2005 (M_w computed in the present study). The earthquake was located in the SEZ in the Koyna region and this fault is conspicuous with normal faulting earthquakes[5]. The seismic moment for this earthquake is estimated to be 3.9×10^{23} dyn-cm. The circular radius of the rupture of the fault plane is about 960 m. Stress drop of this event varies between 16 and 19 MPa. Kanamori and Anderson[16] demonstrated that the average stress drop is higher for intra-plate earthquakes compared to inter-plate earthquakes. The stress drop has been estimated by several workers for the 1993 Latur (M 6.2), 1997 Jabalpur (M 5.8), 1969 Bhadrachalam (M 5.7), 1970 Broach (M 5.2) and Koyna earthquakes and is found to vary between 2 and 25 MPa (Figure 4). A maximum stress drop of 19 MPa obtained for the 14 March earthquake is comparable to the results which have been obtained from an earlier study[17]. The stress drop for the Koyna–Warna earthquakes (magnitude 1.5–4.7) was estimated to be in the range 0.03 to 19 MPa, with the M 4.7 earthquake having the maximum stress drop of 19 MPa. In general, the Koyna–Warna region is conspicuous with higher stress drop in comparison to other source regions in the Peninsular shield. A probable explanation for the high stress drop is due to the presence of competent material within the source volume. Velocity tomography study[18] has revealed the presence of high velocity zone in the Koyna–Warna seismic source region and this high velocity was interpreted in terms of competent material.

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ACKNOWLEDGEMENTS. We thank the Director, NGRI, Hyderabad for permission to publish this work. Digital data provided by Mr H. V. S. Satyanarayana from the local network is acknowledged.

Received 4 March 2006; revised accepted 25 April 2006

Coastal processes along the Indian coastline

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Based on the measured data, wave height and current speed at a few locations are presented along with the estimated sediment transport rates. The maximum significant wave height recorded during the passage of a cyclone along the west coast in a water depth of 27 m was 6 m. The current measurements show that the maximum currents vary from about 1.4 m/s in the open ocean to about 3.2 m/s in the Gulf of Khambhat. The gross longshore sediment transport rate was about 1×10^6 m^3 per year along south Kerala and south Orissa. The estimated longshore sediment transport rates show that net transport along the east coast of India is towards the north, whereas along the west coast it is mostly towards the south.

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Keywords: Basic wind speed, currents, sediment transport rate, shoreline erosion, wave height.

INFORMATION on winds, waves, tides, currents, geomorphology and rate of sediment transport along a coast is required for planning and design of coastal facilities. Beach erosion is a universal problem and it has been estimated that 70% of all the beaches in the world are eroding[1]. Any attempt to handle the coastal problems either to arrest erosion or prevent deposition requires a thorough understanding of the factors and processes involved in the coastal geomorphological system.

Oceanography of the Indian coastal region is dominated by three seasons, viz. southwest monsoon (June to September), northeast monsoon (October to January) and fair weather period (February to May). The continental shelf along the east coast is narrow, whereas along the west coast, the width of the shelf varies from about 340 km in the north to less than about 60 km in the south. Rivers are identified as the major sources of sediment along the Indian coast, among which the Ganges and Brahmaputra contribute a major share of suspended sediments to the Bay of Bengal, and the Indus to the Arabian Sea. Sediment discharge through the Indian rivers[2] into the sea is about 1.2×10^{12} kg/yr. Deposits in the gulf, tidal marshes, bays, beach deposits and aeolian inland transports are found to be the primary sinks for sediments moving along the Indian coast.

Based on the data collected, stretches of the Indian coastline affected by erosion, wave and current characteristics and sediment transport rate at a few locations are presented here.

