

Longshore sediment transport in the surf zone based on different formulae: a case study along the central west coast of India

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Abstract Understanding longshore sediment transport (LST) is a prerequisite for designing an effective coastal zone management strategy. The present study estimates the LST along the central west coast of India based on four bulk LST formulae: (1) the Coastal Engineering Research Center (CERC) formula, (2) the Walton and Bruno formula, (3) the Kamphuis formula and (4) the Komar formula. The Delft3D-wave module is used for estimating nearshore waves with measured directional wave data at a water depth of 9 m as the input parameter. Wave data for the validation of the nearshore wave transformation model is measured using the InterOcean S4DW wave gauge. The model results show that waves approach from the south 90 % of the time in a year and that they generate predominantly northerly longshore currents. Upon comparison with the measured data, the findings show that the estimates based on the Kamphuis formula agree with the field data. A high ratio (~1) of the monthly net and gross transport rates indicates that the LST is dominating in one direction in all months except February and July. The study shows that a slight change in the angle of the wave approach during the Asian summer monsoon period (JJAS) can significantly alter the direction and magnitude of the LST. Inter-annual variations in the LST based on the data for 2009 and 2011 show that the variations in the annual net and gross LST rates in different years are less than 7 %.

Keywords Coastal engineering · Coastal zone management · Longshore sediment transport · Nearshore currents · Nearshore waves · Nearshore dynamics

Introduction

One of the most dynamic environments on our planet is the coastal zone where land, ocean and atmosphere interaction take place. The coastal zone is affected by locally generated waves and swells arriving from long distances (United States Army Corps of Engineers [USACE] 1984). When waves enter shallow water, their heights and wavelengths are altered by the processes of refraction and shoaling before breaking. Waves breaking in a surf zone generate turbulence, exert shear stress on the sea bottom and cause sediment suspension (Yang 1996). The longshore current generated by obliquely incident breaking waves plays an important role in transporting sediment in the nearshore zone and is a key component of most coastal engineering studies (Kumar et al. 2003). The challenging problem currently faced by coastal engineers is the estimation of nearshore waves, longshore currents and longshore sediment transport (LST) (Van Rijn et al. 2013). Even though a number of predictive models are developed, it is difficult to evaluate the accuracy of the models (Bayram et al. 2001; Van Rijn et al. 2013). Therefore, understanding longshore sediment transport becomes a requisite task for designing an effective coastal zone management strategy.

Numerous studies on LST have been conducted all around the world (Pilkey and Cooper 2002). Based on either ship-reported deep-water wave data or on visually observed wave and littoral environmental observations, many studies report quantitative LST at different localities along the Indian coast (see Shanasa and Kumar 2014 for details). However, a numerical modelling technique to quantify the longshore sediment

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transport rate (LSTR) is only attempted in a few studies. Mohanty et al. (2012) and Shanias and Kumar (2014) estimated the LSTR based on the numerical model using the Coastal Engineering Research Center (CERC) formula (USACE 1984). Kumar et al. (2003) examined the performance of three LST formulae based on the data collected for a 4-month period and Shanias and Kumar (2014) examined the performance of four LST formulae based on one year of measured wave data.

In this paper, a study is carried out using the measured nearshore wave data collected at 3-h intervals for a period of two years as input to the nearshore wave transformation model Delft3D-wave module (WL Delft Hydraulics 2011). The estimation of LSTR is done using four well-known formulae. This study is a part of the shoreline management plan for selected locations along the Karnataka coast. The study focuses on LST and its relationship between the waves along the central west coast of India. Variations in the LSTR estimate for different coastal inclination are examined, and inter-annual variations in the LSTR are studied based on two years of data.

The paper is structured as follows: Section 2 provides a description of the study area. Section 3 briefly describes the data used in the study, the details of nearshore wave transformation and the formulae used for the estimation of longshore currents and LST. In Section 4, the results of the study are presented along with discussions related to offshore and nearshore wave characteristics, longshore currents and LST. Finally, the conclusions are presented in Section 5.

Study area

The area selected for the study is Malpe, the largest fishing harbour in the state of Karnataka, India, which is geographically located at $13^{\circ}19'02.3''\text{N}$, $74^{\circ}42'57.4''\text{E}$ along the west coast of India (see Fig. 1). Depth contours of 20, 50, 100 and 200 m occur at 12, 48, 90 and 108 km off Malpe. The 10 m depth contour along the study area is inclined 17° to the west from the true north. The continental shelf off Karnataka has an average width of 80 km with the nearshore depth contours aligned approximately parallel to the coastline.

A few islands are situated off the coast. The major one is St. Mary's Island, which is located 4 km off the coast near Malpe. The Udayavara River joins the Arabian Sea near Malpe. Tides in the region are mixed semi-diurnal dominant, with a mean spring tide range of 1.21 m and a mean neap tide range of 0.56 m. Areas near the river mouths along the coastline of Karnataka State suffer permanent erosion due to natural shifting and the migration of the river mouths. The erosion becomes severe during the south-west (summer) monsoon season (June–September) due to high floods in the river and strong wave action (Hegde et al. 2004). The coast is exposed to the seasonally reversing monsoon winds. The climate of

this region is marked by heavy rainfall (the annual rainfall is 300 cm), high humidity and oppressive weather conditions in the summer.

Data and methodology

Data collection

Measured directional wave data using the directional wave rider buoy off Malpe (13.2754°N , 74.6823°E) in a water depth of 9 m is used as input to the wave transformation model. Wave data was recorded for a duration of 30 min at a frequency of 1.28 Hz at three-hour intervals for a period of one year from January to December 2009. Wave data collected off Kundapura (13.6175°N , 74.6223°E) for January to December 2011 is also used in the study to determine inter-annual variations. The wave data analysis is similar to that reported in Kumar et al. (2012). The significant wave height (H_{m0}), which equals $4\sqrt{m_0}$, and the mean wave period (T_{m02}), which equals $\sqrt{m_0/m_2}$, $\sqrt{\frac{m_0}{m_2}}$ are obtained from the wave spectrum. Where $m_n = \int_0^{\infty} f^n S(f)df$ and $S(f)$ is the spectral energy density at frequency f , the period corresponding to the maximum spectral energy density, i.e., the spectral peak period (T_p), is estimated from the wave spectrum.

Wave data for the validation of the nearshore wave transformation model was measured using the InterOcean S4DW wave gauge. The S4DW was moored for a week in April 2009 at a location with a water depth of 2.5 m. It was moored 0.5 m above the seabed. The S4DW is designed by InterOcean to measure and record the true magnitude and direction of horizontal motion without the effect of vertical movement due to wave action. Water flows through an electromagnetic field generated by the current meter, thus producing a voltage proportional to the flow velocity of the water. The voltage is sensed by two orthogonal pairs of electrodes located symmetrically on the equator of the sensor, and the direction of the current is measured by an internal flux-gate compass. The S4DW wave gauge records pressure that is converted into depth data, and the data records are transformed from the time domain to the frequency domain using the fast Fourier Transform. The data are sampled at a rate of 2 Hz every three hours, and H_{m0} and T_{m02} are obtained from the wave spectrum.

