direction of wave orthogonal with x axis. The effect of bottom friction is incorporated using the relationship (Skovgaard *et al.*, 1975),

$$\frac{dK_f}{dt} = -\left(\frac{8}{3L}\frac{dc}{dh}\right)a_m f_e K_f \qquad (6)$$

where, a_m = horizontal particle amplitude at bed, given as,

$$a_m = \frac{H}{2}\frac{1}{\sinh Kh}$$

By Jonsson and Carlsen (1976), the friction parameter, f_e, is given as,

$$f_e = 0.3 \qquad \text{for } a_m/k_N < 1.57$$

$$\frac{1}{4\sqrt{f_e}} + \log\left(\frac{1}{4\sqrt{f_e}}\right) = -0.08 + \log(a_m/k_N)$$

$$\text{for } a_m/k_N > 1.57$$

where, k_N = Nikuradse roughness parameter. There is a lot of inconsistency in arriving k_N, and

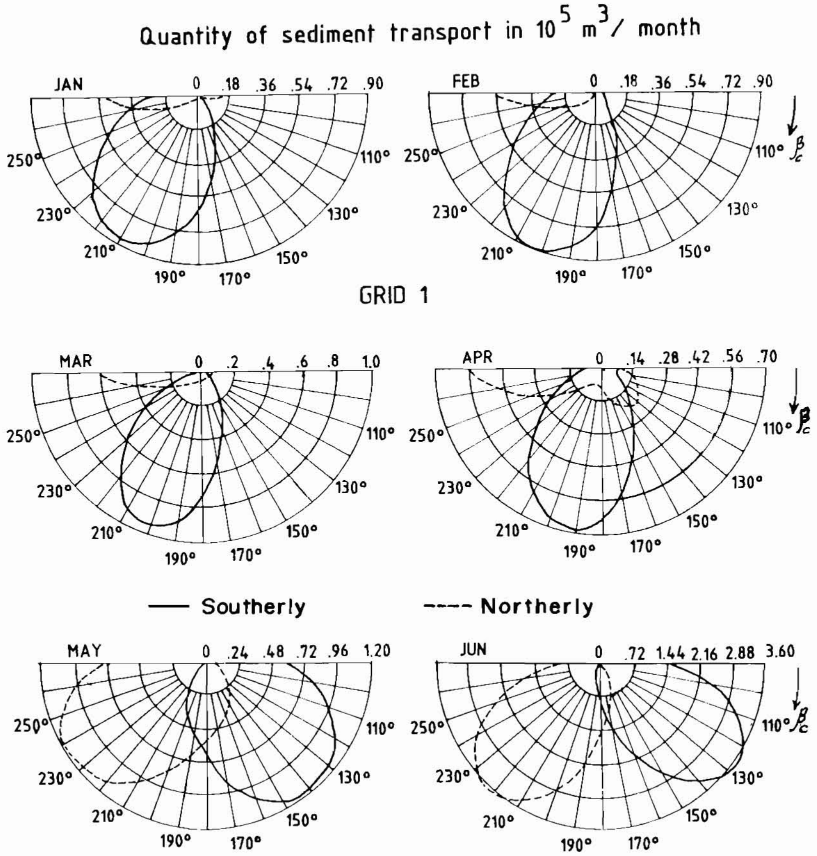

Figure 3a. Variation of monthly longshore transport rate with coastal orientation between Cochin and Karwar from January to June.

it has been considered as twice the 90% particle size at sea bed as suggested by LAMBRAKOS (1982).

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

In order to retain the individual wave data points in the computation, the summation procedure for estimating the monthly transport rate in the model is given by,

$$Q_m = \frac{1}{12} \sum_{H=0}^{H=\infty} \sum_{T=0}^{T=\infty} \sum_{\theta'=\beta_c}^{\theta'=\beta_c+\pi} Q \times f_m(H, T, \theta') \quad (7)$$

where, Q = annual volume rate of longshore transport from Eqn. (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 (Figure 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 Figure 2. Using Eqn. (7), the direction and monthly longshore sediment transport rate for every 10° variation in the ori-