The Indian coastline is about 7517 km, about 5423 km along the mainland and 2094 km the Andaman and Nicobar, and Lakshadweep Islands (Table 1). The coastline comprises of headlands, promontories, rocky shores, sandy spits, barrier beaches, open beaches, embayment, estuaries, inlets, bays, marshy land and offshore islands[3]. According to the naval hydrographic charts, the Indian mainland consists nearly 43% sandy beaches, 11% rocky coast with cliffs and 46% mud flats and marshy coast. Oscillation of the shoreline along the Indian coast is seasonal. Some of the beaches regain their original profiles by March/April. Fifty per cent of the beaches that do not regain their original shape over an annual cycle undergo net erosion. Shoreline erosion in the northern regions of Chennai, Ennore, Visakhapatnam and Paradip ports has resulted due to construction of breakwaters of the respective port. At present, about 23% of shoreline along the Indian mainland is affected by erosion (Table 1).

Along Gujarat coast, shoreline erosion is observed at Ghoga, Bhagwa, Dumas, Kaniar, Kolak and Umbergaon, and sediment deposition leading to the formation of sand spits at the estuarine mouths of the Tapti, Narmada, Dhadar, Mahe, Sabarmati, Kim, Purna and Ambika. Erosion has been observed at Versoa, Mumbai; near Kelva fishing port, north of Mumbai and at Rajapuri, Vashi and Malvan along the Maharashtra coast. Along Goa coast, erosion is noticed at Anjuna, Talpona and Betalbatim. Erosion along the beaches near river mouths has been commonly noticed along Karnataka coast[4]. Coastal erosion and submergence of land have been reported at Ankola, Bhatkal, Malpe, Mulur, Mangalore, Honnavar, Maravante and Gokarn in Karnataka. About 60 km of beach (19% of the total length of shoreline) is affected by erosion. The problem is relatively more severe in Dakshina Kannada and Udupi coasts, where about 28% of the total stretch is critical. In Uttara Kannada region, about 8% of the coast is subjected

Table 1. Types of coastline in different maritime states

State	Sandy beach (%)	Rocky coast (%)	Muddy flats (%)	Marshy coast (%)	Total length* (km)	Length of coast affected by erosion** (km)
Gujarat	28	21	29	22	1214.7	36.4
Maharashtra	17	37	46	–	652.6	263.0
Goa	44	21	35	–	151.0	10.5
Karnataka	75	11	14	–	280.0	249.6
Kerala	80	5	15	–	569.7	480.0
Tamil Nadu	57	5	38	–	906.9	36.2
Andhra Pradesh	38	3	52	7	973.7	9.2
Orissa	57	–	33	10	476.4	107.6
West Bengal	–	–	51	49	157.5	49.0
Daman and Diu					9.5	–
Pondicherry					30.6	6.4
Total mainland	43	11	36	10	5422.6	1247.9
Lakshadweep					132.0	132.0
Andaman and Nicobar					1962.0	–
Total					7516.6	1379.9

*According to the Naval Hydrographic Office.
**Information collected from respective states.

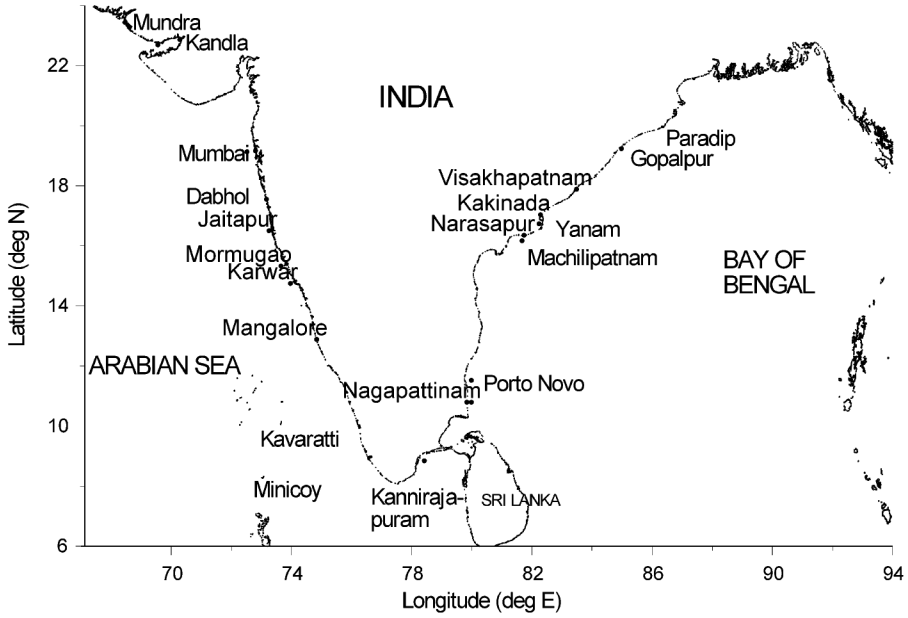

Figure 1. Location of wave measurement.