The measurement of the grain size distribution of nearshore sediments is carried out using an electromagnetic sieve shaker, which contains six sieves with mesh sizes of 2000, 1000, 500, 250, 125 and 63 μm , respectively, along with a pan. The median grain size is extracted by the following geometric (modified) Folk and Ward (1957) graphical measures using GRADISTAT: a grain analysis package (Blott and Pye 2001). The LSTR measured by Kumar et al. (2003) using traps

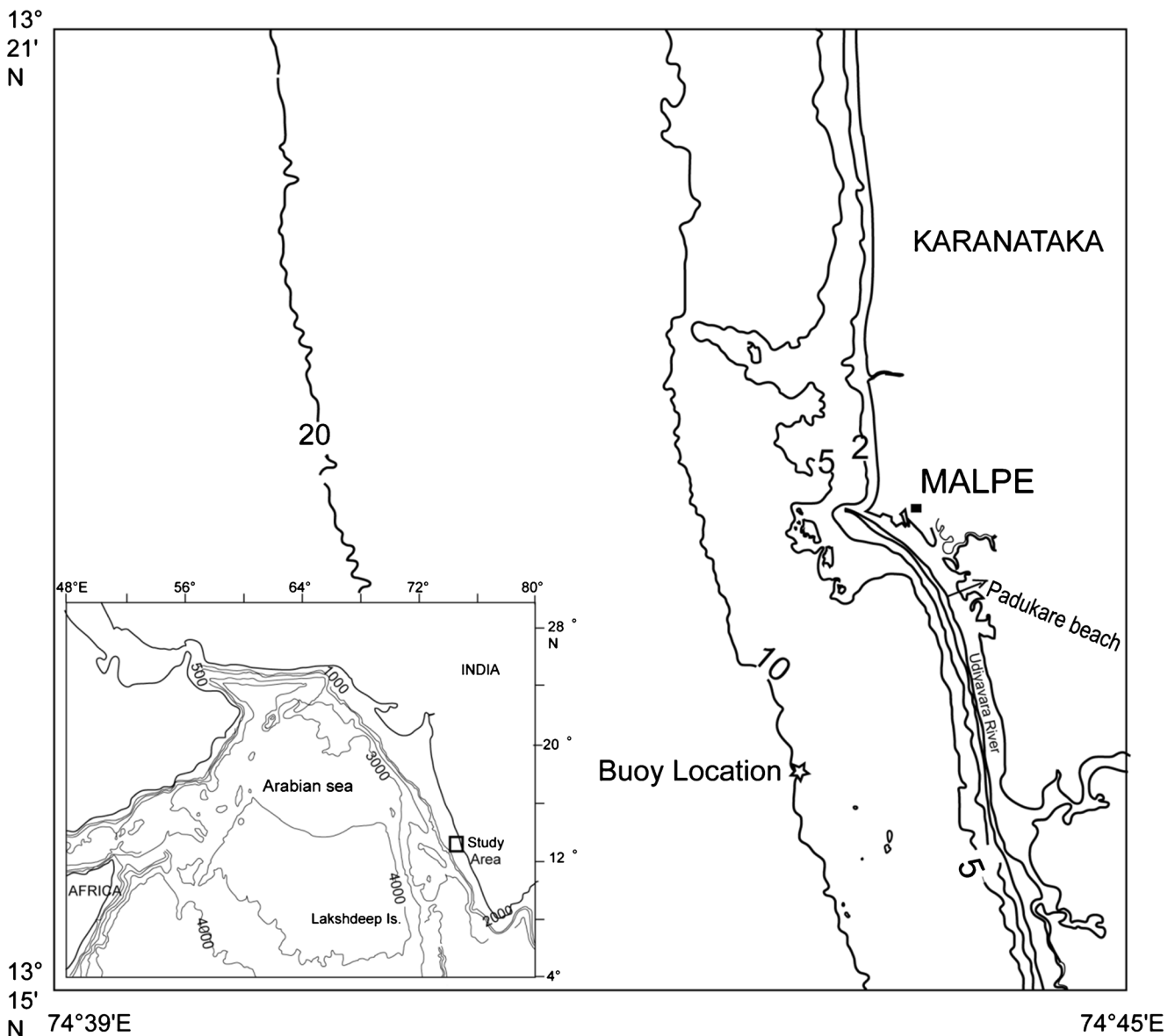


Fig. 1 The bathymetry of the study area along with measurement location. The depth contours are in metres (m)

deployed on a 4 km-long beach along the Karnataka coast for a period of 4 months is used for validation of the LSTR estimates obtained from this study. The details of the data collection and analysis are presented in Kumar et al. (2003).

Nearshore wave transformation

The Delft3D-wave module (WL Delft Hydraulics 2011) developed by WL Delft Hydraulics is used for the nearshore wave transformation. This model is a slightly adapted version of the SWAN model (Booij et al. 1999), which is capable of simulating complicated interactions and transformations experienced by waves propagating through space: refraction due to bottom and current variations, shoaling, transmission/blockage through/by obstacles, the effects of wind,

whitecapping, depth-induced wave breaking, bottom friction and non-linear wave-wave interactions. Bathymetry data used in the model is the measured nearshore data (coast to 5 m water depth) in 2009 and the data from 5 to 12 m is obtained by digitizing the navigational hydrographical chart. The measured significant wave height, the wave period corresponding to the spectral peak and the mean wave direction at a water depth of 9 m are used as the input wave parameters for the model.