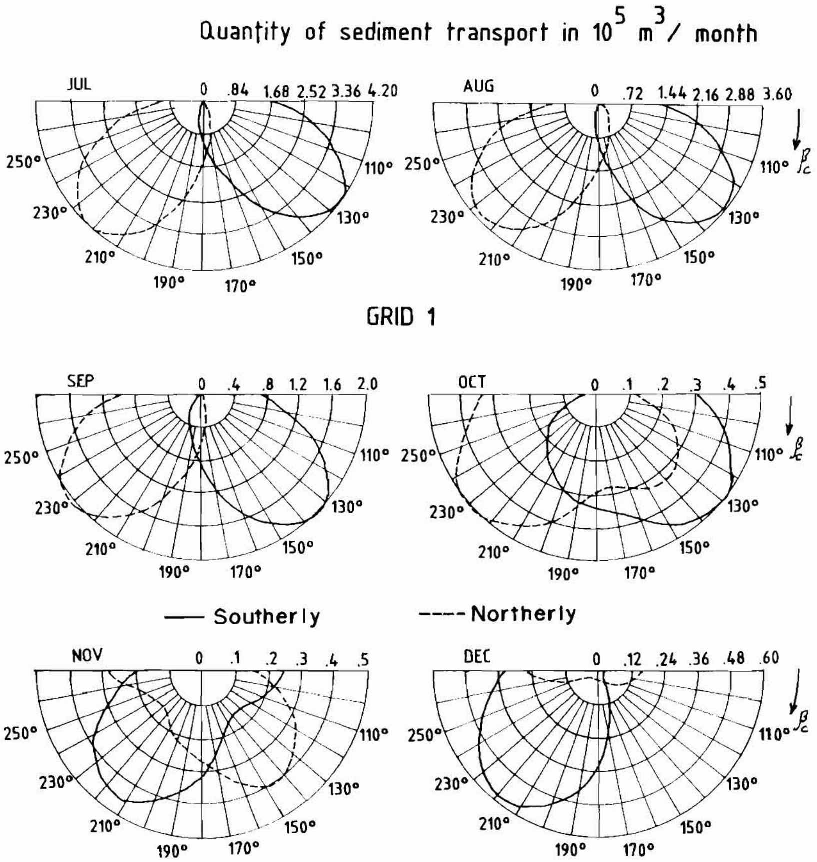

Figure 3b. Variation of monthly longshore transport rate with coastal orientation between Cochin and Karwar from July to December.

entation of the coastline in each grid are estimated and presented as rose diagrams for the grids 1, 2 and 3 in Figures 3a and b, 4a and b and 5a and b, respectively. The following procedure is then adopted to obtain a 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 clockwise direction (β_c) as shown in Figure 2, either using a survey instrument in the field or using the protractor from the detailed maps; (2) identify the grid in which the coastal segment of interest falls (Figure 1); (3) referring to the rose diagrams of the corresponding grid, the longshore sediment transport rate is read for the known orientation of the coastal segment; (4) linear interpolation is made for the coast oriented with an intermediate angle.

For example, the orientation of the coastal segment at Mangalore beach is 163° to north. From Figure 1, it is seen that Mangalore coast lies on the west coast in grid 1. Referring to the rose diagrams corresponding to grid 1 in Figure 3a, for the month of January, the sediment transport rate for the orientation of 160° and 170° are 0.243×10^5 m^3 and 0.405×10^5 m^3 respectively. Hence, for Mangalore having orientation of 163°, using linear interpolation, the sediment transport rate in January is estimated to be 0.292×10^5 m^3 per month in a southerly direction and there is no significant transport in a northerly direction. WALTON (1973) has presented similar rose diagrams for the Florida coast and CHANDRAMOHAN *et al.* (1990) has presented them for the south Indian coast.

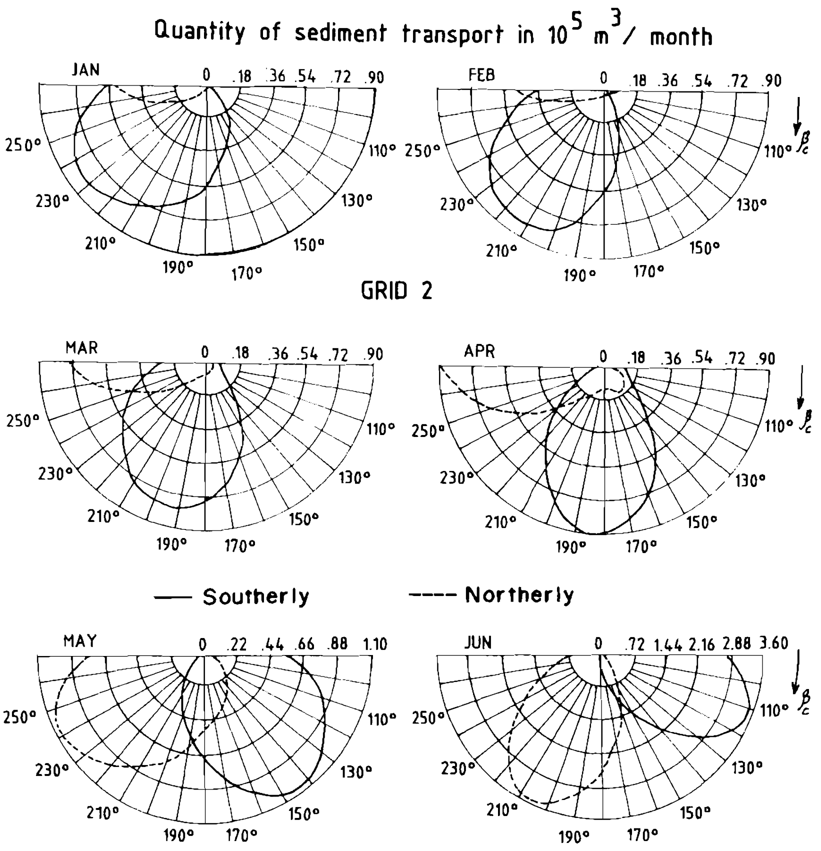

Figure 4a. Variation of monthly longshore transport rate with coastal orientation between Goa and Tarapur from January to June.