Table 2. Basic wind speed at 10 m height for some locations[13]

Location	Basic wind speed (m/s)
Bhuj	50
Bahruch	47
Vadodara	44
Mumbai	44
Panaji	39
Mangalore	39
Kozhikode	39
Lakshadweep	39
Thiruvananthapuram	39
Pondicherry	50
Chennai	50
Port Blair	44
Vijaywada	50
Visakhapatnam	50
Bhubaneshwar	50
Kolkata	50

to severe erosion[5]. In many river mouths, the sand pit erodes causing shift in river course or inlet migration. In Kerala, about 360 km long coastline is exposed to erosion[6–8].

Along Tamil Nadu coast, the erosion rate observed at Poompuhar, Tarangampadi, Nagapattinam, Mandapam, Manapadu, Ovari, Kanyakumari, Pallam, Manavalakurichi and Kolachel is about 0.15, 0.65, 1.8, 0.11, 0.25, 1.1, 0.86, 1.74, 0.60 and 1.2 m/yr respectively[9]. The maximum rate of erosion along Tamil Nadu coast is about 6.6 m/yr near Royapuram, between Chennai and Ennore port[10]. The accretion rate at Cuddalore, Point Calimere, Ammapattinam, Kilakarai, Rameswaram, Tiruchendur, Manakudi and Muttam is observed to be about 2.98, 3.4, 0.72, 0.29, 0.06, 0.33, 0.57 and 0.17 m/yr respectively. Usha and Subramanian[11] reported that the coast near Ovari is exposed to severe erosion in June, whereas alternate erosion and accretion trend has been noticed in Kanyakumari. It was also stated that the accretion had taken place in Palk Bay, viz. Ammapattinam, Mandapam and Rameswaram. Andhra Pradesh coast has frequently been affected by cyclones and inundated by storm surges. Erosion is noticed at Uppada, Visakhapatnam and Bhimunipatnam. Erosion is noticed at Gopalpur, Paradip and Satbhaya in Orissa. Growth of long sand spits at Chilka lake indicates the movement of littoral sediment and subsequent deposition. Major length of the West Bengal coast is represented by the Sundarban region of the Ganges mouth with shoals, sand spits, mud flats and tidal swamps[3]. Beach erosion is noticed at Digha, Bankiput and Gangasagar regions of the West Bengal coast[12].

The Andaman and Nicobar is a group of about 265 islands, most of which are composed of rocks like fossiliferous marine petroliferous beds, conglomerates, sandstone and limestone[3]. Land subsidence of 0.8 to 1.3 m has occurred at the Andaman and Nicobar Islands due to the 26 December 2004 tsunami and has resulted in shoreline erosion in some islands. The Lakshadweep, an archipelago of coral islands in the Arabian Sea consists of 36 islands, 12 atolls, three reefs and five submerged coral banks. Coastal erosion in all these islands has been a constant threat. Shore protection work has been taken up in all the inhabited islands and a total length of 40 km has been so far protected.

The average wind speed during the southwest monsoon period is about 35 km/h (9.7 m/s), frequently rising up to 45–55 km/h (12.5–15.3 m/s). The average wind speed during northeast monsoon prevails around 20 km/h (5.6 m/s).