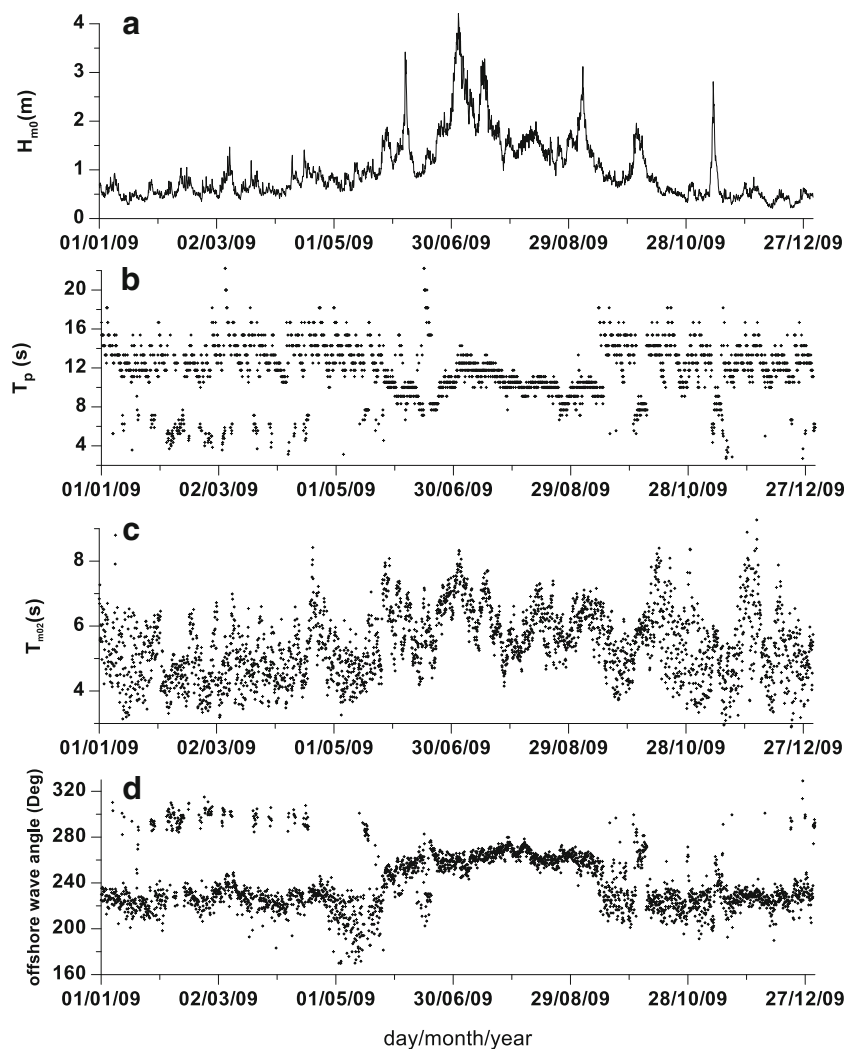
The model domain is divided into a rectangular 200×200 grid with a resolution of 25 m in x and 50 m in the y-direction. The spectral resolution consists of 25 intervals from 0.05–1 Hz. In the Delft3D-wave module, other input variables such as alpha and gamma for the depth-induced breaking are taken as 1 and 0.73 (Battjes and Stive 1985) and the bottom friction

coefficient value is taken as $0.067 \text{ m}^2 \text{ s}^{-3}$ (Bouws and Komen 1983). The transformed offshore wave characteristics are extracted at a water depth of 2.5 m since the average depth of closure based on Hallermeier (1978) for the study area is 2.1 m. Model simulation was conducted from January–December in 2009 and 2011.

Formulae used for the estimation of longshore currents and LST

The LSTR is calculated by applying four bulk longshore sediment transport formulae: (1) the CERC formula (USACE 1984), (2) the Walton and Bruno (1989), (3) the Kamphuis (2002) and (4) the Komar (1998). The details are presented in the appendix. Each of these formulae uses different input parameters including wave height, period, wave direction, sand grain size, sand porosity, beach slope, surf zone width, water density, longshore current and empirical coefficients. The input parameters such as wave height, period and wave direction for the estimation of the LSTR are obtained from the Delft3D–wave module.

Fig. 2 Wave characteristics measured at a 9 m water depth during 2009: **a** significant wave height, **b** peak wave period, **c** mean wave period and **d** mean wave direction



Results and discussions

Offshore wave characteristics

Based on the measured data, it is found that, about 80 % of the time, significant wave height (H_{m0}) is less than 1.5 m with an annual average value of ~ 1 m. About 20 % of the time, H_{m0} values are high (ranging from 1.5 to 4.2 m) and the maximum value (4.2 m) is observed during the peak summer monsoon period (Fig. 2). Earlier studies reported significant wave heights up to 6 m during the summer monsoon along the west coast of India and $H_{m0} < 1.5$ m during the rest of the period (Kumar et al. 2003). Significant wave height values are low during the pre-monsoon season (February–May) and post-monsoon season (October–January) compared to the H_{m0} value during the monsoon season. The average H_{m0} values during the pre- and post-monsoon seasons are 0.7 m and 0.6 m, respectively, while the average H_{m0} value during the monsoon is 1.6 m. Relatively high values are observed during the post-monsoon season for a short period due to the occurrence of the

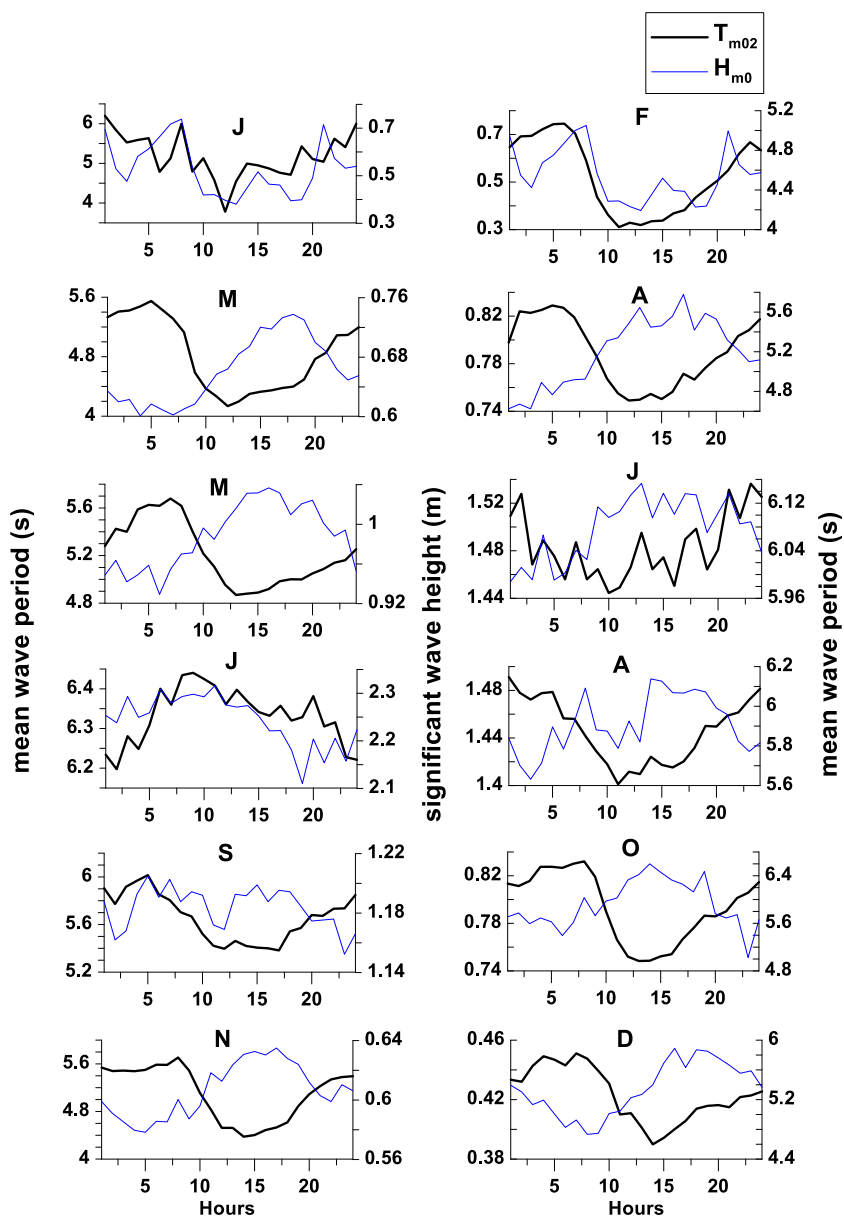
cyclonic storm Phyan in the Arabian Sea. Variation in H_{m0} in one day is up to 1.6 m with an average value of 0.2 m.