RESULTS AND DISCUSSION

Grid 1 covers the coast from Cochin to Karwar (625 Km), grid 2 from Goa to Tarapur (730 Km) and grid 3 from Umbergaon to Porbandar (1,175 Km) (Figure 1). Annual gross and net transport rates for the grids 1 to 3 are presented in Figure 6. The transport rates at selected locations of the study area are presented in Table 1.

Cochin to Karwar (Grid 1)

Referring to Figure 3a and b, for the coast between Cochin and Karwar, the monthly sediment transport rate exceeds 3 × 10^5 m^3 during June to September, and it is relatively low during the rest of the year. The annual net transport is towards the south (Figure 6). Coasts inclined 130° to north would undergo high sediment transport rates, with a gross volume of 1.73 × 10^6 m^3/year and a net volume of 1.39 × 10^6 m^3/year. The average orientation of the coastline over grid 1 is about 150°, and for this, the annual gross and net transport rates are 1.6 × 10^6 m^3 and 1.1 × 10^6 m^3 respectively.

Referring to Table 1, the Mangalore coast is subjected to annual transport rate of 0.36 × 10^6 m^3 in the north and 1.07 × 10^6 m^3 in the south. The BEACH EROSION BOARD (1987) has reported an annual southerly net transport of 0.1 × 10^6 m^3 for this region. The annual net transport is relatively high at Tellicherry and Karwar, and low at Malpe and Coondapur.

Goa to Tarapur (Grid 2)

Figure 4a and b indicates that for the coastline between Goa and Tarapur, the direction of long-

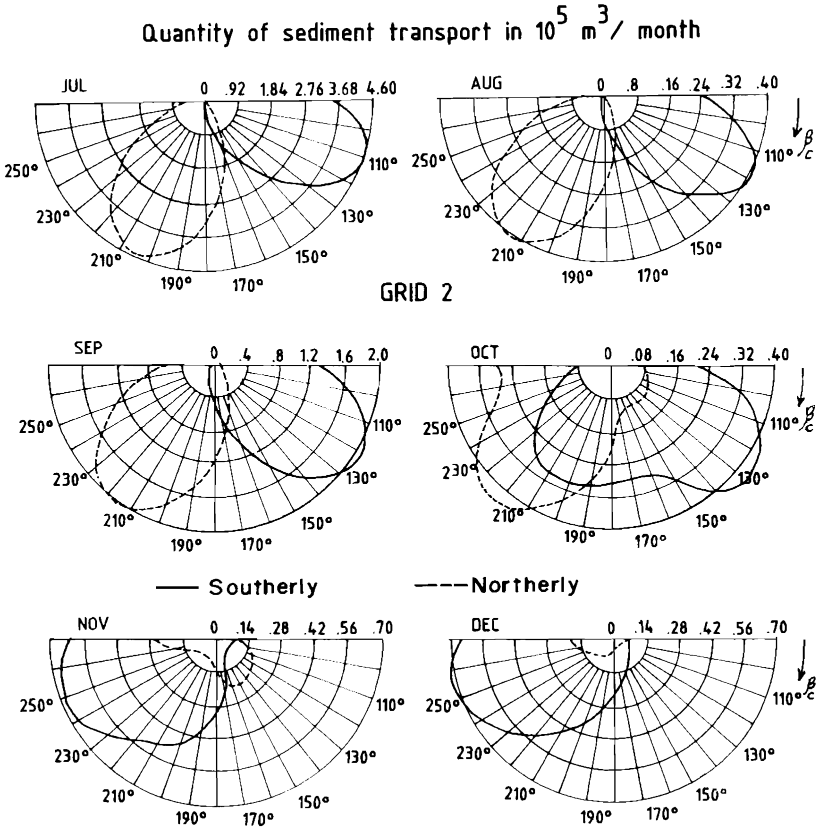

Figure 4b. Variation of monthly longshore transport rate with coastal orientation between Goa and Tarapur from July to December.

shore sediment transport is northerly during June to September and southerly for the rest of the year. Monthly transport rate exceeds 2 × 10^5 m^3 from June to September, and is low about 0.4 × 10^5 m^3 from December to February.