Table 3. Wave characteristics at different locations based on measured data

Location	Water depth (m)	Duration of data (month)	Range of *Hs* (m)	*Hs* for 100 year return period (m)	Predominant average wave period (s)
Mundra*	18	6	0.1–2.2	4.4	2–6
Kandla*	15	12	0.1–2.8	4.4	3–11
Veraval**	15	4	N.A.	5.3	N.A.
Dahej*	20	7	0.1–2.0	3.0	2–10
Hazira*	15	7	0.1–2.9	4.2	2–14
Daman*	27	7	0.1–6.0	8.0†	3–15
Umbergaon*	37	6	0.2–4.8	6.6†	3–16
Vadhavan point*	24	8	0.3–2.8	3.4	3–15
Bombay high*	75	19	0.4–5.1	7.8	3–16
Mumbai**	30	3	N.A.	5.1	N.A.
Uran*	10	5	0.2–2.5	3.2	4–16
Dabhol*	14	5	0.4–4.6	7.1	3–8
Ratnagiri**	10	12	N.A.	3.9	N.A.
Jaitapur*	16	12	0.1–3.3	5.6	3–15
Mormugao*	23	12	0.3–5.9	9.7†	3–9
Mormugao**	14	4	N.A.	5.1	N.A.
Karwar*	16	48	N.A.	6.1	N.A.
Mangalore**	13	5	N.A.	4.1	N.A.
Kavaratti*	10	4	N.A.	2.1	N.A.
Kalpeni*	11	12	0.2–2.3	3.1	3–12
Androth*	11	12	0.3–2.5	3.6	3–9
Agatti*	15	12	0.3–1.8	2.2	3–11
Minicoy*	10	12	0.3–1.7	2.3	3–11
Kannirajapuram*	12	12	0.3–1.9	2.3	3–9
Nagore*	10	12	0.2–2.0	3.2	2–9
Pillaiperumalnallur*	15	12	0.2–2.1	2.7	2–9
Porto Novo*	80	6	0.3–2.1	2.8	3–12
Machalipattanam*	20	8	0.5–2.3	3.0	3–15
Narasapur*	10	11	0.2–4.2	4.6	4–12
Yanam*	90	12	0.3–2.8	3.5	3–15
Tikkavanipalem*	12	12	0.3–3.9	4.2	3–10
Visakhapatnam**	17	36	N.A.	4.9	N.A.
Gopalpur*	10	12	0.2–2.5	3.1	3–9
Gopalpur*	15	12	0.2–3.3	4.8	4–8
Paradip*	16	9	0.1–3.7	6.3	3–10
Sunderban*	20	3	N.A.	2.1	N.A.

*Based on data collected by NIO, Goa.
**Based on data collected by Central Water and Power Research Station, Pune[14].
†Cyclone crossed near the measurement locations; N.A., Details not available.

Table 4. Estimated deep water significant wave height based on ship reported data

Grid	Latitude (°)	Longitude (°)	*Hs* for 100 yr return period (m)
1	20–25	85–95	7.82
2	15–20	85–90	8.00
3	15–20	80–85	7.85
4	10–15	80–85	7.60
6	5–10	75–80	8.40
7	5–10	70–75	8.91
8	10–15	70–75	8.24
9	15–20	70–75	8.88
10	20–25	65–75	8.34

During cyclonic period, wind speed often exceeds 100 km/h (27.8 m/s). Tropical storms known as cyclones frequently occur in the Bay of Bengal during October–January. Basic wind speed (3 s gust wind speed) along the coastline[13] varies from 39 to 50 m/s (Table 2). The maximum wind speed estimated by India Meteorological Department for the supercyclone 1999 was 259 km/h (71.9 m/s).

The west coast of India experiences high wave activity during the southwest monsoon with relatively calm sea conditions prevailing during rest of the year. On the east coast, wave activity is significant both during southwest and northeast monsoons. Extreme wave conditions occur under severe tropical cyclones, which are frequent in the Bay of Bengal during the northeast monsoon period. Along the west coast, waves approach from west and WSW during southwest monsoon, west and WNW during northeast monsoon and southwest during fair weather period. In the east coast, waves approach from southeast during southwest monsoon and fair weather period, and from northeast during northeast monsoon.