The average value of the mean wave period (T_{m02}) is 4.9 s and 5.4 s during the pre- and post-monsoon seasons while that during the monsoon is 5.9 s (Fig. 2). The mean wave period values are slightly higher during the post-monsoon period (2.9–10 s) with high values occurring during October, and they persist in the range of 3–9 s during the pre-monsoon and monsoon seasons. The hourly variation of wave height and period indicates that, during March, April, May, November and December, the wave height reaches a maximum value around 18:30 UTC (i.e., around 13:00 h local time) because of the strong sea breeze persisting over the coastal region (Fig. 3). Due to the sea breeze, variations in the nearshore wave conditions are observed, and they result in an increase in H_{m0} and a

decrease in T_{m02} . During the peak monsoon season (June and July), the land breeze is weak and the swells dominate along the west coast of India (Anoop et al. 2015).

A large variation is observed in the spectral peak period (T_p) during the pre- and post-monsoon seasons due to the presence of swells along the west coast of India. The T_p mostly persists between 8 and 12 s during the monsoon season. The average value of the T_p during the monsoon season is 11 s, and the average value of the T_p during the non-monsoon period is 12 s. Relatively low values of the T_p during the monsoon are due to the presence of locally generated waves and young swells. About 60 % of the time during the year, the spectral peak period ranges from 12.5 to 22.2 s. During the rest of the period, it ranges from 2.7 to 12.5 s. Long period swells ($T_p \approx 22.2$ s) were observed in the month of March. In

Fig. 3 Variation of hourly average significant wave height (H_{m0}) and mean wave period (T_{m02}) in different months



the study area, the waves are predominantly from the SW direction, with 65 % of the waves approaching from 218 to 263°. During the pre- and post-monsoon seasons, the waves are observed coming from the SW direction, but with the onset of the monsoon season, waves from W (255–270°) become prominent (Fig. 2).

Validation of wave transformation model

The measured data at a water depth of 2.5 m in the study area for 7 days are compared with the simulated model results, which were extracted at the same location. Nearshore (\approx 2.5 m water depth) wave characteristics are extracted at location 13.314° N, 74.719° E. The statistical parameters used for comparison are the Root Mean Square Error (RMSE), correlation coefficient (cc), bias and Scattering Index (SI). A small error in the RMSE (0.067 m) is observed with a low value in the bias (0.017 m) and the SI (0.083). Also, the model results have a good correlation (cc = 0.73) with the measured data (Fig. 4). Thus, the study indicates that the model results are comparable to the measured values.

Nearshore wave characteristics

The seasonal variation in breaker height (H_b) is similar to the variation in offshore significant wave height (Fig. 5). It is found that, most of the time during the year (\sim 70 %), the nearshore wave height is less than 1.2 m, especially during the non-monsoon period. Most frequently occurring breakers (45 %) are those in the height range of 0.5–1.1 m. More than 60 % of the time, breaker heights are within 0.5–1.5 m.

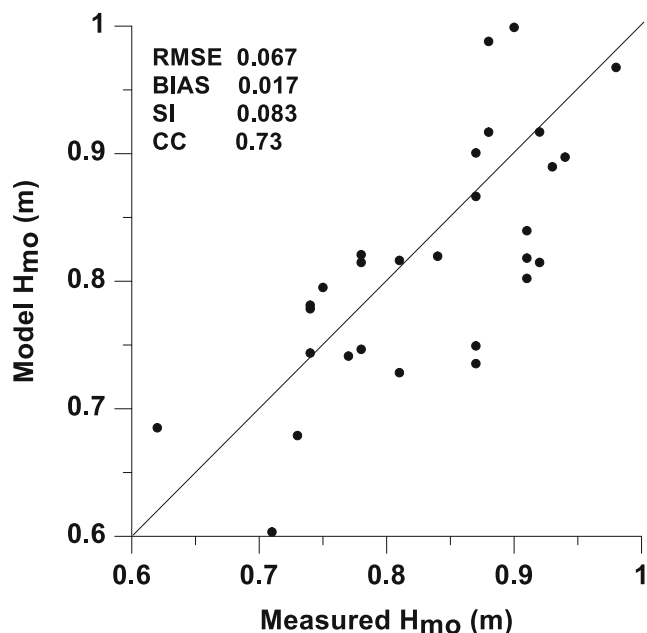


Fig. 4 Comparison of the measured and model estimated H_{m0} at a 2.5 m water depth

Breaker height is at the maximum (2.4 m) during July. The average value of H_b during the pre- and post-monsoon seasons are 0.7 and 0.6 m, whereas during the monsoon season, the average H_b is high (1.6 m) as expected.

Chandramohan et al. (1994) studied surf zone dynamics along the Karnataka coast and reported that the average breaker height at Malpe persisted at about 1 m during June and July and at about 0.6 m during the rest of the year. The wave breaker angle (α_b) is calculated as the difference between the peak wave direction and the direction normal to the depth contour at the breaker location. The α_b mostly persisted between -20 and 20° during the year (Fig. 5). Negative values of α_b indicate breakers north of the shore-normal while positive values of α_b indicate breakers south of the shore-normal. The average value of the peak period for positive α_b is 12.2 s, indicating the arrival of swells from the SW. The average value of the peak period for negative α_b is 7 s, indicating seas from the NW.