Coasts having an inclination of 130° to north would undergo high transport rate, with a gross volume of 1.69 × 10^6 m^3/year and a net volume of 1.34 × 10^6 m^3/year. The annual net transport is towards the south for the coasts having inclined up to 160° to north, and towards north for the coasts inclined more than 170° to the north. The Goa coast undergoes a northerly transport of 0.63 × 10^6 m^3/year and a southerly transport of 0.76 × 10^6 m^3/year (Table 1).

The annual net transport is negligible near Malvan, Dabhol, Murud and Tarapur, and they behave as nodal drift points.

Umbergaon to Porbandar (Grid 3)

Between Umbergaon and Valsad, the sediment transport is towards the south from October to April and northwards during the rest of the year (Figure 5a and b). The annual net transport is towards the north. Monthly transport rate is high, exceeding 3 × 10^5 m^3 from May to September, and is low, about 0.5 × 10^5 m^3 during the rest of the year. Between Diu and Porbandar, the sediment transport is towards the east throughout the year except November. The monthly transport rate is high, exceeding 2.3 × 10^5 m^3 during June to August.

GENERAL DISTRIBUTION

The monthly longshore sediment transport rate and direction at different locations along the study

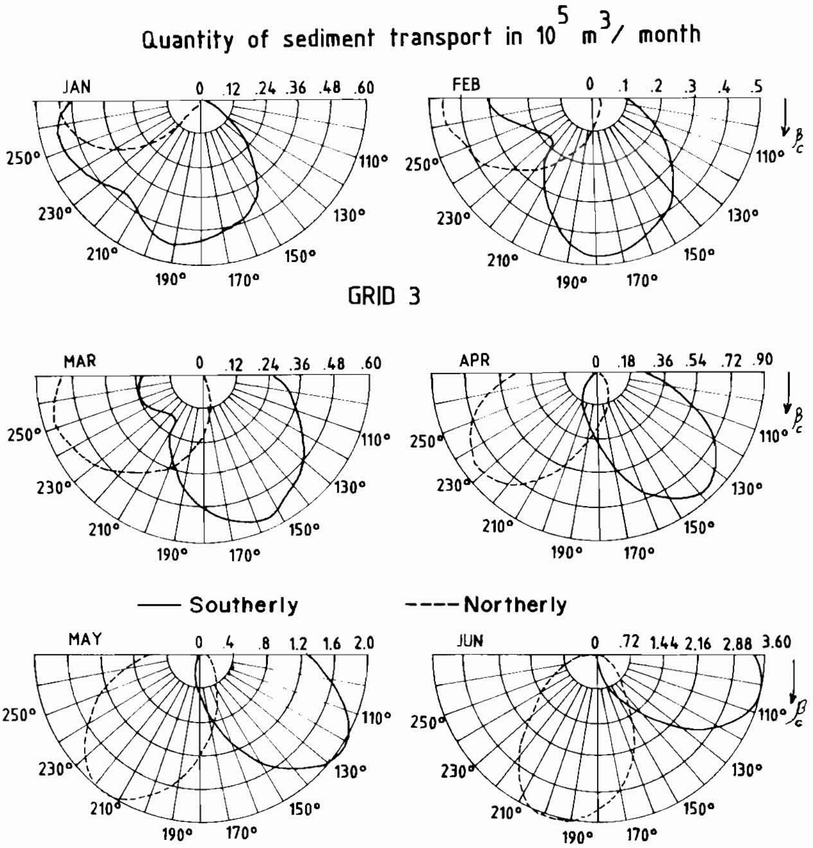

Figure 5a. Variation of monthly longshore transport rate with coastal orientation between Umbergaon and Porbandar from January to June.

region is shown in Figure 7. The longshore transport is southerly from January to May, and October. During June to September, the transport is northerly along Maharashtra and south Gujarat coasts and southerly along the Karnataka and north Kerala coasts. The distribution of annual gross and net transport is shown in Figure 8. Annual gross sediment transport rate is high (1.5 × 10^6 m^3–2.0 × 10^6 m^3) along the coasts of north Kerala, north Karnataka and south Gujarat. The annual net transport is towards the south along Karnataka and north Kerala coasts. The Maharashtra coast experiences negligible quantity of annual net transport. The trend of the annual net transport obtained in the model, closely agrees with the prevailing coastal processes along the west coast of India. The coast of Maharashtra is very stable and it does not have a problem of annual net erosion or excess deposition. The increase in annual net transport volume near Bombay, Goa and Mangalore are balanced by the sediments brought by the large rivers at these places.