Table 5. Currents at shallow water along the Indian coast

Station	Water depth (m)	Location distance from bed (m)	Period	Speed (m/s)	Predominant direction (deg)
Kharo creek	18	10	December 1994	0.3–1.0	240, 300
Positra	20	10	December 1993	0.4–0.5	180, 360
Kandla	10	4	March 1996	0.05–1.6	180, 360
	10	4.5	October 1996	0.05–1.5	180, 360
Vadinar	25	20	March 1994	0.2–0.8	60, 270
Muldwaraka	17	11	January 2000	0.1–0.5	290, 120
Dahej	24	23	July to October 2003	0.01–3.2	180, 360
Dhabol	9	5.6	October 1994	0.1–0.5	330, 150
Mormugao	23	10	April 1998	0.02–1.2	180, 360
	23	7	January 1998	0.03–0.3	180, 360
	5	2.5	April 1996	0.03–0.6	120–300
	8	2.5	November 1995	0.05–0.5	90–270
	3	1.5	April 1996	0.02–0.6	110–270
	3	1.5	September 1996	0.1–0.6	110–300
Karwar	10	5	May–June 1988	0.02–0.5	90, 270
	14	7	May–June 1988	0.02–0.6	180–270
Mangalore	9	6	May 1999	0.05–0.4	180, 360
Kochi	8	6	April 1998	0.05–0.4	170–220
	6.5	4.5	April 1998	0.05–0.9	170–350
	4	3	October 1998	0.05–1.4	180–270
Kannirajapuram	4	2	February 1997	0.01–0.3	215
	4	2	August 1997	0.01–0.2	30–60
	4	2	December 1997	0.01–0.2	210
	7	3.5	March 1997	0.01–0.3	215
	7	3.5	July 1997	0.01–0.3	45–360
	12	6	March 1997	0.1–0.9	270
	12	6	August 1997	0.1–0.9	60
Nagapattinam	16	8	February 1995	0.12–0.6	30, 330
	16	8	August 1995	0.04–0.4	180, 360
	14	7	March 1995	0.1–0.4	180, 360
	14	7	September 1995	0.11–0.5	180, 360
Chinnakuppam	14	7	August 1996	0.03–0.3	180–225
Mahabalipuram	9	7	March 1996	0.1–0.3	30–360
Tikkavanipalem	12	9	January 1998	0.02–0.3	90, 270
Gopalpur	15	3	January 1994	0.1–0.4	225
	15	7	February 1994	0.05–0.4	45, 225
Paradip	15	9	May 1996	0.1–0.8	65
	30	29	November 1996	0.1–1.2	30–60

Design of coastal structures calls for information on design significant wave height (*Hs*) having a certain return period of, say, 100 years. Such a design wave height is obtained by collecting data of short term, i.e. three-hourly, over a long period. Based on wave measurements (Figure 1) carried out by National Institute of Oceanography, (NIO) Goa and from the published literature[14], wave characteristics at different locations are presented in Table 3. These are site specific data and cannot be considered for locations other than the measured one and for other periods. Since measured wave data cover only short periods (mostly one year or less), ship-reported visual observations documented in Indian daily weather reports published by India Meteorological Department, Pune were also compiled for a period of 18 years from 1968 to 1986 for different regions ($5° \times 5°$ grid) along the Indian coastline[15], and design deep water significant wave height for 100 year return period was estimated (Table 4).

Tidal range along the Indian coastal region varies from 8.5 m at Bhavnagar, Gulf of Khambhat to 0.5 m along the peninsular tip of India. Survey of India predicts tide levels at important places along the Indian coast and Tide Tables[16] are published ever year. The different tide levels at a few locations are presented in Figure 2.

Currents near the river mouth are mainly influenced by tides. Regions along the open coast within a few kilometres from the coastline are mostly dominated by wind and seasonal circulation pattern. Currents in the Gulf of Kachchh and Gulf of Khambat are highly influenced by tides. The measured current speed is found to vary from about 1.4 m/s in the open ocean to about 3.2 m/s in the Gulf of Khambhat. The magnitude and direction of the current velocity measured at a few locations along the Indian coastline are given in Table 5.