Longshore currents

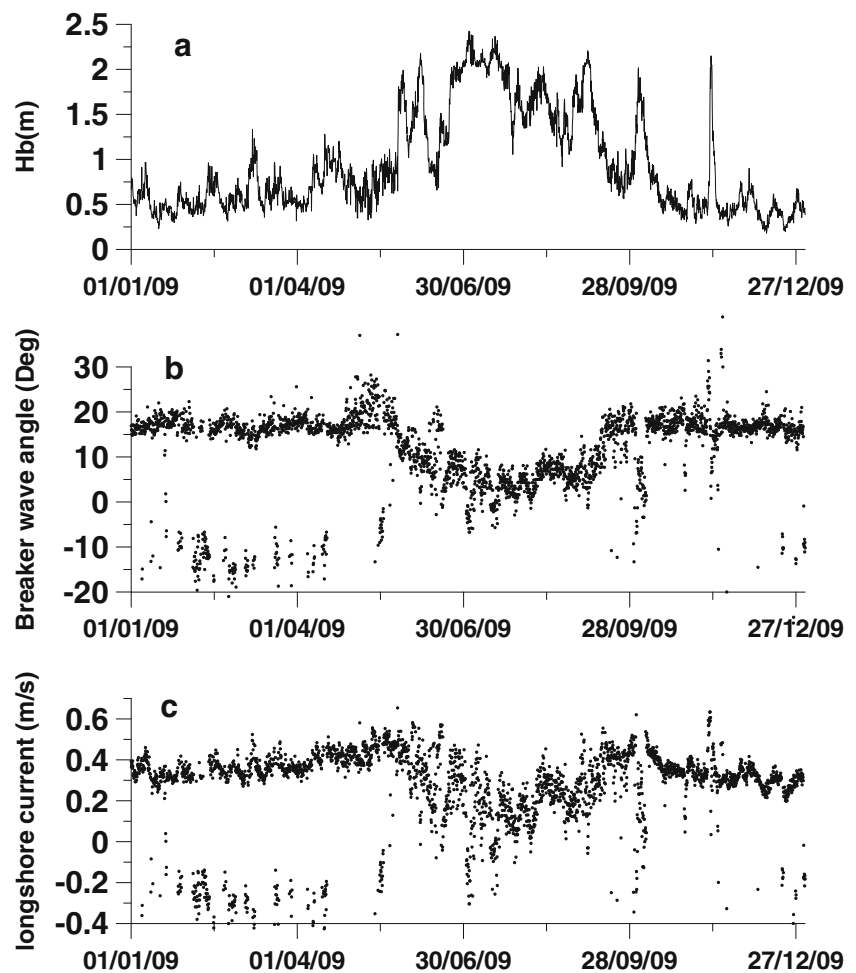
Since the coastline along the study area is inclined 9° to the west with respect to true north, longshore current direction towards 171° is taken as flow towards the south and longshore current direction towards 351° is considered flow towards the north. Estimated longshore currents show significant variations in their direction and magnitude (Fig. 5). From January–March, the longshore current direction is transitional, but it dominates in a northerly direction. The estimated current speed, based on Longuet-Higgins (1970, Eq. A4), varied from -0.42 to 0.65 m/s. Temporal variation of the longshore current over a period of one day was up to 0.7 m/s: indicating the importance of considering multiple data in a day.

Chandramohan et al. (1994) studied the daily variation of longshore current velocity along the west coast of India and reported that, at Malpe, the longshore current is northward most of the year and the average longshore current velocity persists at about 0.25 m/s in June and 0.1 m/s during the rest of the year. The measured longshore current along the central west coast of India varies from 0.1 – 0.6 m/s with an average speed of 0.3 m/s (Kumar et al. 2003). The longshore current estimated in the present study is similar to the values based on measurement. The longshore current direction varied with respect to the breaker angle: southerly currents are generated by breakers north of the shore-normal while intense breakers south of the shore-normal during the peak monsoon season result in strong northerly currents.

Longshore sediment transport

Wave breaking induces longshore currents and sediment transport in the surf zone. For the study area, the waves approach from south of the shore normal for most of the time

Fig. 5 Nearshore wave characteristics showing time series plot of **a** breaker wave height, **b** breaking wave angle and **c** longshore current estimated based on Longuet-Higgins (1970)



(90 %) in the year. This, in turn, generates predominantly northerly longshore currents. The LST estimated for each month indicates that the predominant direction of the LST is from the south to the north in the study area. The LSTR is low during pre- and post-monsoon seasons, where the wave activity is low ($H_b \approx 0.68$ and 0.5 m). During the monsoon season, the wave activity is high compared to the pre- and post-monsoon seasons and the generated high LSTR. Based on visual observation, Chandramohan et al. (1994) reported that the direction of LST is northward during June and from September to December and southward during the rest of the year. In the present study, the direction of sediment transport is mostly from the south to the north except during January to March during which the direction of LST is transitional but predominantly in the northerly direction (Table 1). The annual net transport is found to be northerly, and it is 1.12 , 0.82 , 0.33 and $0.89 \times 10^6 \text{ m}^3$, respectively, for the CERC, Walton and Bruno, Kamphuis and Komar formulae. The corresponding annual gross values are 1.26 , 0.92 , 0.35 and $1.01 \times 10^6 \text{ m}^3$.

Relatively high values are seen in the estimates of the LSTR using the CERC and Komar formulae, which is ~ 1.3

times that of the Walton and Bruno formula and ~ 3.5 times that of the Kamphuis formula. The LST of more than one million cubic meters of sediment per year on average estimated in the present study based on the CERC formula is found to be unusual and can lead to large coastline variations, which are not observed along the study area. Wang et al. (1998) recommended using the CERC formula for wave heights more than 4 m. However, along the Malpe coastal region, the measured wave data indicate that, about 80 % of the time, H_{m0} is less than 1.5 m with an average annual value of ~ 1 m and a maximum value of 4.2 m. Estimation of the LSTR based on the Komar formula ($0.89 \times 10^6 \text{ m}^3/\text{yr}$) is also close to the CERC estimate since the parameters in both formulae are the same and need to be calibrated for the study area. The applicability of the CERC formula and the need for calibration for a particular site is discussed in the literature (e.g., Miller 1999). Smith et al. (2009) tested the CERC formula by calibrating the K value and reported that the formula gave excellent results if K is calibrated with measured data and is applied to similar breaker types. Estimation of the LSTR using the Walton and Bruno formula also requires calibration since it shows comparatively higher values.

Table 1 Monthly net and gross LSTR estimated during 2009

Month	Net LSTR (m ³ /month)				Gross LSTR (m ³ /month)				Net to Gross LSTR ratio			
	CERC	Walton	Kamphuis	Komar	CERC	Walton	Kamphuis	Komar	CERC	Walton	Kamphuis	Komar
Jan	32,841	48,385	12,568	19,453	37,477	54,658	13,302	22,546	0.88	0.89	0.94	0.86
Feb	16,253	20,154	9491	11,045	33,420	45,261	12,005	23,958	0.49	0.45	0.79	0.46
Mar	42,276	49,647	23,706	30,496	56,079	64,901	25,675	41,910	0.75	0.76	0.92	0.73
Apr	70,123	68,760	30,424	47,641	83,577	80,546	32,601	60,079	0.84	0.85	0.93	0.79
May	137,371	102,101	36,109	104,552	143,192	107,294	37,498	109,783	0.96	0.95	0.96	0.95
Jun	235,308	115,878	59,232	201,793	236,053	116,339	59,765	202,413	1.00	1.00	0.99	1.00
July	113,965	48,477	30,904	107,725	183,327	72,685	51,746	167,874	0.62	0.67	0.60	0.64
Aug	159,358	80,265	40,971	140,104	159,659	80,425	41,148	140,384	1.00	1.00	1.00	1.00
Sep	152,153	99,366	34,932	124,376	155,537	102,012	35,657	127,080	0.98	0.97	0.98	0.98
Oct	79,785	81,057	25,334	54,163	85,770	84,371	26,742	59,762	0.93	0.96	0.95	0.91
Nov	55,723	63,095	12,448	42,075	55,990	63,628	12,466	42,250	1.00	0.99	1.00	1.00
Dec	27,850	46,418	8703	14,779	30,309	51,284	8990	16,181	0.92	0.91	0.97	0.91