COMPARISON WITH FIELD EXPERIMENTS

Field experiments were conducted for two months in March and April, 1990 at Karwar (Figure 1). The surfzone suspended sediment traps (CHANDRAMOHAN *et al.*, 1991), and surfzone streamer traps (KRAUS *et al.*, 1989) were used in arrays across the surfzone as shown in Figure 9. The traps were deployed in the surfzone for 6 hours continuously every day, and from the volume of the trapped sediment, the average sedi-

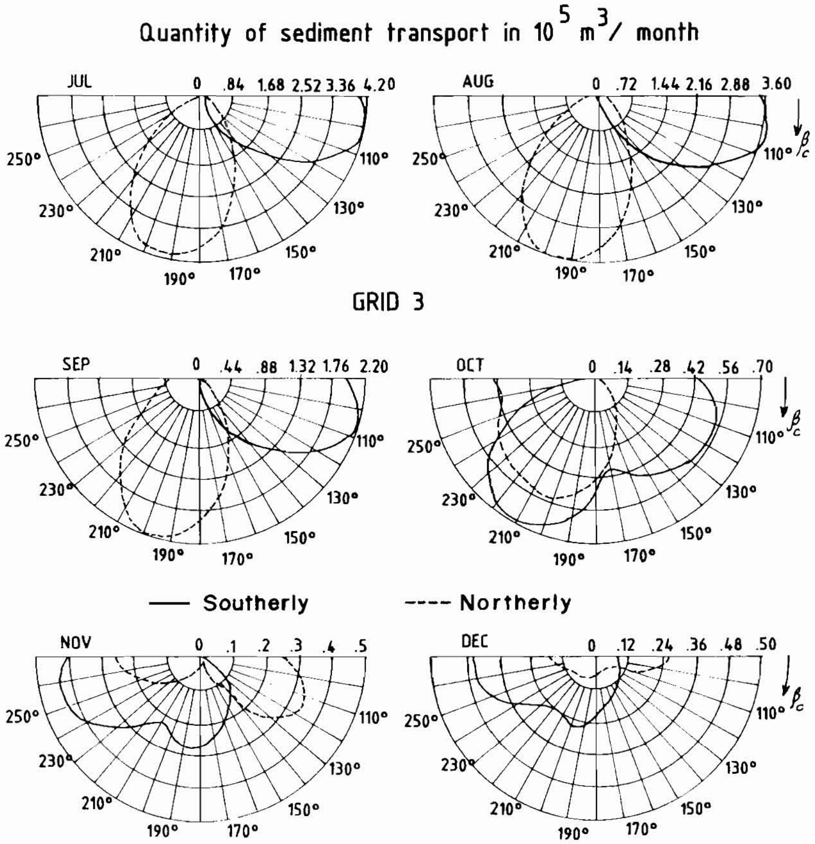

Figure 5b. Variation of monthly longshore transport rate with coastal orientation between Umbergaon and Porbandar from July to December.

ment load across the surfzone was estimated. Other details of the trap experiments are discussed in CHANDRAMOHAN *et al.*, 1991. The average longshore current across the surfzone was determined using fluorescent dye. The sediment transport rate (Q) is estimated from the sediment load across the surfzone (S) and the corresponding average longshore current velocity (V), using $Q = S \times V$. The average longshore transport rates in March and April, based on field experiments were, 2,030 m^3 and 3,762 m^3 respectively, whereas, the model shows 9,058 m^3 and 3,758 m^3 respectively. It indicates a close agreement between the model result and field experiment in April, but a slight deviation in March. The direction of the transport remained the same both in the model and field experiment. The deviation of the result in March might be attributed to the difficulties in keeping the arrays firm for 6 continuous hours during high waves.

The coastal stretches in the vicinity of Malvan, Vengurla and Devgarh ports on the Maharashtra coast are quite stable as no significant accretion or erosion problem could be noticed. This is also evident from the present study which indicates that the annual net sediment transports occurring at these places are almost negligible.

CONCLUSIONS

The present study is based on the ship-reported, visually-observed wave data, and it is assumed that the coast is comprised of long and open sandy beaches with an adequate sand supply. Because

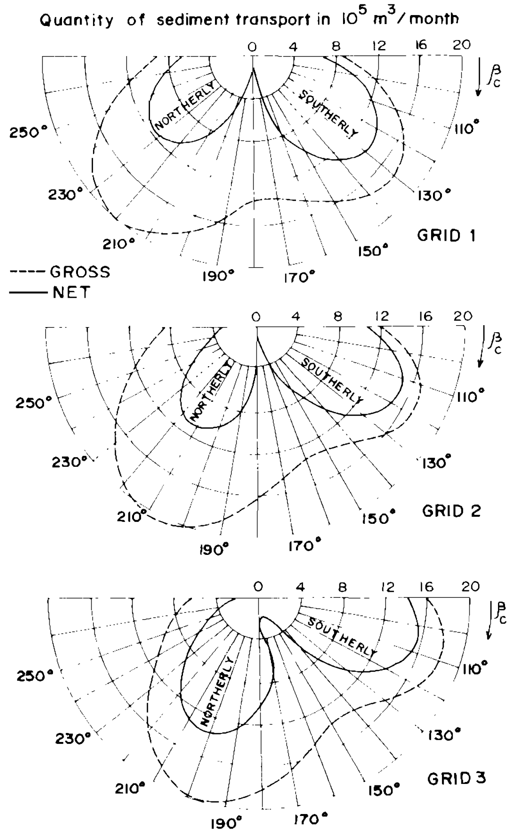

Figure 6. Variation of annual gross and net longshore transport rates with coastal orientation.