Studies on sediment transport along the east coast of India were initiated by La Fond and Prasada Rao[17]. The

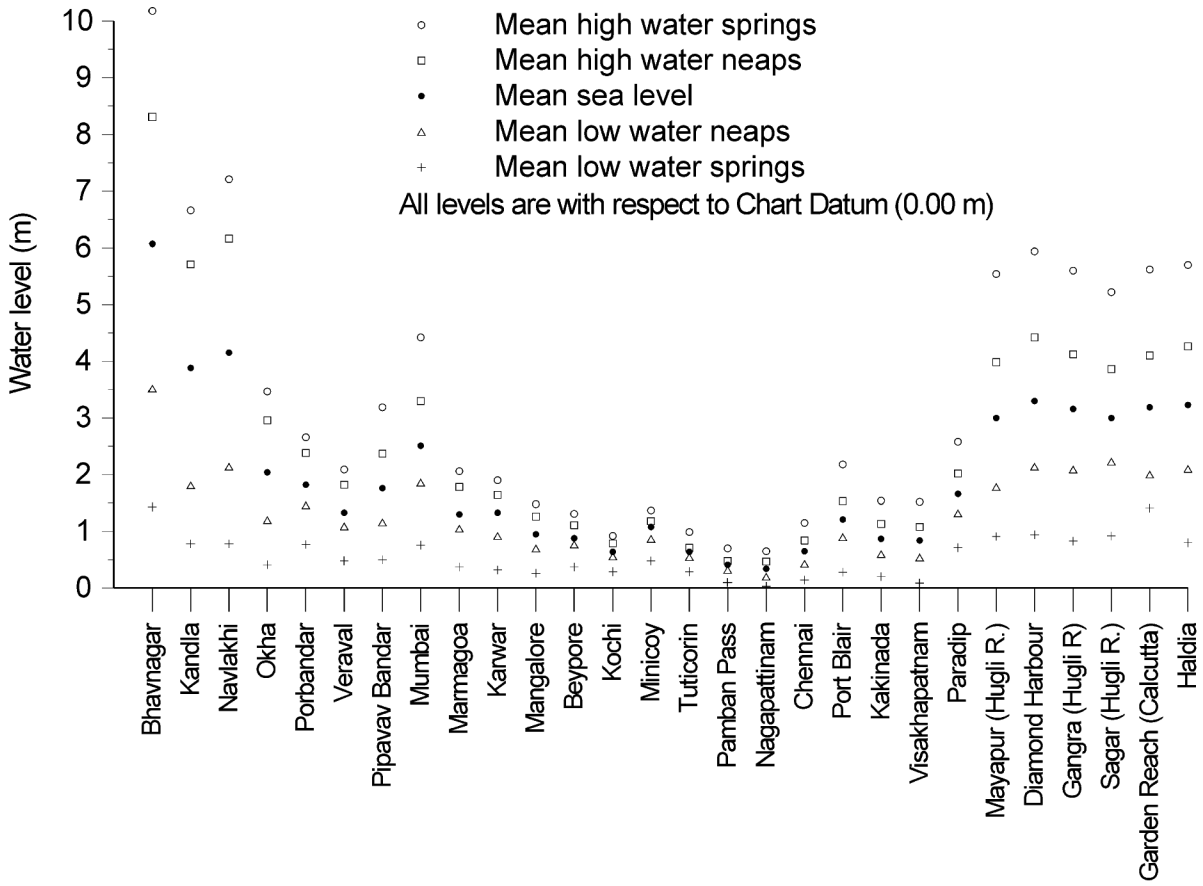

Figure 2. Different water levels at few locations along the Indian coastline.

longshore sediment transport rate (LSTR) reported[4,18–24] for different locations along the Indian coast (Table 6, estimated based Walton and Bruno[25]) shows local reversals in the transport direction in a number of locations along the west coast. The sediment deposition/siltation noticed at most of the harbour channels and river mouths are mainly due to their interference to free passage of longshore sediment transport. Along the east coast, longshore transport is southerly from November to February, northerly from April to September and variable in March and October. Along the west coast, longshore sediment transport is generally towards the south from January to May and in October. It was found that the annual gross sediment transport rate was high ($\approx 1 \times 10^6$ m^3) along the coast of south Orissa and south Kerala.