The average gross LSTR based on the measurement using sediment traps during the period February–May along the central west coast of India is 726 m³/day (Kumar et al. 2003). In the present study, the average gross transport rate estimated by the four formulae for the same period (February–May) is 2635, 2483, 898 and 1964 m³/day (based on the CERC, Walton and Bruno, Kamphuis and Komar formulae, respectively). The estimated values indicate that the Kamphuis formula is in good agreement with the measured data. Schoonees and Theron (1996) evaluated different formulae against an extensive database and reported that the Kamphuis formula is the best formula for LSTR estimation. For the present study area, K is calibrated by comparing the estimated LSTR with that based on the Kamphuis formula since the estimates based on Kamphuis are close to the measured LSTR values for the central west coast of India. The K value is found to be 0.11 for the CERC formula and 0.15 for the Walton and Bruno formula.

Based on daily littoral environmental observations and the Walton and Bruno formula, Chandramohan et al. (1994) reported the annual LSTR at Malpe as 1.07×10^5 m³. The low values reported may be due to error in the visual observation of the breaker parameters, which also are based on a single data in a day. Shanas and Kumar (2014) found that the percentage variations in the LSTR estimate are large for a data interval of more than 12 h. They estimated an annual net LSTR of 0.16×10^6 m³ and an annual gross LSTR of 0.31×10^6 m³/yr. based on the Kamphuis formula for a location 50 km north of the present study area. The annual gross LSTR is similar for both locations studied. However, even through the two locations are within 50 km distance, there is a large difference in the net LSTR.

The ratio of net and gross transport rates reveals a basic pattern of sediment transport (Soomere et al. 2008). Generally,

the small ratio of net and gross transport rates indicates that no dominating transport direction exists in that area (Soomere et al. 2008). The high ratio (~1) in the present study indicates that the LST is dominating in one direction except during February and July (see Table 1). The low value (0.59) of the ratio of the net and gross transport in July indicates a northerly transport as well as a southerly transport during that month.

Breaker parameters and influence on LST

The direction of LST largely depends on the direction of incoming waves with respect to the shoreline, which in turn determines the direction of the longshore current. Since the average H_b during the monsoon period (~1.6 m) is around 2.5 times the value during the pre- and post-monsoon periods (~0.7 and 0.6 m), the estimated LSTR based on the CERC, Walton and Bruno, Kamphuis and Komar formulae during the monsoon period (4 months) is 58, 40, 53 and 63 % of the annual LSTR. The non-monsoon period (8 months) contributes to about 42, 60, 47 and 37 % of the annual LSTR. The estimated LSTR based on the CERC, Walton and Bruno, Kamphuis and Komar formulae during the monsoon period was 47, 61, 53 and 43 % of the total LSTR for the location 50 km north of the study area (Shanas and Kumar 2014).

During the non-monsoon period, the LSTR mainly depends on the breaker height, whereas during the monsoon period, the LSTR variation is high and it is influenced by the angle of the breaker. This is similar to the observation of Shanas and Kumar (2014). The monthly variation of grain size also indicates that, due to high wave energy, the grain size is coarser during the monsoon season compared to the grain size during the non-monsoon season. The coarser grain size during the monsoon period should have reduced the transport rate. However, the study shows that the transport rate is higher

during the monsoon period, which indicates the higher influence of the breaker angle and breaker height on LST compared to the influence of sediment size.

Sensitivity of offshore angle on the LSTR estimate

The sensitivity of the offshore wave angle on the LSTR estimate is tested for two periods in the year: one in the monsoon season (June) and the other in the non-monsoon season (October). Numerical model results are obtained for the selected period by altering the angle of the wave approach from the actual angle. The altering of the offshore angle is done by adding 1 to 5° to the actual angle (s°) or by reducing it by 1 to 5° (Table 2). The LSTR for the respective month based on breaker characteristics from the same location is estimated and compared with the LSTR obtained without changing the offshore angle. It is observed that relative error in the net LSTR estimate based on the Kamphuis formula during the monsoon season for a + 5(−5°) error in the offshore wave direction is 15(10)%, while that in the estimate of the gross LSTR is 13(9)%. During the non-monsoon season, the percentage difference in the net estimates is low and is found to be 5.2(2.1)%. The percentage difference in the gross LSTR during the non-monsoon season is negligible. Thus, the study shows that the influence of the wave angle on the LSTR is high during the monsoon season.

Sensitivity of coastal inclination on LST

Using the extracted nearshore wave climate, the anticipated change in the LSTR for a deviation in coastal orientation up to ±4° to the existing alignment is studied. It is found that a 1° shift from the actual orientation can significantly alter the annual LSTR (Table 3). The influence of coastal inclination on LST is more compared to the influence of the offshore

Table 3 Variation of annual net and gross LSTR with respect to change in coastal inclination

Angle (°)	Annual net LSTR (m ³)	% error in net LSTR	Annual gross LSTR (m ³)	% error in gross LSTR
s-4	424,953	31	435,949	22
s-3	402,487	24	416,875	17
s-2	378,507	17	396,752	11
s-1	352,435	9	376,821	5
s*	324,824	0	357,595	0
s + 1	295,843	-9	338,131	-5
s + 2	264,582	-19	318,349	-11
s + 3	230,367	-29	299,362	-16
s + 4	193,728	-40	285,116	-20

* s actual coastal inclination

wave angle. The percentage difference in the net annual LSTR based on the Kamphuis formula is found to be +31(−40) for a shift of −4(+4)°. For the gross annual LSTR, the percentage difference is +22(−20). The relatively high percentage difference in the annual LSTR shows that even a small deviation in the coastal inclination can cause a large variation in estimates of the LSTR.