Table 1. *Longshore transport rate at important places.*

Places	Northerly	Southerly
Ponnani	0.287	1.240
Calicut	0.349	1.089
Tellicherry	0.192	1.516
Kasargod	0.294	1.218
Mangalore	0.362	1.069
Malpe	0.562	0.819
Coondapur	0.508	0.873
Honavar	0.375	1.049
Karwar	0.199	0.19
Goa	0.634	0.763
Vengurla	0.409	0.938
Malvan	0.686	0.734
Devgarh	0.556	0.805
Ratnagiri	0.925	0.625
Jaigarh	0.600	0.820
Dabhol	0.686	0.735
Murud	0.712	0.720
Bombay	1.313	0.540
Tarapur	0.712	0.720
Umbergaon	1.523	0.386
Valsad	0.980	0.594
Diu	0.856	1.512
Veraval	0.163	1.651
Mangrol	0.287	1.197
Navibandar	0.390	1.018
Probandar	0.263	1.250

Units are 10^6 m^3/yr

the Indian west coast also comprises many headlands and estuaries, care must be taken in applying the results to all morphological elements of the coast.

The estimated annual gross sediment transport rate is high (1.5×10^6 m^3 to 2.0×10^6 m^3) along the coasts of north Kerala, north Karnataka and south Gujarat. The annual net transport is towards the south along Karnataka and north Kerala coasts. Maharashtra coast experiences negligible quantity of annual net transport. The coasts near Malvan, Dabhol, Murud and Tarapur appear to be nodal drift points.

In spite of the size and regional significance of the Indian west coast, information available on sediment dynamics in the nearshore region is very limited. In this context, the present study provides first hand information on the prevailing sediment transport environment for the entire coastline. Further, the model results agree closely with the values obtained from trap experiment. The rose diagrams provide the monthly and annual sediment transport rates as well as direction of transport for a given coastal segment along the Indian west coast. The consolidated results presented in Table 1 will help coastal engineers understand the sediment transport rates for almost all important places situated along the coast.

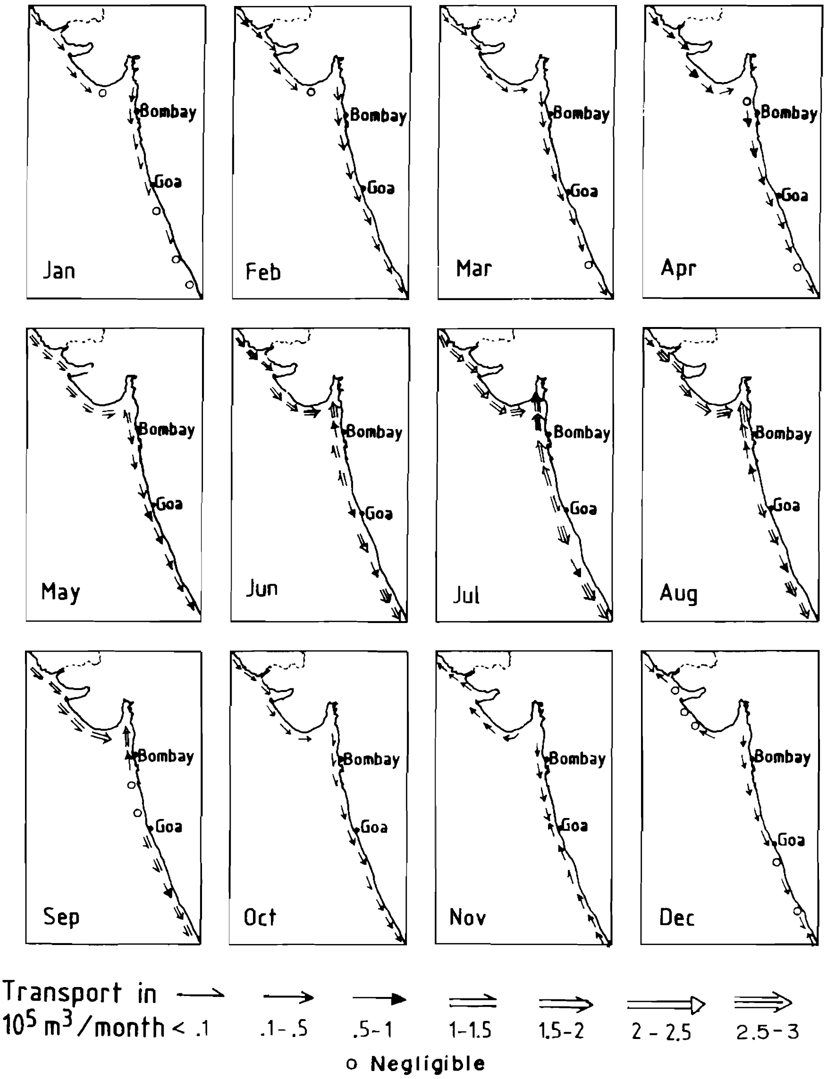

Figure 7. Monthly sediment transport along the coast of west India.