Chandramohan[26] estimated the LSTR based on ship-reported data. The study showed that coasts near Malvan, Dabhol, Murud and Tarapur appear to be nodal drift points with equal volume of transport in either direction annually. Coasts near Tarangampadi, Karaikal, Nagore, Tuticorin, Virapandiapattinam and Manakkodam in Tamil Nadu behaved like nodal drift points, with an equal volume of transport in either direction annually. Annual net transport was northerly on the east Gujarat coast. The coast between Pondicherry and Point Calimere in Tamil Nadu, and Maharashtra coast experience negligible quantity of annual net transport. The annual net transport at the southernmost tip of the Indian Peninsula (Kanyakumari) was negligible. The annual net sediment transport at Visakhapatnam[27] was northerly, which is similar to that observed at Tikkavanipalem, 30 km south of Visakhapatnam. Sundar and Sarma[28] have reported that the annual net sediment transport rate (0.94×10^6 m^3/yr) at Gopalpur, Orissa was northerly, which is similar to that observed between Prayagi and Puri (Table 6).

The Indian coast, in general, experiences seasonal erosion and some of the beaches regain their original profiles by March/April. Fifty per cent of the beaches, which do not regain their original shape over the annual cycle, undergo net erosion. At present, 23% of the shoreline along the Indian mainland is affected by erosion. Basic wind speed at 10 m above ground level along the Indian coast varies from 39 to 50 m/s. The maximum significant wave height recorded during the passage of a cyclone along the west coast of India in a water depth of 27 m was 6 m. The current measurements show that the maximum currents vary from about 1.4 m/s in the open coast to about 3.2 m/s in the Gulf of Khambhat. The gross longshore sediment transport rate was about 1×10^6 m^3/yr along south Kerala and south Orissa. Estimated longshore sediment transport rates

Table 6. Sediment transport rate at different locations

Location	Net transport (m^3/yr)		Gross transport (m^3/yr)
West coast of India			
Kalbadevi	118,580	South	147,621
Ambolgarh	189,594	South	299,997
Vengurla	53,040	South	120,141
Calangute	90,000	South	120,000
Colva	160,000	North	160,000
Arge	69,350	North	200,773
Gangavali	142,018	South	177,239
Kasarkod	40,186	North	77,502
Maravanthe	25,372	North	29,836
Malpe	14,169	South	106,641
Padubidri	89,358	South	385,469
Ullal	36,165	South	38,273
Kasargod	736,772	South	958,478
Kannur	19,434	South	561,576
Kozhikode	114,665	South	256,697
Nattika	192,818	North	660,276
Andhakaranazhi	202,096	South	599,484
Alleppey	16,929	North	62,519
Kollam	383,784	South	805,296
Thiruvananthapuram	99,159	North	1231,153
Kolachel	302,400	West	946,500
East coast of India			
Ovari	1,500	South	251,300
Tiruchendur	64,100	North	87,500
Kannirajapuram	117,447	North	145,979
Naripayur	36,600	South	122,500
Muthupettai	5,200	South	8,900
Pudhuvalasai	5,300	South	42,900
Vedaranivam	51,100	North	94,100
Nagore	96,000	South	433,000
Tarangampadi	200,600	North	369,400
Poompuhar	146,000	North	478,800
Pondichery	134,400	North	237,000
Periyakalapet	486,900	North	657,600
Tikkavanipalem	177,000	North	405,000
Gopalpur	830,046	North	949,520
Prayagi	887,528	North	997,594
Puri	735,436	North	926,637

show that the net transport along the east coast of India is towards the north, whereas along the west coast it is mostly towards the south.

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ACKNOWLEDGEMENTS. We thank the Director, NIO, Goa for encouragement and support. We also thank our colleagues who were involved in data collection. This is NIO contribution number 4114.

Received 9 December 2005; revised accepted 27 March 2006