Wave climatology for different bins and sensitivity to the estimated LSTR

We have also examined the sensitivity of the LSTR estimate based on wave climatology for different directional bins. We classified the measured offshore data into different directional bins of 30° ranging from 170 to 350°. The wave climatology for different directional bins in different classes of wave height and period (H_{m0} ranging from 0.5 to 3.5 m and T_p ranging from 3 to 21 s) is presented in Fig. 6. The occurrences of

Table 2 Monthly variation of LSTR with respect to change in offshore angle during June and October

Angle (°)	Net LSTR in June (m ³)	% difference in net LSTR	Gross LSTR in June (m ³)	% difference in gross LSTR	Net LSTR in October (m ³)	% difference in net LSTR	Gross LSTR in October (m ³)	% difference in gross LSTR
s*	59,232	0	59,765	0	25,334	0.0	26,742	0.00
s + 1	57,784	-2	58,515	-2	25,150	-0.7	26,729	-0.05
s + 2	56,163	-5	57,086	-4	24,929	-1.6	26,698	-0.16
s + 3	54,435	-8	55,545	-7	24,644	-2.7	26,645	-0.36
s + 4	52,377	-12	54,085	-10	24,346	-3.9	26,648	-0.35
s + 5	50,322	-15	52,676	-13	24,028	-5.2	26,578	-0.62
s-1	60,712	2	60,999	2	25,482	0.6	26,749	0.03
s-2	61,977	5	62,182	4	25,613	1.1	26,732	-0.04
s-3	63,195	7	63,340	6	25,724	1.5	26,705	-0.14
s-4	64,267	8	64,367	8	25,788	1.8	26,658	-0.31
s-5	65,261	10	65,308	9	25,857	2.1	26,577	-0.62

* s-actual offshore angle

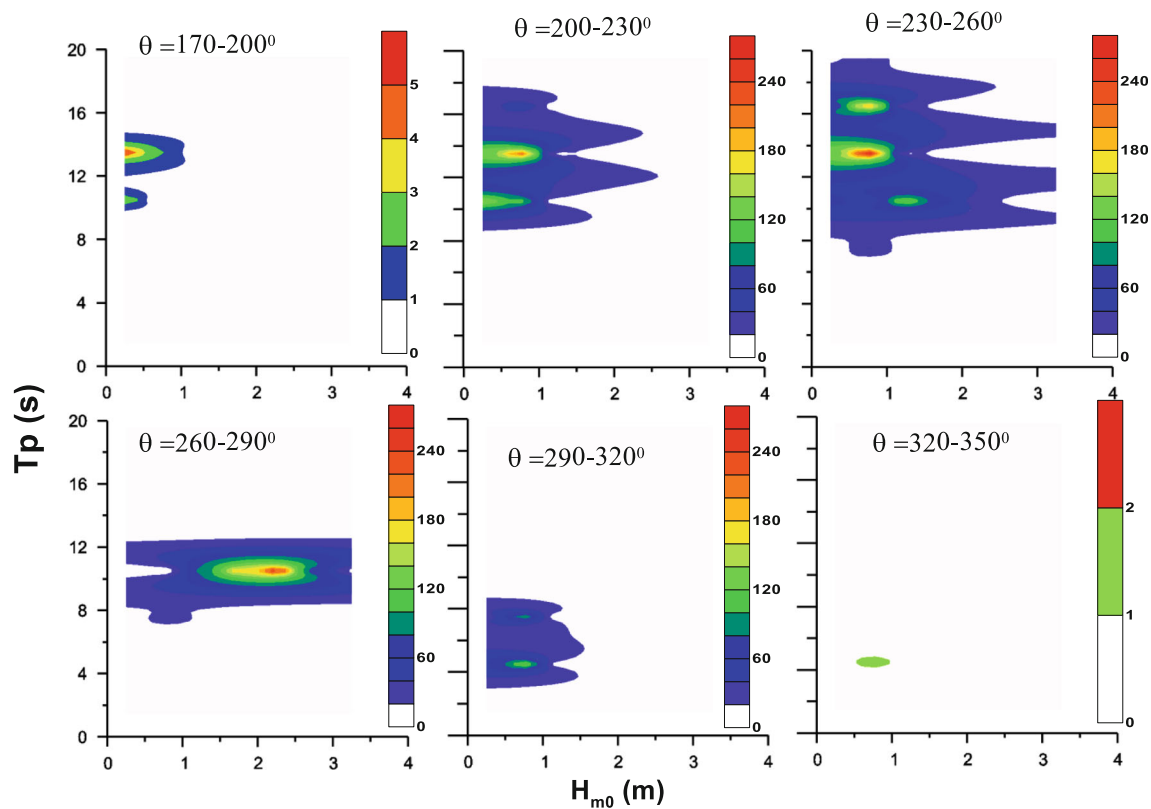


Fig. 6 Wave climatology for different directional bins in different classes of wave height and period

waves in each class from the measured data at a 10 m water depth are determined. The breaker characteristics from the model outputs are extracted similar to the earlier approach and the LSTR is estimated using the Kamphuis formula. The annual net and gross LSTR estimated by this approach are $-5.5 \times 10^5 \text{ m}^3$ and $7.45 \times 10^5 \text{ m}^3$, respectively. The estimated LSTR for this case, compared to the time series data at half hour intervals, is $\sim 70\%$ higher for the annual net and almost double for the annual gross value.

Similarly, the wave transformation model has been run for the average condition of wave characteristics in the study area for different months during 2009. The estimated LSTR for this approach also has large variation compared to the estimated LSTR for the model run with full data. The annual net and gross LSTR estimated for this approach is $-1.54 \times 10^5 \text{ m}^3$ and $4.65 \times 10^5 \text{ m}^3$, respectively.

Both of the approaches give a higher percentage of variation in the LSTR, and hence, the uncertainty in the estimation is clear. Since the seasonal dependent variations of wave characteristics are larger, the uncertainty will be higher.

Interannual variation in LST

Kumar et al. (2012) observed that the wave characteristics at a 9 m water depth off Malpe and Honnavar do not vary significantly. Hence, the wave data measured in 2011 off Kundapur, a location between Malpe and Honnavar, is used as the model

input for estimating the nearshore wave parameters off Malpe. Then the LSTR is estimated using the Kamphuis formula. Based on the LSTR estimate for 2009 and 2011, the inter-annual variation is studied. The study indicates considerable variation in the monthly net LSTR during January, February and June with a higher (~ 2 times) net LSTR during 2009 than during 2011 (Table 4). During August, September and October, the monthly net LSTR is higher during 2011 than during 2009. Variation in the gross LSTR is also observed during the peak monsoon season (August), with the LSTR during August 2011 being 1.5 times that during August 2009. Even though the difference in the average monthly significant wave height and mean wave period is less during 2009 and 2011 for most of the months (Table 4), changes occur in the wave direction. As evident from the sensitivity analysis, the direction of wave approach is a major factor influencing the longshore sediment transport. The relative error in the net LSTR estimate based on the Kamphuis formula during the monsoon season for a $+5(-5^0)$ error in the offshore wave direction is 15(10)%, while that in the estimate of the gross LSTR is 13(9)%. Hence, considerable variation in monthly net and gross LSTR is observed during different months. The annual net LSTR estimated based on the Kamphuis formula is $3.0 \times 10^5 \text{ m}^3$ during 2011 and $3.2 \times 10^5 \text{ m}^3$ during 2009 in the northerly direction. The annual gross LSTR is $3.63 \times 10^5 \text{ m}^3$ during 2011 and $3.57 \times 10^5 \text{ m}^3$ during 2009.