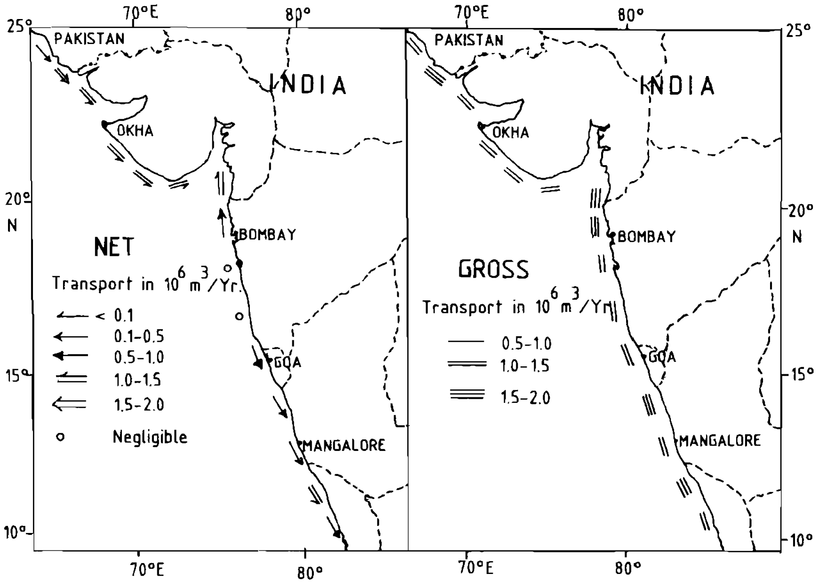

Figure 8. Annual sediment transport along the coast of west India.

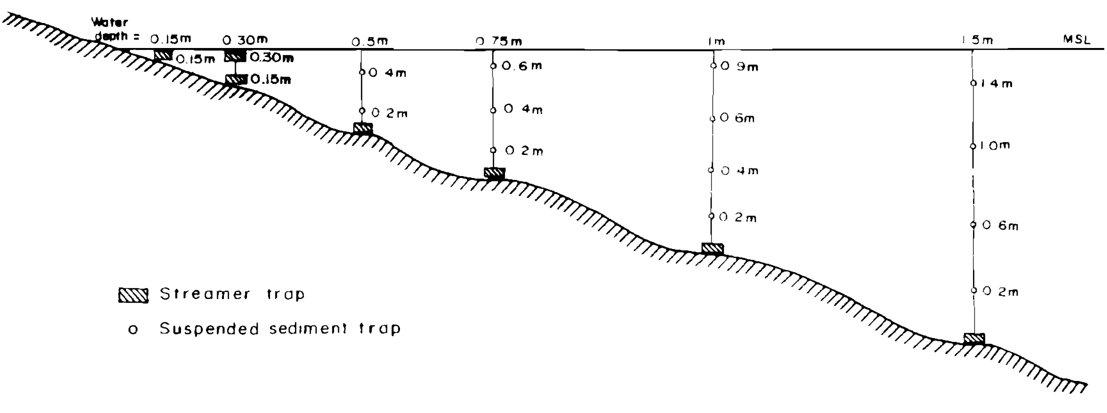

Figure 9. Arrays of sediment traps.

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LITERATURE CITED

BEACH EROSION BOARD, 1987. Agenda notes of 15th meeting, Central Water & Power Research Station. Pune, India.

CHANDRAMOHAN, P.; NAYAK, B.U., and RAJU, V.S., 1988. Application of longshore transport equations to Andhra coast, East coast of India. *Coastal Engineering*, 12, 285–297.

CHANDRAMOHAN, P.; NAYAK, B.U., and RAJU, V.S., 1990. Longshore-transport model for south Indian and Srilankan coasts. *Journal Waterway, Port, Coastal and Ocean Division* (ASCE), 116, 408–424.

CHANDRAMOHAN, P.; NAYAK, B.U., and SANIL KUMAR, V.V., 1991. Sediment transport study using surfzone sediment traps. *Technical Report*, N.I.O., Goa, India (in press).

GRAFF, V. and OVEREEM, V.J., 1979. Evaluation of sediment transport formulae in coastal engineering practice. *Coastal Engineering*, 3, 1–32.

HYDROGRAPHIC CHARTS, 1976. Naval Hydrographic Office, Government of India, Nos. 202–220.

JARDINE, T.P., 1979. The reliability of visually observed wave heights. *Coastal Engineering*, 3, 33–38.

JONSSON, I.G. and CARLSEN, N.A., 1976. Experimental and theoretical investigations in an oscillatory rough turbulent boundary layer. *Journal Hydrographic Research*, 14, 45–60.

KRAUS, N.C.; GINGERICH, K.J., and ROSATI, J.D., 1989. Duck 85 surf zone sand transport equipment. *Technical Report*, CERC, U.S. Army Corps of Engrs, Washington, DC.

LAMBRAKOS, K.F., 1982. Seabed wave boundary layer measurements and analysis. *Journal Geophysical Research*, 87, 4171–4189.

MUNK, W.H. and ARTHUR, R.S., 1952. Wave intensity along a refracted ray. *Gravity Waves, National Bureau of Standards Circular 521,* United States Government Printing Press, Washington, DC, pp. 95–109.

ORR, T.E. and HERBICH, J.B., 1969. Numerical calculation of wave refraction by digital computer. *Coastal and Ocean Engineering Division, Report No. 114,* Texas A&M University, College Station, Texas.

SHIPS WEATHER CODE, 1982. India Meteorological Department, Government of India, Pune, India.

SHORE PROTECTION MANUAL, 1975. Coastal Engineering Research Centre, U.S. Army, Washington, DC.

SHORE PROTECTION MANUAL, 1984. Coastal Engineering Research Centre, U.S. Army, Washington, DC.

SKOVGAARD, O.; JONSSON, I.G., and BERTELSEN, J.A., 1975. Computation of wave heights due to refraction and friction. *Journal Waterway, Harbors and Coastal Division* (ASCE), 1, 15–32.

WALTON, T.L., JR., 1973. Littoral drift computations along the coast of Florida by means of ship wave observations. *Technical Report No. 15*, University of Florida, Gainesville, Florida.

WILLIS, D.H., 1980. Evaluation of sediment transport formulae in coastal engineering practice—Discussion. *Coastal Engineering*, 4, 177–181.

□ RÉSUMÉ □

On a estimé le transport de sédiments parallèlement à la côte de Cochin à Porbandar à partir de données de houle observées de 1968 à 1986 d'un bateau. Les transports sédimentaires sont assez élevés pendant la période de mousson du SW, de juin à septembre. Le taux global annuel de transport est élevé (1,5–2 × 10^6 m^3) sur les côtes du Kerala, au nord du Karnataka et du Sud du Gujerat. La côte de Maharashtra présente un transport net annual assez faible (0,1 × 10^6 m^3). Le transport net annuel est au Sud le long des côtes du Kerala et du Karnataka. Les côtes de Malvan, Dabbol, Murud et Tarapur sont des points nodaux de dérive avec un volume transporté égal dans chaque direction. *Catherine Bousquet-Bressolier, Géomorphologie EPHE, Montrouge, France.*

□ RESUMEN □

Observaciones de olas realizidas desde buques (1968–1986), han permitido estimar el transporte de sedimentos a lo largo de la costa Oeste de la India entre Cochin y Porbandar. Para las costas de: Kerala, Norte de Karnataka y Sud de Gujarat, durante el período de Junio a Setiembre, época de del Monsón del SW, el volumen del material transportado fue relativamente alto (1.5 a 2 × 10^6 m^3). En Maharashtra, el transporte neto anual calculado fue relativamente bajo (0.1 × 10^6 m^3). En las costas Norte de Kerala y Karnataka la dirección del transporte neto fue hacia el Sud. Próximo a las zonas costeras de Malvan, Dabhol, Murud y Tarapur, se presentan dos puntos nodales, con igual volumen anual transportado en las direcciones dominantes. *Néstor W. Lanfredi, CIC-UNLP, La Plata, Argentina.*

□ ZUSAMMENFASSUNG □

An der Westküste Indiens wurde zwischen Cochin und Porbandar der küstenparallele Sedimenttransport abgeschätzt. Dies geschah mit Hilfe von Wellenmessungen, die vom Schiff aus durchgeführt wurden (1968 bis 1986). Während des Südwestmonsuns, also von Juni bis September, wird relativ viel Sediment küstenparallel versetzt. Die jährliche Rate des gesamten Sedimenttransports ist an den Küsten Nordkeralas, Nordkarnatakas und Südgujarats hoch (1.5–2 × 10^6 m^3). Dagegen weist die Küste von Maharashtra einen vergleichsweise niedrigen jährlichen Nettotransport auf (0.1 × 10^6 m^3). Entlang den Küsten Nordkeralas und Karnatakas ist der jährliche Nettotransport südwärts gerichtet. Die Küstenabschnitte bei Malvan, Dabhol, Murud und Tarapur scheinen Knotenpunkte zu sein, da bei ihnen im Jahr jeweils gleiche Sedimentmengen in beiden Richtungen transportiert werden.—*Helmut Brückner, Department of Geography, University of Marburg, Germany.*