Table 4 Monthly net and gross LSTR estimated based on Kamphuis and the monthly average value of significant wave height, mean wave period and peak wave period during 2009 and 2011

Month	2009 Net LSTR (m ³ /month)	2011	2009 Gross LSTR (m ³ /month)	2011	2009 Mean Hmo (m)	2011	2009 Mean Tmo (s)	2011	2009 Mean Tp (s)	2011
Jan	12,568	6274	13,302	10,094	0.5	0.5	5.2	4.2	12.3	10.3
Feb	9491	5240	12,005	9211	0.6	0.5	4.5	3.9	9.9	9.3
Mar	23,706	19,055	25,675	20,814	0.7	0.6	4.8	4.4	12.8	11.9
Apr	30,424	25,104	32,601	26,833	0.8	0.7	5.2	4.6	13.0	13.3
May	36,109	30,639	37,498	35,318	1.0	0.9	5.2	5.1	12.1	12.5
Jun	59,232	27,000	59,765	56,636	1.5	2.2	6.1	6.5	10.7	10.6
Jul	30,904	30,755	51,746	37,803	2.3	2.0	6.4	6.6	11.5	10.6
Aug	40,971	54,187	41,148	61,026	1.5	1.7	5.9	6.3	9.7	10.7
Sep	34,932	48,849	35,657	48,973	1.2	1.4	5.6	6.4	12.3	12.0
Oct	25,334	33,642	26,742	33,642	0.8	0.7	5.9	6.6	12.5	13.8
Nov	12,448	12,765	12,466	12,765	0.6	0.6	5.1	5.9	11.6	12.4
Dec	8703	9326	8990	10,144	0.4	0.5	5.2	5.2	12.0	12.0

Role of present study on the coastal management strategies

Coastal erosion is observed along the Padukare beach (Fig. 1) during southwest monsoon and in order to protect the beach, Government of Karnataka requested the central Government to construct coastal protection measures. Since site-specific data on coastal dynamics is not available, a study is carried out to generate this data for planning coastal protection measures and shoreline management plans. The data on waves and LSTR presented in this study are prerequisite to successful coastal zone management under impacts of natural and anthropogenic factors.

The present study emphasizes the need to have measured directional wave data covering an annual cycle with a short interval (~1 h) before planning coastal protection measures, since the variation in H_{m0} in one day is up to 1.6 m. Seasonal variations of nearshore waves and longshore sediment transport provided in this paper is an useful information for the scientific understanding of coastal processes and management. The interannual variation in the net LSTR for the study area is around 7 %, and the interannual variation for the gross LSTR is 1.6 %, indicating that the interannual variations in LSTR are not significant and the LSTR values presented in this paper can be used for formulating an effective coastal zone management plan at Padukare, Karnataka, west coast of India. Since the annual net LSTR of $\sim 3.0 \times 10^5 \text{ m}^3$ is towards north, if any groin or breakwater is planned in the coastal zone, it will result in shoreline advancement in the southern areas and erosion in the northern part.

The study indicates that the estimate of the LSTR based on grouping the waves in different class intervals may not be accurate since wave direction is a sensitive parameter for the study

area and most of the waves have a direction between 230 and 260° (Fig. 6). This makes the 30° bins result in error in the LSTR estimate. The study shows that within a distance of 50 km along the coast, there is a large difference in the net LSTR, even though the gross LSTR is similar and hence site specific data is required for planning coastal protection measures.

Conclusions

To assess the effect of human interventions in the coastal zone and plan remedial measures, it is necessary to have the information on the nearshore processes. The measured data indicates that, about 80 % of the time, the significant wave height is less than 1.5 m with an annual average value of ~1 m. The average breaker height during the monsoon period (1.6 m) is 3 times the value during the pre- and post-monsoon periods (0.7 and 0.6 m). The estimated longshore sediment transport rate (LSTR) based on the CERC, Walton and Bruno, Kamphuis and Komar formulae during the monsoon period (4 months) is 58, 40, 53 and 63 % of the total LSTR. The non-monsoon periods (8 months) contribute about 42, 60, 47 and 37 % of the total LSTR. The average transport coefficient K for the coast studied is 0.11 for the CERC and 0.15 for the Walton and Bruno formula, and it is much lower than the generally used value of 0.39. The annual estimates of the LSTR indicate a predominant northerly transport along the study area with a net LSTR of $3.2 \times 10^5 \text{ m}^3$. The influence of breaker angle on the LST is high during the monsoon season. The sensitivity of coastal inclination on the LST is more compared to the off-shore wave angle. Even a small deviation (4°) in the coastal inclination can cause a large variation (20 %) in estimates of the LSTR. The inter-annual variation of the LSTR showed

that, even though considerable variation in the monthly values are observed, the inter-annual variation of the annual net and gross transport is less than 7 %.

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Annexure: LST formulae used in the study

i) The CERC Formula (USACE 1984)

The LSTR is calculated from the empirical equation relating to the longshore energy flux in the breaker zone as given by Eq. (A1),

$$Q = \frac{K A \rho g H_b^2 T \sin(2\alpha_b)}{64\pi} \quad (A1)$$

where Q = the LSTR (m^3/yr), K = the dimensionless empirical proportionality constant (taken as 0.39), H_b = the breaking wave height (m), T = the wave period (s), $A = \left(\frac{1}{(\rho_s - \rho)} g(1-p)\right)$, ρ_s = the sediment density (kg/m^3), ρ = the density of water (kg/m^3), α_b = the angle between the breaking wave crest and the local shoreline (deg), g = acceleration due to gravity (m/s^2) and p = Porosity (0.4).

ii) The Kamphuis (2002) Formula

Kamphuis (2002) developed an empirical formula that includes the beach slope and sediment grain size based on their laboratory experiments and field data. It is given by Eq. (A2):

$$Q = \left(\frac{2.27 H_b^2 T_p^{1.5} m^{0.75} d_{50}^{0.25} \sin(\alpha_b)}{(\rho_s - \rho) g (1-p)} \right) \quad (A2)$$

where T_p = the peak wave period (s), d_{50} = the sediment median grain size (mm), and m = the slope of the sea bottom under the surf zone.

iii) The Walton and Bruno (1989) Formula

Using the breaker height and longshore current velocity, the LSTR is calculated as shown in Eq. (A3):

$$Q = \frac{K A \rho g H_b W V C_f}{0.78 \left(\frac{5\pi}{2}\right) \left(\frac{V}{V_0}\right)_{LH}} \quad (A3)$$

where W = the surf zone width (m), C_f = the friction coefficient (dimensionless), and $(V/V_0)_{LH}$ = theoretical dimensionless longshore current velocity with the mixing parameters as 0.4. The longshore current (V) is estimated based on the formulae given by Longuet-Higgins (1970) as

$$V = 20.7 m (g H_b)^{1/2} \sin(2\alpha_b) \quad (A4)$$

iv) The Komar (1998) Formula

In this case, the LSTR, measured as a volume using the significant wave height proposed by Komar and Inman (1970), is given as shown in Eq. (A5).

$$Q = 0.46 \rho g^{3/2} H_b^{5/2} \sin(\alpha_b) \cos(\alpha_b) \quad (A5)$$

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